



Performance enhancement of parabolic dish solar cookers using thermal energy storage

Katlego Aubrey Lentswe



orcid.org 0000-0001-7253-7729

Thesis accepted in fulfilment of the requirements for the degree
Doctor of Philosophy in Physics at the North-West University

Promoter: Prof. A Mawire

Co-promoter: Dr. AB Shobo

Graduation ceremony: May 2024

Declaration

I, Katlego Aubrey Lentswe, declare that this thesis entitled 'Performance enhancement of parabolic dish solar cookers using thermal energy storage' and the work presented in it are my own. I confirm that:

- i. This work was done while I was a candidate for a research degree at the North-West University.
- ii. Where any part of this thesis has previously been submitted for a degree or any other qualification at the North-West University or any other institution, this has been clearly stated.
- iii. Where I have consulted the published work of others, this is always clearly stated.
- iv. Where I have quoted from the work of others, the source is always given. Apart from such quotations, this thesis is entirely my own work.
- v. I have acknowledged all main sources of assistance.

Acknowledgements

I am grateful to my supervisors, Prof. Ashmore Mawire and Dr. Adedamola Shobo, who chose to believe in me, and gave me a chance to pursue my dreams. Their professional guidance during this research is immeasurable.

I appreciate my parents, Mr. MA Lentswe and Mrs D. M Lentswe (late), for laying out a solid educational foundation in my life. I would also like to thank my sister Boipelo Lentswe for her emotional and moral support throughout my academic journey. I also acknowledge my son Gofaone and girlfriend for moral support during my study.

I am grateful for financial support provided by North-West University, Service SETA and SOLTRAIN in terms of postgraduate bursaries. I also appreciate all the support from the physics staff members and management. I would also like to thank my colleagues at the North-West University for the fruitful discussions related to my research work.

I would like to show gratitude to the Lord Jehovah for caring for me in this academic journey.

List of publications

This thesis comprises some or all the information presented in the following published journal and conference articles that appear in the same order in the thesis:

1. **Lentswe K.**, Mawire, A., Owusu P., Shobo A. (2021). A review of parabolic solar cookers with thermal energy storage. *Heliyon* 7, e08226.
<https://doi.org/10.1016/j.heliyon.2021.e08226>
2. Mawire A., **Lentswe K.**, Owusu P., Shobo A., Darkwa J., Calautit J., Worall M. (2020). Performance comparison of two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking. *Solar Energy* 208, 1166-1180.
<https://doi.org/10.1016/j.solener.2020.08.053>
3. Mawire A., **Lentswe K.**, Owusu P. (2022). Performance of two solar cooking storage pots using parabolic dish solar concentrators during solar and storage cooking periods with different heating loads. *Results in Engineering* 13, 100336.
<https://doi.org/10.1016/j.rineng.2022.100336>
4. Tegenaw P.D., **Lentswe K.**, Mawire A., Owusu P., Vanierschot M. (2021). A thermal model of a solar cooker with thermal energy storage using computational fluid dynamics. In the International Solar Energy Society (ISES) conference proceedings Database, Solar World Congress 2021 (SWC 2021), Virtual, 517-522.
<http://proceedings.ises.org/paper/swc2021/swc2021-0052-Tegenaw.pdf>
5. **Lentswe, K.A.**, Mawire A., Owusu P., Shobo, A.B. (2021). An experimental study of a combined solar cooking and thermal energy storage system for domestic applications. In the Proceedings of South African Institute of Physics (SAIP) conference, SAIP 2021, 22-30 July 2021, Potchefstroom, South Africa, 590-597.
<http://saip.org.za/Proceedings/Track%20F/96.pdf>
6. **Lentswe, K.**, Mawire, A. (2022). Charging energetic and exergetic evaluation of a combined solar cooking and thermal energy storage system. In the Proceedings of the 11th International Conference on Renewable Energy Research and Application, ICRERA 2022, September 18-21, 2022, Istanbul, Turkey, 71-76.
<https://ieeexplore.ieee.org/document/9922710>
7. **Lentswe K.**, Mawire A., Owusu P. (2022). Experimental energetic and exergetic performance of a combined solar cooking and thermal energy storage system. *Energies* 15, 8334.
<https://doi.org/10.3390/en15228334>

The author contribution statements are given at the end of each published paper in this thesis.

Table of Contents

Declaration	2
Acknowledgements	3
List of publications	4
List of figures.....	9
List of Tables	13
List of abbreviations and symbols	15
Abstract	17
Chapter 1: Introduction	19
1.1 Background of the study	19
1.2 Problem statement	20
1.3 Aim and objectives.....	21
1.4 Outline of the thesis.....	22
References	22
Chapter 2: A review of parabolic solar cookers with thermal energy storage	25
Overview and abstract.....	25
2.1 Introduction	26
2.2 Types of solar cookers.....	27
2.2.1 Solar box cooker.....	27
2.2.2 Concentrated solar cookers	28
2.2.3 Indirect solar cookers.....	29
2.3 Thermal energy storage for solar cookers	30
2.4 Previous recent reviews on solar cookers	31
2.5 Objective and justification	34
2.6 Parabolic solar concentrating cookers with sensible heat thermal energy storage (SHTES)	34
2.6.1 Parabolic trough cookers with SHTES	34
2.6.2 Parabolic dish cookers with SHTES	38
2.7 Parabolic solar concentrating cookers with latent heat thermal energy storage (LHTES)	47
2.7.1 Parabolic trough cookers with LHTES	47
2.7.2 Parabolic dish cookers with LHTES.....	50
2.8 Conclusion.....	61
Credit author contribution statement	62
References	62
Chapter 3: Performance comparison of two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking	70

Overview and abstract	70
3.1 Introduction	70
3.2 Materials and method	76
3.2.1 Parabolic dish solar cooker	76
3.2.2 Solar cooking pot and storage materials	77
3.2.3 Wonderbag cookers.....	80
3.2.4 Experimental method	81
3.2.5 Experimental thermal analysis.....	85
3.3 Results and discussion	87
3.4 Future work.....	99
3.5 Conclusion.....	100
Credit author contribution statement	101
Declaration of competing interest.....	101
Acknowledgement	102
Appendix A.....	102
References	104
Chapter 4: Performance of two solar cooking storage pots using parabolic dish solar concentrators during solar and storage cooking periods with different heating loads.	109
Overview and abstract.....	109
4.2 Introduction	110
4.2 Materials and methods.....	112
4.3 Experimental thermal analysis.....	117
4.4 Results and discussion	118
4.5 Conclusion.....	127
Credit author contribution statement	129
Declaration of competing interest.....	129
Acknowledgement	129
References	129
Chapter 5: A thermal model of a solar cooker with thermal energy storage using computational fluid dynamics.....	133
Overview and abstract.....	133
5.1 Introduction	133
5.2 Numerical model.....	135
5.3 Experimental validation	136
5.4 Heat transfer mechanisms.....	137
5.4.1 Transient heating	137

5.4.2 Steady state.....	138
5.5 Conclusion.....	139
Credit author contribution statement	139
Acknowledgements.....	140
References	140
Chapter 6: An experimental study of a combined solar cooking and thermal energy storage system for domestic applications.....	142
Overview and abstract.....	142
6.1 Introduction	142
6.2 Experimental setup and procedure	144
6.3 Thermal analysis.....	146
6.4 Results and discussion	147
6.5 Conclusion.....	150
Credit author contribution statement	150
Acknowledgement	150
References	150
Chapter 7: Charging energetic and exergetic evaluation of a combined solar cooking and thermal energy storage system.....	153
Overview and abstract.....	153
7.1 Introduction	153
7.2 Experimental method and setup	154
7.3 Thermal analysis.....	157
7.4 Results and discussion	158
7.5 Conclusion.....	163
Credit author contribution statement	164
Acknowledgement	164
References	164
Chapter 8: Experimental energetic and exergetic performance of a combined solar cooking and thermal energy storage system	166
Abstract and overview.....	166
8.1 Introduction	167
8.2 Experimental setup and procedure	171
8.3 Thermal performance parameters	174
8.3.1 Energy analysis.....	174
8.3.2 Exergy analysis	175
8.3.3 Experimental uncertainty.....	176

8.4 Results	176
8.5 Discussion of the Results.....	185
8.5.1 Charging Energetic and Exergetic Performance with Different Flow Rates and Heating Loads	185
8.5.2 Discharging Energetic and Exergetic Performance with Different Flow Rates and Heating Loads	187
8.5.3 Comparison of results with other researchers and cost.....	189
8.6 Conclusion.....	190
Credit author contribution statement	191
Acknowledgement	192
References	192
Chapter 9: Conclusions and recommendations.....	196
9.1 Conclusions and summary of the research work.....	196
9.2 Recommendations for possible future work.....	199

List of figures

Figure 2.1: Different types of solar box cookers: (a) without reflector, (b) with single reflectors, (c) with double reflectors, (d) with three reflectors, (e) with four reflectors and (f) with eight reflectors. The figure was reproduced from Ref. [10], with the permission of Elsevier Publishing.....	27
Figure 2.2: (a) A schematic diagram of a parabolic dish concentrating solar cooker, (b) a square parabolic dish solar concentrating cooker (SPD-SCC) with a pot. (a) was reproduced from Ref. [24], with the permission of Elsevier Publishing. (b) was reproduced from Ref. [25], with the permission of Elsevier Publishing.....	29
Figure 2.3: A schematic diagram of an indirect solar cooker. The figure was reproduced from Ref. [24], with the permission of Elsevier Publishing.....	30
Figure 2.4: A parabolic trough solar thermal cooker (PTSC) with a cooking box containing thermal oil. The figure was reproduced from Ref. [58], with the permission of Elsevier Publishing.....	35
Figure 2.5: A photograph of the experimental setup of a portable solar cooker and water heater. The figure was reproduced from Ref. [73], with the permission of Elsevier Publishing.....	39
Figure 2.6: (a) A photograph of a solar cooker pot with cooked chicken and chips (b) A labelled diagram of a solar cooking storage pot. The figure was reproduced from Ref. [84], with the permission of Elsevier Publishing.....	42
Figure 2.7: A photograph of a parabolic trough cooker integrated with LHTES. The figure was reproduced from Ref. [87], with the permission of Elsevier Publishing.....	47
Figure 2.8: A photograph of an experimental setup of a parabolic dish cooker combined with an insulated solar receiver/thermal energy storage. The figure was reproduced from Ref. [99], with the permission of Elsevier Publishing.....	52
Figure 3.1: A photograph of the parabolic dish solar cooker used in the cooking tests.....	77
Figure 3.2: Photographs of the storage cooking pot; (a) plan view, (b) side view and (c) the storage cooker painted black in a solar cooking experiment.....	78
Figure 3.3: Schematic of the storage cooking pot showing the dimensions.....	79
Figure 3.4: A photograph of the insulating wonderbag slow cooker used for heat retention cooking tests.....	80
Figure 3.5: Experimental testing of the two storage cooking pots with two parabolic dish solar cookers.....	82
Figure 3.6: Wonderbag cookers with the storage pots placed inside them during the heat retention off sunshine cooking experiments.....	84

Figure 3.7: (a) Direct solar radiation, wind speed profiles and, (b) temperature profiles of the two storage pots on 28 February 2020.....	88
Figure 3.8: Rice and potatoes cooked with water using the wonderbags combined with (a) the oil storage cooking pot and (b) the erythritol storage cooking pot on 28 February 2020.....	89
Figure 3.9: (a) Direct solar radiation, wind speed profiles and, (b) temperature profiles of the two storage pots on 9 March 2020.....	90
Figure 3.10: (a) Direct solar radiation, wind speed profiles and, (b) temperature profiles the two storage pots on 24 March 2020.....	91
Figure 3.11: (a) Direct solar radiation, wind speed profiles and, (b) temperature profiles the two storage pots on 25 March 2020.....	92
Figure 3.12: Chicken, tomatoes and chips (fries) cooked with sunflower oil using the wonderbags combined with (a) the oil storage cooking pot and (b) the erythritol storage cooking pot on 25 March 2020 during the first cooking period.....	94
Figure 3.13: Solar cooking (a) and storage cooking times (b) for different thermal masses of food.....	95
Figure 4.1: Photographs of (a) the parabolic dish solar cooker used in solar cooking tests, and (b) the wonderbag slow cooker used in off-sunshine storage cooking tests.....	113
Figure 4.2: (a) A photograph and (b) schematic diagram of the solar storage cooking pot.....	115
Figure 4.3: (a) Solar radiation and wind speed during the solar cooking period, and (b) temperature profiles of the two pots during solar and storage cooking periods for 1 kg load of water on May 29, 2020.....	120
Figure 4.4: (a) Solar radiation and wind speed during the solar cooking period, and (b) temperature profiles of the two pots during solar and storage cooking periods for a 1 kg load of oil on June 23, 2020.....	121
Figure 4.5: (a) Solar radiation and wind speed during the solar cooking period, and (b) temperature profiles of the two pots during solar and storage cooking periods for a 2.5 kg load of water on May 20, 2020.....	123
Figure 4.6: (a) Solar radiation and wind speed during the solar cooking period, and (b) temperature profiles of the two pots during solar and storage cooking periods for a 2.5 kg load of oil on July 30, 2020.....	124
Figure 4.7: Effect of the load on the (a) storage efficiency and, (b) heat utilisation efficiency.....	125
Figure 5.1: Photograph of the parabolic dish solar cooker with TES system implemented in the cooking pot. Left: parabolic solar collector, right: cooking pot with TES system.....	134

Figure 5.2: Schematic view of the geometry of the solar cooker with a TES system. The X's denote the locations of the temperature measurements for validation.....	136
Figure 5.3: Validation of the numerical simulations with the experiments of Mawire et al. [4].....	137
Figure 5.4: Temperature (K) profiles in the cooking pot at different time instants.....	138
Figure 5.5: Steady state temperature profile.....	139
Figure 6.1: Experimental setup of a solar parabolic dish cooker combined with a TES system. (1) Storage tank, (2) DC pump, (3) Flow meter, (4) Receiver, (5) Solar parabolic dish cooker and (6) Cooking pot.....	144
Figure 6.2: (a) Magnified photographs of the receiver, the (b) storage tank and, (c) schematic diagram of the experimental setup.....	145
Figure 6.3: (a) Direct solar radiation, (b) temperature profiles of the receiver, and (c) temperature profiles of the storage tank using 1 kg of water as the test load performed on 17 May 2021 using a flow-rate of 2 ml/s.....	148
Figure 7.1: A photograph of the experimental setup.....	155
Figure 7.2: A photograph showing the main components of the receiver.....	156
Figure 7.3: The photograph of the storage tank showing dimensions.....	156
Figure 7.4: A schematic diagram of the experimental setup.....	157
Figure 7.5: Water heating experimental results using a mass of 0.5 kg and a charging flowrate of 2 ml/s. (A) Direct solar radiation and wind speed, (B) the temperature profiles of the solar and (C) the temperature profiles of a storage tank. The experiments were performed on 10 July 2021.....	159
Figure 7.6: Water heating experimental results using a mass of 0.5 kg and a charging flowrate of 4 ml/s. (A) Direct solar radiation and wind speed. (B) the temperature profiles of the solar and (C) the temperature profiles of a storage tank. The experiments were performed on 3 July 2021.....	161
Figure 7.7: Experimental results of the effect of flow rate showing; (A) the average solar radiation and average wind speed, (B) the average energy rate, and energy efficiency and (C) the exergy rate and exergy during the charging cycles.....	162
Figure 8.1: An outdoor experimental setup of an SK-14 parabolic dish cooker combined with a TES system. The experimental components that were utilized are (1) a storage tank, (2) DC pump, (3) flow meter, (4) receiver, (5) solar parabolic dish cooker, and (6) a cooking pot.....	171
Figure 8.2: Photographs of the (a) receiver, (b) storage tank, and (c) a schematic flow diagram of the experimental setup.....	172
Figure 8.3: Experimental results of two test loads (water and sunflower oil) for a load of 0.5 kg utilizing a flow rate of 2.0 mL/s. (A) Direct solar radiation and wind speed (A1-water, A2-	

sunflower oil), (B) the temperature profiles of the solar receiver (B1-water, B2-sunflower oil), and (C) the temperature profiles of a storage tank (C1-water, C2-sunflower oil). Experimental dates were 10 July 2021 and 13 July 2021 for water and oil tests.....177

Figure 8.4: Experimental results of two test loads (water and sunflower oil) for a load of 0.5 kg utilizing a flow rate of 4.0 mL/s. (A) Direct solar radiation and wind speed (A1-water, A2-sunflower oil), (B) the temperature profiles of the solar receiver (B1-water, B2-sunflower oil), and (C) the temperature profiles of a storage tank (C1-water, C2-sunflower oil). Experimental dates were 3 July 2021 and 4 July 2021 for water and oil tests, respectively.....180

Figure 8.5: Experimental results of two test loads (water and sunflower oil) for a load of 1.0 kg utilizing a flow rate of 2.0 mL/s. (A) Direct solar radiation and wind speed (A1-water, A2-sunflower oil), (B) the temperature profiles of the solar receiver (B1-water, B2-sunflower oil), and (C) the temperature profiles of a storage tank (C1-water, C2-sunflower oil). Experimental dates were 17 July 2021 and 20 July 2021 for water and oil tests, respectively.....183

List of Tables

Table 2.1: A table summary of recent reviews.....	32
Table 2.2: A summary of parabolic solar concentrating cookers with sensible heat thermal energy storage (SHTES).....	44
Table 2.3: Summary of solar concentrating cookers with latent heat thermal energy storage (LHTES).....	58
Table 3.1: Properties of the cooking pots.....	78
Table 3.2: Thermophysical properties of the two storage materials used in this study.....	79
Table 3.3: Properties of the wonderbag cookers.....	81
Table 3.4: Details of the instrumentation.....	83
Table 3.5: A summary of the experimental conditions during the solar cooking periods.....	83
Table 3.6: A summary of the experimental test conditions during the storage cooking periods.....	84
Table 3.7: A summary of storage cooking temperatures attained using the wonderbag.....	95
Table 3.8: A summary of the solar cooking period experimental results.....	97
Table 3.9: A summary of the storage cooking period experimental results.....	98
Table 3.10: A comparison of recent work on storage cooking pots.....	99
Table 4.1: Thermophysical properties of the two storage materials used in this study [34].....	114
Table 4.2: Test conditions using water as the cooking load.....	115
Table 4.3: Test conditions using sunflower oil as the cooking load.....	114
Table 4.4: A summary of the solar heating and storage heat utilisation experimental results using water as the load.....	124
Table 4.5: A summary of the solar heating and storage heat utilisation experimental results using sunflower oil as the load.....	125
Table 6.1. A comparison of receiver charging and discharging efficiencies on different days using 1.0 kg of water.....	148
Table 8.1: Effect of the flowrate on the energetic and exergetic parameters for water and sunflower oil loads during charging cycles with a load of 0.5 kg.....	185
Table 8.2: Effect of the mass on the energetic and exergetic parameters for water and sunflower oil loads during charging cycles with 2.0 ml/s.....	185
Table 8.3: Effect of the flowrate on the energetic and exergetic of water and sunflower oil loads during discharging cycles with a load of 0.5 kg.....	187
Table 8. 4: Effect of the mass on the energetic and exergetic parameters for water and sunflower oil loads during discharging cycles with 2 ml/s.....	188

Table 8.5: A comparison of the present work with previous work done by other researchers.....	188
Table 8.6: Estimated total cost of the combined solar cooking and TES system.....	189

List of abbreviations and symbols

Abbreviations

CFD	Computational Fluid Dynamics
CNSL	Cashew Nutshell Liquid
HTF	Heat Transfer Fluid
LHTES	Latent Heat Thermal Energy Storage
LPG	Liquefied Petroleum Gas
SHTES	Sensible Heat Thermal Energy Storage
PCM	Phase Change Material
TCTES	Thermo-Chemical Thermal Energy Storage
TES	Thermal Energy Storage

Roman Symbols

Symbol	Property	Units
A_{ap}	Aperture area of the parabolic dish	m^2
A_c	Dish aperture area	m^2
c	Specific heat capacity	$kJkg^{-1}K^{-1}$
G	Direct solar radiation	Wm^{-2}
H	Height	m
I_{av}	Cumulative moving average solar radiation	Wm^{-2}
I_i	Initial solar radiation	Wm^{-2}
m	Mass	kg
m_f	Final mass	kg
m_{ini}	Initial mass	kg
$m_{loss} \%$	Percentage mass loss	$\%$
N	Number of samples	-
ΔT	Temperature difference	$^{\circ}C$
t_f	Final time	s
t_i	Initial time	s
T_{av}	Cumulative moving average temperature	$^{\circ}C$
T_b	Temperature of the bottom of tank	$^{\circ}C$

T_{Rin}	Inlet of the receiver	°C
T_{Rout}	Outlet of the receiver	°C
T_u	Temperature of the top of the tank	°C
Δt	Time difference	s
$P_R(Pr)$	Receiver power	W
P	Pressure	Pa
R	Radius	m
Ra_L	Rayleigh number	-
Q_{inc}	Total solar energy incident of dish aperture area	J
$Q_{ust}(Q_s)$	Total energy stored during the solar cooking	J
Q_{uti}	Total utilization of energy	J
V	Velocity vector	ms ⁻¹
$\dot{V}$	Flowrate of the oil during the circulating period	mls ⁻¹

Greek Symbols

Symbol	Property	Units
α	Thermal diffusivity	m ² s ⁻¹
β	Thermal expansion coefficient	K ⁻¹
g	Gravitational acceleration	m s ⁻²
ρ	Density of the fluid	kg m ⁻³
ρ_{av}	Average density	kg m ⁻³
η_{ch}	Charging efficiency	%
η_{dis}	Discharging efficiency	%
$\eta_{storage}(\eta_s)$	Solar thermal energy storage efficiency	%
η_{uti}	Heat utilisation efficiency	%
μ	Dynamic viscosity	kg m ⁻¹ s ⁻¹
ν	Kinematic viscosity	m ² s ⁻¹

Abstract

The performance enhancement of a parabolic dish solar cooker using thermal energy storage (TES) is evaluated. A detailed literature review of solar parabolic cookers with thermal energy storage for off-sunshine cooking is presented. Both parabolic trough and parabolic dish solar cookers are included in the review. The review concludes that most studies are on the experimental evaluation of parabolic dish solar cookers with limited numerical studies done. The review also suggests that other crucial factors, such as the choice of sensible or latent heat storage materials, environmental impact, different foods to be cooked, and social acceptance should also be investigated. Cooking experiments are conducted during solar and storage cooking periods with two identical solar cooking storage pots. Sunflower oil is used as the sensible heat storage material in one storage pot, while erythritol is used as a phase change material in the other pot. The two pots are enclosed in insulated wonderbag slow cookers to assess their thermal performance during non-sunny periods. The sunflower oil storage cooking pot shows faster cooking times (1.8-5.0 h) and higher maximum storage temperatures (124-145 °C) compared to the erythritol storage cooking pot (3.8-6.6 h; 118-140 °C) during solar cooking periods. The heat utilisation efficiencies of the erythritol pot (4.8-14.3 %) are greater than those of the sunflower pot (3.7-6.0 %) during storage off-sunshine cooking periods. A comparative experimental study on the effect of different cooking loads for two solar cooking pots incorporated with different thermal energy storage (TES) materials is presented. Five different loads are utilized in the cooking experiments (0.5, 1.0, 1.5, 2.0, 2.5 kg) using water and sunflower oil as the heating fluids. The effect of the load on the storage and heat utilisation efficiencies is investigated. When utilizing water as the test load, the erythritol pot shows slightly greater heat utilization efficiencies (13-49 %) compared the sunflower oil pot (17-46 %). When sunflower oil is used as the cooking fluid, the sunflower oil pot shows greater heat utilisation efficiencies (9.4-28 %) compared to the erythritol pot (9.2-19 %). A thermal model of a solar cooking pot is developed using computational fluid dynamics (CFD) for sunflower oil as the storage medium. The model shows good agreement with experimental results, and the variances between the model and experimental results are attributed to solar flux fluctuations in the experiments. Natural convection is the primary heat transfer mechanism in the TES system at first, creating a rather flat temperature profile. After 4 hours, the cooking pot attains a constant state temperature of 405.8 K, which is adequate to cook a variety of foods and vegetables.

A combined solar cooker with a sunflower oil storage tank (dual-purpose) is preliminary experimentally investigated during charging and discharging processes using 1.0 L of water. During the charging cycle, water is heated up to around 75 °C in a cooking pot with storage tank temperatures attaining temperatures above 100 °C. During discharging, the heat transfer was poor with the heated water only achieving temperatures just above 40 °C. Experimental charging energy and exergy thermal performance parameters of the dual-purpose solar cooking and TES system are also evaluated. Four different charging flowrates (2, 3, 4 and 5 ml/s) are used in the experimental charging tests. The average charging energy rate and the charging efficiency generally increases with an increase in the flowrate except for the highest flowrate (5 ml/s), due to lower average direct solar radiation conditions during the experimental test with the highest flowrate. Detailed energy and exergy thermal performance evaluations of the dual-purpose solar cooking and TES system during charging and discharging cycles are presented. The effects of the flowrate (2, 3, 4 and 5 ml/s) and load (0.5, 1.0, 1.5 and 2.0 kg) are investigated using sunflower oil and water as the heating loads. Charging results show that increasing the charging flowrate enhanced the average energy and exergy rates, as well as their related efficiencies. Water outperformed sunflower oil in terms of average charging energy and exergy efficiency. The average charging energy and exergy rates for water, as well as their related efficiencies, declined slightly as the mass load increased. The average charging energy, exergy rates, and efficiencies for sunflower oil decreased significantly as the mass increased, and sunflower oil showed lower values when compared to water. For the discharging results, the correlations between the energy and exergy thermal performance parameters with respect to flowrate and heating load are not well defined for both heating loads, possibly due to different initial storage tank temperatures at the start of discharging, and an inefficient discharging process that needs to be optimized in the near future.

Keywords: Charging and Discharging; Energy and Exergy; Parabolic Dish Solar Cooker; Thermal Energy Storage; Sunflower Oil and Water; Thermal Performance Evaluation

Chapter 1: Introduction

1.1 Background of the study

In third-world countries, cooking with sources of energy that release harmful gases is a day-to-day activity. These sources of energy range from biomass to petroleum fuels such as paraffin [1]. In developing countries located in Africa, the energy demand for cooking in rural areas relies on burning energy sources such as agricultural waste, paraffin and firewood which results in deforestation and premature deaths due to lung diseases as a result of inhaling smoke [2]. In a bid to reduce gas emissions produced by these fuels, there is a need to introduce a permanent energy resource which is affordable and environmentally friendly such as solar energy for cooking purposes. The most popular and abundant renewable energy resource that can be accessed in rural areas of Africa is solar energy, and it is free and readily available. It is estimated that there are more than 275 sunny days in a year with a mean daily solar radiation of about 5-7 kWh/m², and the total energy received by earth from the sun is about 120 TW [3]. This is evidence that solar energy might meet the energy demand in the domestic sectors for rural areas in developing countries.

Solar energy applications such as solar cooking and water heating would be beneficial to the domestic sectors in rural Africa, thus they need to be developed further. Cooking with the sun must be promoted and encouraged in disadvantaged communities in Africa because energy from the sun is free, and solar cookers are easy to operate. Utilizing solar cookers in Africa will reduce emissions of toxic gases that are produced during cooking with biomass or fossil fuels. Solar energy is an alternative clean energy source which can be used for cooking food, particularly in developing countries where traditional forms of cooking such as burning wood, agricultural waste and animal dung are still prevalent [4, 5]. Solar cookers are considered as viable alternative cooking devices for both urban and rural areas in regions with high solar radiation. Advantages of solar cookers are that they are environmentally friendly, user friendly, cheap to maintain, and they reduce deforestation [6-9]. Another advantage is that solar cookers reduce health issues such as eye and lung diseases which are disproportionately high among rural women in many developing countries where biomass is the primary source of energy for cooking [10, 11].

Solar cooking offers an affordable cooking option for disadvantaged communities. There are three main types of solar cookers which are (a) panel solar cookers, (b) solar box cookers and (c) concentrating solar cookers. A simple panel solar cooker is composed of reflective panels that surround the cooking vessel or pot that is covered with plastic/glass to trap sun rays. The reflective panels reflect sun rays to the cooking vessel or pot, and they are usually made of aluminium. The disadvantages are that their performance deteriorates under windy conditions and cooking temperatures are moderately high. The solar box cooker is composed of an insulated box, a transparent glass or plastic cover and one or more reflective mirrors that are used to reflect the sun's rays to the cooking chamber. The main disadvantage of this type of solar cooker is that it achieves lower temperatures for efficient cooking in a short period of time. Concentrating solar cookers can achieve higher temperatures for most cooking processes which include roasting, frying, baking, and boiling. One of the most common types of concentrating solar cookers is the parabolic dish cooker. The parabolic dish cooker is composed of a parabolic reflective surface, and a stand to support a cooking pot in the focal region. Parabolic dish cookers also have a tracking mechanism to focus solar radiation properly at the focal point or region. The parabolic dish cooker is the most suitable in terms of the cooking speed and its ability to perform different cooking processes. The main disadvantage of solar cookers is that they cannot be utilized during cloudy, low and non-sunshine periods such as at night because their operation solely depends on the solar radiation [12].

1.2 Problem statement

Since solar cookers cannot operate during off-shine periods, a viable or alternative solution to alleviate this mismatch is to combine solar cookers with thermal energy storage (TES) systems [13]. Even though parabolic dish cookers are popular and can achieve high temperatures for different cooking processes, they cannot be used during periods without the sun, as is the case with all other types of solar cookers. To alleviate this problem, TES can be directly combined with the cooking pot of a parabolic dish cooker, which is the direct storage cooking mode [14]. In the indirect storage configuration, a TES system can be combined with a parabolic dish cooker so that heat can be transported from the solar receiver to the TES system where cooking occurs [15]. A heat transfer fluid is usually used for transporting heat, and indoor cooking is possible with the indirect mode of cooking. These

two modified configurations allow for cooking during non-shine hours, thus improving the effectiveness of solar cookers. There is rather limited recent research work that has focused on solar cookers with TES, especially in the indirect mode for the dual purpose of cooking and storing energy for other domestic applications such as water heating [16-18]. The research thus proposes the use of TES, both in the direct and indirect modes, to enhance the effectiveness of parabolic dish solar cookers. The novel issue addressed by this research is that, while the majority of parabolic dish cookers with TES systems perform a single task, which is to cook food, a multi-purpose parabolic dish cooker TES enables the user to cook food and store energy during sunny periods, and the stored thermal energy can then be used during non-sunshine periods for cooking as well as other domestic purposes such as cleaning dishes and bathing. There is a need to implement and promote multi-purpose parabolic dish cookers with TES to meet the energy supply and demand in rural communities especially in the developing world. Instead of purchasing or fabricating individual solar cooking systems which may be more expensive, the advantage of a multi-purpose parabolic dish cooker with TES is that it can perform multiple tasks simultaneously, for example cooking and storing TES simultaneously. The stored TES can be used for multiple domestic purposes such as cooking, bathing, washing dishes and clothes and preparing hot drinks such as coffee and tea.

1.3 Aim and objectives

The aim of this research is to characterize, enhance and optimize the performance of parabolic dish cookers using thermal energy storage. To achieve this, the objectives of the study are to:

- Develop specialized cooking pots that can be filled with storage media for the direct storage mode of operation using parabolic dish solar cookers.
- Experimentally investigate and compare the performance of the specialized cooking pots with both sensible and latent heat storage.
- Investigate and enhance the performance of the specialized cooking pots for non-shine hours using slow insulated wonderbag cookers.
- Develop a model for the specialized cooking pot with storage.
- Experimentally investigate the performance of a parabolic dish solar cooker with heat storage in the indirect mode based on energy and exergy analyses.

1.4 Outline of the thesis

The thesis begins with the introduction where the background of the study, problem statement and the aim and objectives are presented. In Chapter 2, a detailed literature review on parabolic dish solar cookers with thermal energy storage is presented. In Chapter 3, the experimental performance comparison of two solar cooking storage pots combined with wonderbag slow cookers is presented during solar and storage off-sunshine cooking periods. The thermal performance of two solar cooking storage pots containing sunflower oil and erythritol as storage media is investigated and compared. The performance of two solar cooking storage pots with different heating loads is presented in Chapter 4. A comparative experimental study on the effect of different cooking loads for two solar cooking pots incorporated with two different TES media is presented. Sunflower oil and erythritol are the two TES media considered in the comparison. Chapter 5 presents a thermal model of a solar cooker with TES using computational fluid dynamics (CFD). A CFD model is developed to evaluate the fluid flow and heat transfer mechanisms within the solar cooker, and it is validated with experimental results.

An experimental study of a combined solar cooking and thermal energy storage system for domestic applications is presented in Chapter 6. In this chapter, preliminary experimental results of a combined solar cooker with a sunflower oil storage tank are presented. Preliminary charging energetic and exergetic experimental evaluations of a combined solar cooking and thermal energy storage system are presented in Chapter 7. Detailed experimental charging energy and exergy results of the thermal performance of a solar cooker combined with a thermal energy storage system are presented in Chapter 8. Charging experiments are carried out with four different flowrates (2, 3, 4 and 5 ml/s) for the dual purpose of cooking and TES. Discharging results using the same flowrates as in the charging processes are also presented. Chapter 9, the last chapter, presents an overall summary of the research results and recommendations for future work.

References

- [1] Eva, I.J., Mahi, A., & Saharier, F. (2021). *Well-to-Wheel Life Cycle Analysis of Liquefied Petroleum Gas* (Doctoral dissertation, Department of Mechanical and Production Engineering (MPE), Islamic University of Technology (IUT), Board Bazar, Gazipur, Bangladesh).

- [2] Mandelli, S., Barbieri, J., Mattarolo, L., & Colombo, E. (2014). Sustainable energy in Africa: A comprehensive data and policies review. *Renewable and Sustainable Energy Reviews*, 37, 656-686.
- [3] Saxena, A., Srivastava V., & Srivastava, G. (2012). A technical note on performance testing of a solar box cooker provided with sensible storage material on the surface of absorbing plate. *International Journal of Renewable Energy Technology*, 3, 165-173.
- [4] Bond, T., & Templeton, M. R. (2011). History and future of domestic biogas plants in the developing world. *Energy for Sustainable Development*, 15, 347-354.
- [5] Bhutto, A. W., Bazmi, A. A., & Zahedi, G. (2013). Greener energy: Issues and challenges for Pakistan—wind power prospective. *Renewable and Sustainable Energy Reviews*, 20, 519-538.
- [6] Wentzel, M., & Pouris, A. (2007). The development impact of solar cookers: a review of solar cooking impact research in South Africa. *Energy Policy*, 35, 1909-1919.
- [7] Yettou, F., Azoui, B., Malek, A., Gama, A., & Panwar, N. L. (2014). Solar cooker realizations in actual use: An overview. *Renewable and Sustainable Energy Reviews*, 37, 288-306.
- [8] Keith, A., Brown, N. J., & Zhou, J. L. (2019). The feasibility of a collapsible parabolic solar cooker incorporating phase change materials. *Renewable Energy Focus*, 30, 58-70.
- [9] Arunachala, U. C., & Kundapur, A. (2020). Cost-effective solar cookers: A global review. *Solar Energy*, 207, 903-916.
- [10] Staton, D. M., & Harding, M. H. (1998). Health and environmental effects of cooking stove use in developing countries. *The Renewable Energy Policy Project and the Center for Renewable Energy and Sustainable Technology*, (accessed October 2021).
- [11] Gordon, S. B., Bruce, N. G., Grigg, J., Hibberd, P. L., Kurmi, O. P., Lam, K. B. H., ... & Martin, W. J. (2014). Respiratory risks from household air pollution in low and middle income countries. *The Lancet Respiratory Medicine*, 2, 823-860.
- [12] Balachandran, S., & Swaminathan, J. (2022). Advances in Indoor Cooking Using Solar Energy with Phase Change Material Storage Systems. *Energies*, 15, 8775.
- [13] Goel, V., Saxena, A., Kumar, M., Thakur, A., Sharma, A., & Bianco, V. (2022). Potential of phase change materials and their effective use in solar thermal applications: A critical review. *Applied Thermal Engineering*, 119417.
- [14] Battocchio, C., Bruni, F., Di Nicola, G., Gasperi, T., Iucci, G., Tofani, D., ... & Venditti, I. (2021). Solar cookers and dryers: environmental sustainability and nutraceutical content in food processing. *Foods*, 10, 2326.
- [15] Li, G., & Zheng, X. (2016). Thermal energy storage system integration forms for a sustainable future. *Renewable and Sustainable Energy Reviews*, 62, 736-757.
- [16] Nkhonjera, L., Bello-Ochende, T., John, G., & King'onde, C. K. (2017). A review of thermal energy storage designs, heat storage materials and cooking performance of solar cookers with heat storage. *Renewable and Sustainable Energy Reviews*, 75, 157-167.
- [17] Panchal, H., Patel, J., & Chaudhary, S. (2019). A comprehensive review of solar cooker with sensible and latent heat storage materials. *International Journal of Ambient Energy*, 40, 329-334.

- [18] Muthusivagami, R. M., Velraj, R., & Sethumadhavan, R. (2010). Solar cookers with and without thermal storage—a review. *Renewable and Sustainable Energy Reviews*, 14, 691-701.

Chapter 2: A review of parabolic solar cookers with thermal energy storage

Overview and abstract

In this chapter, a literature review of previous work done on parabolic solar cookers with thermal energy storage systems is presented. This chapter consists of work that has been published in the Heliyon journal ([Heliyon 7\(10\), 2021](#))

Biomass and fossil fuels are mostly used in rural areas of developing countries for cooking. These energy resources have negative impacts on the environment and human health mainly due to deforestation and greenhouse gas emissions. A cleaner and environmentally friendly form of cooking is solar cooking using the sun's energy. Parabolic solar cookers perform better than other solar cookers such as box solar cookers since higher temperatures are achieved in a shorter duration. These higher temperatures allow most types of cooking processes such as boiling, frying, roasting, and baking to be possible. The major problem with most conventional solar cookers is that cooking is not possible during off-sunshine periods. Integrating solar cookers with thermal energy storage (TES) makes cooking during off-sunshine periods possible. This chapter presents a comprehensive review of parabolic solar cookers with TES, which is a sustainable cooking solution for developing countries. Previous work on both parabolic trough and parabolic dish solar cookers with TES is presented. Solar cookers with storage are classified according to the two main types of TES technologies which are sensible heat thermal energy storage (SHTES) and latent heat thermal energy storage (LHTES). The main conclusions of the review are that; parabolic dish solar cookers with TES are more common than parabolic trough cookers, more studies have been done using latent heat storage as compared to sensible heat storage, limited modelling work has been presented, most of the parabolic cookers used aluminium sheets as the reflecting material, large scale experimental studies are limited, and fewer studies tackled the techno-economic and socio-economic aspects. The review also highlights research gaps on parabolic solar cookers with TES in terms of the modelling, combined TES (sensible and latent heat), different reflector materials, large-scale experimental setups, and techno-economic and socio-economic analyses. Other important aspects to consider for

parabolic solar cookers with TES include the choice of sensible or latent heat storage materials, environmental impact, types of food to be cooked, and social acceptance.

2.1 Introduction

Cooking is a vital method used by human beings to prepare food for survival, and it is responsible for a large amount of energy consumption in many countries. In developed countries such as the United States of America, cooking accounts for about 37 % - 53 % of total energy consumption [1]. In developing countries located in Africa, Asia, and South America, a major part of the residential energy consumption is utilized for cooking. A study conducted by Karekezi [2] showed that about 80 % of Sub-Saharan African countries still utilize firewood, fossil fuels, biomass, and electricity for cooking food, which results in huge amounts of greenhouse gas emissions and deforestation. This indicates that there is a need for alternative cooking methods that are environmentally friendly and use clean energy resources.

Although only about 14 % of the world's available renewable energy potential is currently being utilized, the percentage utilization of renewables is projected to increase soon due to concerted global efforts to mitigate against global warming due to greenhouse gases emission [3]. Solar energy has gained prominence over recent years as an alternative energy source for developing countries. It is estimated that the solar radiation flux in the sunniest region of the earth is about 1 kW/m^2 , the total global solar radiation per day is about 7 kWh/m^2 , and the total amount of solar energy received on earth is approximately $1.8 \times 10^{11} \text{ MW}$ [4]. This is about 10 000 times larger than the present energy consumption rate from all other commercial energy sources. This indicates that solar energy can be exploited for a wide range of domestic energy requirements, especially cooking.

Solar collectors can be regarded as devices that help to concentrate/collect solar radiation by capturing and converting radiant energy from the sun into thermal or electrical energy. Solar collectors can be categorized into two groups, namely non-concentrated collectors (flat plate collector, evacuated tube collector, etc.) and concentrated collectors (parabolic dish, parabolic trough, etc.). Some of these collectors can be modified easily for solar cooking. A solar cooker is a solar collecting device that uses the energy from the sun to cook food. Solar cookers are not a recent novel idea, and they have undergone several modifications over the

years [5]. However, there is still room for improvements to achieve higher efficiency, lower cost, greater portability, and further adaptability to different environmental conditions. The three main types of solar cookers are: solar box cookers, concentrated solar cookers, and indirect solar cookers, and these will be discussed in the next section.

2.2 Types of solar cookers

2.2.1 Solar box cooker

There are various types of solar box cookers or oven solar cookers that have been fabricated from previous studies [6, 7, 8]. A common solar box cooker consists of an insulated box with a transparent glass or plastic cover that allows solar radiation to pass through. Solar radiation is absorbed by the inner part of the solar box cooker while the transparent cover prevents solar radiant energy from leaving the interior of the box through the greenhouse effect [9]. In some solar box cookers, the interior of the box is painted black to maximize the absorption of solar radiant energy in order to increase the temperature of the cooking vessel placed inside. The insulated box is connected to reflectors which direct more solar radiation to the cooking vessel, thus increasing its cooking efficiency. Figure 2.1 shows different types of solar box cookers; namely (a) one without reflector, (b) one with a single reflector, (c) one with double reflectors, (d) one with three reflectors, (e) one with four reflectors, and (f) one with eight reflectors.

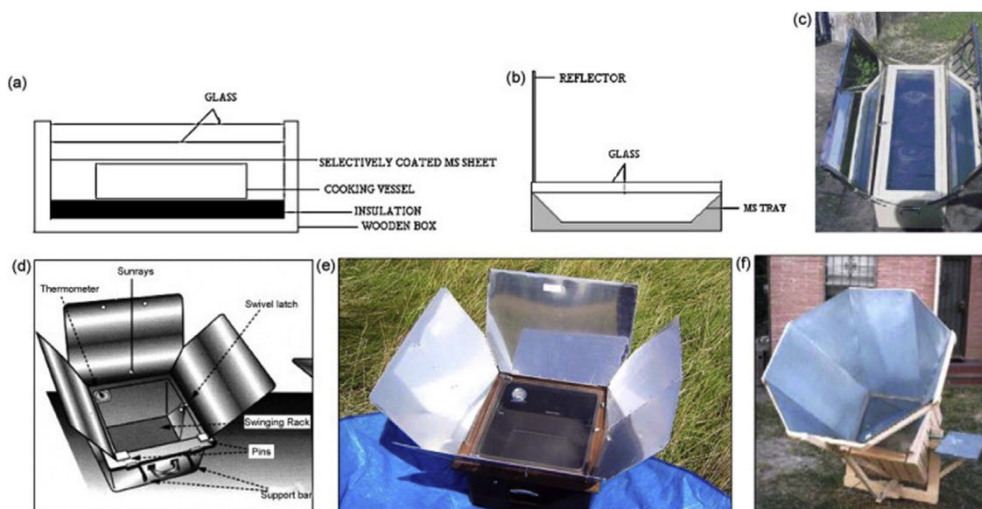


Figure 2.1: Different types of solar box cookers: (a) without reflector, (b) with single reflectors, (c) with double reflectors, (d) with three reflectors, (e) with four reflectors and (f) with eight reflectors. The figure was reproduced from Ref. [10], with the permission of Elsevier Publishing.

One of the main reasons why solar box cookers are preferred over other types of solar cookers is that they have different types of uncomplicated designs. The appeal of solar box

cookers over other types of solar cookers include the fact that they are easy to construct, they are user-friendly and safe to use, they require limited attention during operation, they utilize both the direct and diffusion components of solar radiation and no solar tracking is required [11]. However, the main disadvantages of solar box cookers are that they require longer cooking periods and cannot be used for roasting or frying food. Other disadvantages are that they cannot cook during off-sunshine hours, and some solar box cookers are affected by prevailing weather conditions such as strong winds which result in slower cooking due to heat losses. Cooking with solar box cookers has been the most investigated, and well-documented solar cooking method [12, 13, 14, 15]. Solar box cooking experiments have been carried out at intermediate to high temperatures using different test loads and fluids to improve their thermal performance [16, 17, 18, 19, 20, 21].

2.2.2 Concentrated solar cookers

A category of solar cookers that are less popular but more efficient in terms of reaching higher cooking temperatures are the concentrating solar cookers [22]. A standard concentrating solar cooker is constructed with a framework stand to support the cooking vessel at the focal region and the parabolic reflector. A tracking mechanism is used to position the concentrating solar cooker to face the sun. A solar optical mechanism is also used to direct and concentrate the incident solar radiation to a focal region which enables the attainment of higher temperatures at the focal region. For direct concentrating solar cookers, the cooking vessel is placed at the focal region of the parabolic reflector during cooking periods. One of the most popular direct concentrating solar cookers that is easy to construct and operate is the parabolic dish cooker. A parabolic dish cooker can achieve high temperatures of between 350 °C and 400 °C as compared to other types of concentrating solar cookers [23]. The main disadvantages of the parabolic dish cooker are that it requires constant tracking of the sun, constant attention to prevent the burning of foods and there are fire risks during operation. Figure 2.2 shows a schematic diagram of a parabolic dish solar cooker, and a photograph of a square parabolic dish cooker. Solar concentrating cookers have also been used for intermediate to high-temperature applications using different test fluids [25, 26, 27, 28, 29]. However, these studies do not consider the incorporation of thermal energy storage into these cookers for off-shine cooking.

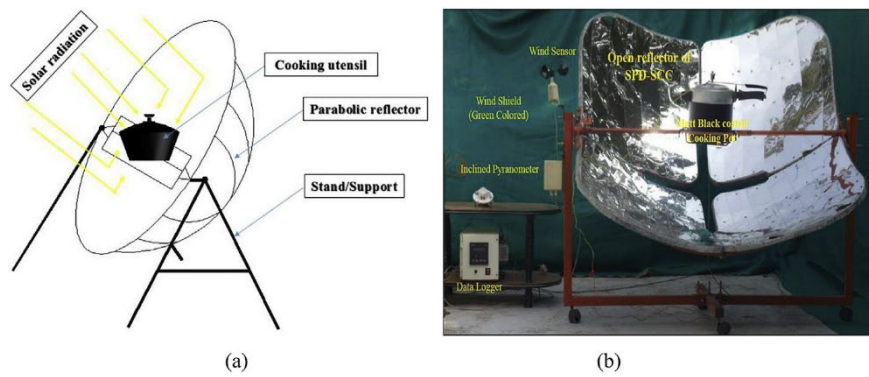


Figure 2.2: (a) A schematic diagram of a parabolic dish concentrating solar cooker, (b) a square parabolic dish solar concentrating cooker (SPD-SCC) with a pot. (a) was reproduced from Ref. [24], with the permission of Elsevier Publishing. (b) was reproduced from Ref. [25], with the permission of Elsevier Publishing.

2.2.3 Indirect solar cookers

Indirect solar cookers use heat transfer fluids such as molten salts or thermal oils to absorb heat from the heat source (at the focal region of the reflector) and transfer the heat to the cooking vessel [30]. The indirect solar cooker is designed in such a way that the cooking vessel is placed separately from the collector. Solar collectors such as a parabolic trough collector/flat plate collector can be placed on a roof or outside a building, and the cooking vessel can be placed indoors. The challenge facing this type of cooker is the high rate of heat loss during the circulation of the heat transfer fluid. However, the main advantage of an indirect concentrating solar cooker is that it can be easily incorporated with a thermal energy storage system for off-sunshine cooking. Figure 2.3 shows a diagram of an indirect concentrating solar cooker using a flat plate collector. The main disadvantage is that indirect solar cookers are expensive to fabricate and maintain. Indirect solar cookers have been used for intermediate to high temperatures for various cooking applications such as cooking vegetables and frying meat [31, 32, 33, 34], using different test loads; and fluids such as sunflower oil and olive oil. Thermal energy storage integrated with indirect solar cookers makes them more versatile for operation during off-shine periods [35].

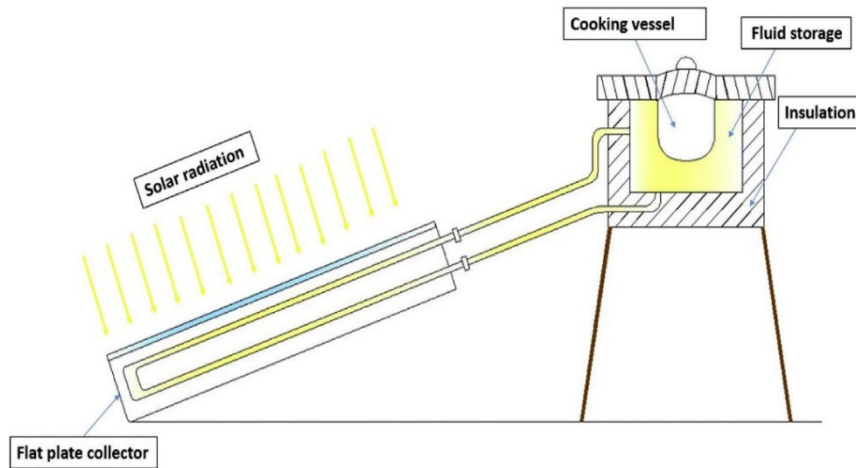


Figure 2.3: A schematic diagram of an indirect solar cooker. The figure was reproduced from Ref. [24], with the permission of Elsevier Publishing.

2.3 Thermal energy storage for solar cookers

Simple solar cookers can be used only when the sun is available as they cannot operate at night, during cloudy days, or when it is raining. However, thermal energy storage (TES) offers a solution for this mismatch between solar energy supply and demand. Combining solar cookers with a TES system enables cooking during periods when the sun is not available. TES can be classified into three main categories which are sensible heat thermal energy storage (SHTES), latent heat energy storage (LHTES), and thermo-chemical thermal energy storage (TCTES). One of the main advantages of a TCTES is that it has high storage densities and heat losses are minimal, but the disadvantage is that it is reported to be expensive [36]. As a result of the expensive nature of TCTES, solar cookers with SHTES and LHTES have only been investigated because of their lower cost and simpler designs. In recent years, a lot of research have reported about SHTES and LHTES systems for solar cookers since these two types of TES systems are economically viable [1, 37, 38, 39, 40, 41, 42].

In a SHTES system, the TES material can store heat and release it because of the heat capacity of the heat storage material used as its temperature changes. This storage medium may either be in the solid or in the liquid phase. The main reasons why SHTES systems are favoured or utilized often is because of their desirable thermal properties, cheapness, and availability. For a given SHTES material, the capacity for storing sensible heat will depend on its specific heat capacity and density [43]. The advantages of SHTES materials are that they are inexpensive and can be sourced locally. The major disadvantage of SHTES is that it requires a large amount of storage space because of the low thermal energy storage density of sensible

heat storage materials. Unlike a SHTES material, a LHTES material stores both sensible heat and latent heat as it undergoes phase transition within a given temperature range. The solid-liquid transition is mostly utilized as the liquid-gas transition involves some complexities. The latent heat of fusion which is absorbed by a phase change material (PCM) as it transforms from the solid to the liquid phase and vice versa, presents a high TES density over a narrow temperature range during the nearly-isothermal transition. One of the main advantages of an LHTES system is that it uses a smaller volume of material to store thermal energy compared to SHTES due to its higher thermal energy storage density and large enthalpy. LHTES is however more expensive than SHTES.

2.4 Previous recent reviews on solar cookers

In recent years, reviews on solar cookers have focused on different parameters such as tracking techniques, heat transfer enhancement technologies, thermal storage materials, cost-effective methods, location/country, and size of the solar collectors to enhance the performance of solar cookers. Table 2.1 shows a summary of recent reviews on solar cookers. It is evident that critical reviews on solar cookers with storage are rather limited, particularly on parabolic concentrating cookers with thermal energy storage which can perform most cooking processes such as boiling, frying, and baking. Additionally, limited studies have reviewed the parameters that affect the performance of parabolic concentrating cookers with thermal energy storage.

Table 2.1: A table summary of recent reviews.

Author and Year	Title	Focus of study	Results	Efficiency (%)
Lahkar and Samdarshi [43] 2010	A review of the thermal performance parameters of box type solar cookers and identification of their correlations	The aim of the review was to compare the correlations of different performance parameters of solar box cookers.	It was found that none of the evaluated parameters were able to predict heat retention.	96.51 and 97.93
Saxena et al. [44] 2011	A thermodynamic review on solar box type cookers	Diverse developments of solar box cookers were reviewed.	Results indicated that solar box cookers are safer to use, save money and food cooked with solar box cookers are more nutritious.	~50
Panwar et al. [45] 2012	State of the art of solar cooking: An overview	A standard of testing solar cookers and thermal properties (such as energy and exergy) analyses were performed.	It is evident that utilizing solar cookers reduces carbon dioxide emission.	67.77
Farooqui [46] 2014	A review of vacuum tube based solar cookers with the experimental determination of energy and exergy efficiencies of a single vacuum tube based prototype	A review of the progress made with the development of vacuum tube-based solar cookers. Also, energy and exergy analyses of a vacuum tube-based solar cooker were conducted.	The energy efficiency and exergy efficiency of the vacuum tube solar cooker were found to be 20-30% and 4-6%, respectively.	-
Yettou et al. [47] 2014	Solar cooker realizations in actual use: An overview	The review focused on the recent advances in the development of solar cooker technologies.	It found that the solar cooking technology has a potential to reduce the rate of energy consumption in the near future.	20-30
Harmim et al. [48] 2014	Solar cooking development in Algerian Sahara: Towards socially suitable solar cookers.	The review focused on solar cooking in the Algerian Sahara environment	It was found that the building-integrated solar cooker was easy to construct, costs less and it was efficient even during the winter season.	-
Iessa et al. [49] 2017	Unverified assumptions, overlooking of local needs and pro-solution biases in the solar cooking literature	A critical review has been studied for solar cooking in Sub-Saharan Africa in order to reduce deforestation, improve health and empower women.	The review showed that solar cooking and its impact are not systematically tested and may not be strong as claimed.	36.38
Herez et al. [24] 2018	Review on solar cooker systems: Economic and environmental study for different Lebanese scenarios	The study focuses on previous work done on the economic and environmental impact of Lebanon using different locations and economic background.	There was a reduction of emission of carbon dioxide from homes, hotels and restaurants. On the economic aspect it was the dependency of solar cooker decreases payback.	20-25

Hage et al. [51] 2018	An investigation on solar drying: A review with economic and environmental assessment.	The aim of the study was to determine the role of main components of solar dryers, economic and environmental assessment and parameters affecting them.	When a certain percentage of time is utilized monthly, about \$ 780 was saved monthly.	-
Indora and Kandpal [52] 2018	Institutional cooking with solar energy: A review.	The aim of the study was to evaluate institutional solar cooking using parabolic dishes, Scheffler dishes and ARUN.	The awareness of institutional solar cooking must be spread to potential users.	-
Elsheikh et al. [53] 2019	Modelling of solar energy systems using artificial neural networks: A comprehensive review.	Artificial neural networks models were deployed to predict thermal parameters of solar systems such as solar cookers, solar dryers, etc.	Deploying artificial neural networks may save time and reduce costs.	-
Omara et al. [38] 2020	Improving solar cookers performance using phase change materials: A comprehensive review.	The aim of this review was to study the feasibility of improving solar cookers when considering geometrical influence and different phase change materials.	Future work must include economic and environmental aspects using solid to liquid PCMs.	124.4
Arunachala and Kundapur [54] 2020	Cost-effective solar cookers: A global review.	An investigation of cost-effective solar box cookers and other solar cookers were conducted on a global scale.	Thorough research must be conducted to improve the efficiency of low-cost solar box cookers.	70-75
Devan et al. [55] 2020	A comprehensive review on solar cookers with a sun tracking system.	An evaluation on solar cooking technology was done.	Installing a tracking system on parabolic dishes increases the performance of the solar cooker.	43
Khatri et al. [56] 2021	Advances in the development of solar cookers for sustainable development: A comprehensive review.	The research focused on the effect of how the main components and heat transfer characteristics affect the overall efficiency.	Social and economic aspects can be improved with better policy implementations.	33
Gokul et al. [57] 2021	A comprehensive review on solar cooker tracking techniques for performance enhancement.	This review discussed tracking systems of solar cookers.	Thermal performance of the solar cookers improved when combined with a tracking system.	31

2.5 Objective and justification

Solar cookers cannot operate during off-shine periods and besides, some cook relatively slower than conventional cookers. However, integrating solar cookers with TES systems such as SHTES and LHTES can overcome such drawbacks. This review aims to present and critically evaluate previous studies that have analyzed the thermal performances of concentrating solar cookers that were coupled with different SHTES and LHTES systems. The review presents the results of different thermal performance parameters for solar concentrating cookers with TES systems. Solar concentrating cookers with heat storage are more attractive than other types of cookers since they can perform most cooking processes such as baking, frying, roasting, and boiling. These cookers are also fast cookers that are reasonably priced. From this review, future work on solar concentrating cookers with TES will be suggested based on the shortcomings of previous studies.

2.6 Parabolic solar concentrating cookers with sensible heat thermal energy storage (SHTES)

2.6.1 Parabolic trough cookers with SHTES

A solar thermal-powered bakery oven was experimentally evaluated by Mishra et al. [57]. The system was proposed as a model of a combined solar and electrically powered bakery oven integrated with a solar parabolic trough collector. Duratherm 600 was used both as the heat transfer fluid and the thermal energy storage medium. A CFD analysis was done to analyze the heat transfer of the copper coils and airflow distribution in the oven. Results indicated that the maximum temperature in the storage tank was about 300 °C, while a temperature of about 168 °C was achieved inside the oven cavity. El Moussaoui et al. [58] experimentally evaluated a parabolic trough solar thermal cooker (PTSC) shown in Figure 2.4. A vacuum tube coupled with a parabolic trough reflector was used as the solar collector. A thermal oil was used both as the heat transfer fluid and the SHTES material. The vacuum tube and parabolic trough reflector were fitted to a solar thermal cooker which contained an insulated cooking box, a cooking vessel, and a storage container. Heat transfer models were developed to evaluate the operation period of the experimental setup, and cooking experiments were conducted. Results showed that potato chips took about 1 h to be cooked while the maximum temperature achieved inside the solar thermal cooker was about 198 °C.

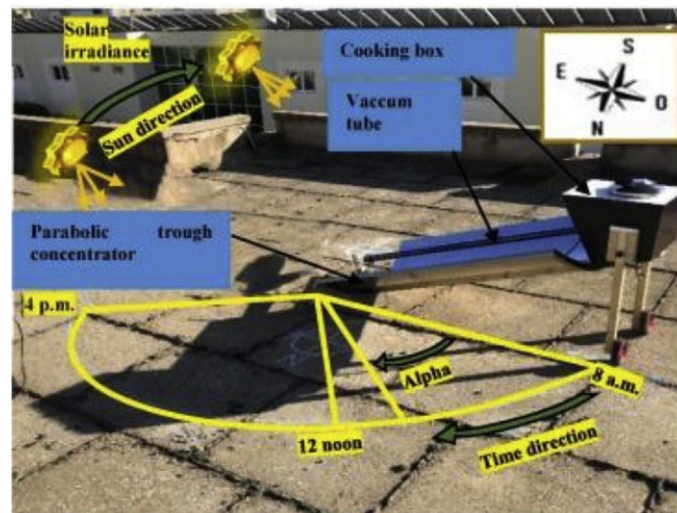


Figure 2.4: A parabolic trough solar thermal cooker (PTSC) with a cooking box containing thermal oil. The figure was reproduced from Ref. [58], with the permission of Elsevier Publishing.

An experiment to test the performance of a parabolic trough solar cooker for indoor cooking was reported by Asmelash et al. [59]. The experimental setup consisted of a parabolic trough with reflecting mirrors, a copper receiver pipe used to absorb sun rays, a cooking pot combined with fins, and a storage tank that stored thermal energy. Soya bean oil was used both as the heat transfer fluid and the heat storage medium. Experimental tests on the effects of the load and varying the diameter of the cooker were performed and analyzed. The results indicated that the maximum temperatures achieved under no-load conditions were about 191 °C for the absorber and about 126 °C for the cooking vessel. However, the maximum cooking efficiency achieved was about 6 %. Dianda et al. [60] reported an experimental investigation of a solar parabolic trough cooker. An indirect parabolic trough solar cooker named the “blazing tube” was used for cooking experiments. The blazing tube was made up of a transparent Pyrex glass vacuum tube, an aluminium parabolic trough reflector, an absorber tube that contained vegetable oil that was utilized as a heat transfer fluid and a heat storage medium, a cooking box that contained a cooking vessel and a storage container. Different cooking tests were performed, such as water heating, frying, and cooking rice, to determine the maximum temperature, the effect of the load, and the duration of the cooking time. The thermal efficiency and output power of the cooker were the parameters evaluated. The results indicated that when the solar radiation was about 930 W/m², the maximum useful power was found to be 1000 W. The maximum efficiency achieved by the experimental setup during the day was about 55 %. Mohan and Vasanthakumar [61] analyzed the effectiveness

of solar-assisted steam cooking using a parabolic trough collector. The experiment aimed to develop and analyze the performance of a solar-assisted steam cooking system using aluminium sheets and galvanized iron sheets as the reflector materials. The setup consisted of an insulated tank, a parabolic trough reflector, an absorber tube that contained water (the heat transfer fluid), and a steam cooker. Cooking experiments were conducted using a variety of food items such as potatoes, carrots, onions, and beans. This was done to compare the nutritional quality of conventional and steam cooking. The second experiment was done to determine the performance of the steam cooker using different reflector sheet materials. The results showed that the maximum outlet temperature and the maximum cooking temperature achieved were 140.2 °C and 150 °C, respectively in the steam cooker.

Hassen et al. [62] investigated the performance of a solar-powered Injera baking oven for indoors cooking. A laboratory model contained an electrical heater was used as the heat source, and it was coupled with a heat storage tank and a baking pan that was used to make Injera. A pump was used to circulate the heat transfer fluid (Shell Thermia B) during charging and discharging cycles. Baking and preheating experiments were done, and it took about 1 h to heat the oil, and 40 min to reach the required baking temperature. Results showed that 5 Injeras were baked in time intervals of 2 min for 10 min at temperatures of 220 °C. Goytom [63] modelled a solar thermal energy-powered Injera baking oven using a finite difference method. The model was aimed to predict the temperature distribution of an Injera baking pan during initial heating up and baking cycles using an unsteady state heat balance model. A parabolic trough was used to collect and reflect the solar radiation onto the receiver tube. An insulated storage tank containing the heat transfer fluid was coupled with a cooking pan. Thermia oil B was used as the heat transfer and storage medium, and a pump was used to circulate the heat transfer fluid in an experimental setup. Simulations were carried out in MATLAB to determine the efficiency of the Injera pan by varying the thickness of the pan. Results showed that there were reasonable heat-up and baking times when the pan thickness was set as 5 mm, and the oil was heated up to 300 °C.

A parabolic trough collector integrated with a cooking system was presented by Yilmaz et al. [64]. The system was composed of a parabolic trough solar collector array, a cooking system, a plate-type heat exchanger, an auxiliary heater, water heating tanks, and Fuchs Renotherm 320 was used as the heat transfer fluid. An analysis of the heat required to cook wheat using

different system design arrangements was carried out. Results showed that the maximum cooking temperature attained was about 100 °C, and the energy required to cook a specified amount of wheat was determined by the energy value of the nominal solar radiation. Arunachala et al. [65] performed an analysis of a solar cooker for night cooking. The experimental setup was a self-circulating system composed of a compound parabolic trough collector, vacuum tubes, and an oil storage tank that was coupled with a cooker. Engine oil was used as the heat transfer fluid in the storage tank. Cooking experiments were done to determine the energy required for cooking, and rice was used as the cooking load. Results showed that the highest temperature achieved by oil was about 110 °C, and it took less than an hour to cook 500 g of rice in the afternoon. An investigation of a solar cooker with a parabolic trough concentrator was done by Noman et al. [66]. The parabolic trough collector was positioned at a fixed latitude to reflect maximum solar radiation to the absorber tube. The absorber tube was fabricated with black painted copper which was used as a receiver for the cooker. Water was used as both the heat transfer fluid as well as the heat storage material. The results showed that the maximum cooking temperature achieved in 4 h was about 53 °C at an ambient temperature of 31 °C with solar radiation being about 927 W/m². Akayleh et al. [29] designed and developed a solar-based cooker with a mechanical sun tracking system. The experimental setup was composed of an automated sun tracking system, hot dish for baking bread, a control unit, two pulleys connected to the gearbox and a parabolic trough. The objective of the experiment was to determine the efficiency of the solar cooker under various conditions. Baking experiments were carried out, and the highest temperature achieved was found to be approximately 85 °C. Widjaja et al. [67] designed and simulated a concentrated solar thermal system with an integrated concrete storage for continuous heat supply. In this study a concentrated solar system for pasteurization was combined with concrete storage for process heating. The aim of the experiment was to compare a parabolic trough collector and compound parabolic concentrator with concrete storage under different boundary conditions. Process heating experiments were carried out in four different countries, and the results showed that using a compound parabolic concentrator operating below 180 °C showed better performance as compared to the parabolic trough collector. Bade and Bandyopadhyay [68] proposed an energy model to determine the characteristics of thermal oil for cooking applications. An energy model based on a cooking system was developed, and Therminol 55 was selected as the thermal oil. The proposed energy model

was dynamic in nature and used the Euler method to predict the temperature. The results showed savings in fuel consumption, and a possible payback period of 1.63 years. Abd-Elhady et al. [69] studied the thermal performance of solar cookers using metallic wires and nanographene. The objective of the study was to improve the heat capabilities of the parabolic trough combined with the storage tank. The solar cooker operated in a thermosiphon mode using Mobil-Therm 605 as heat transfer fluid and storage medium. The results showed that adding nanographene particles contents by up to 0.34×10^{-3} wt% to the heat transfer medium increased the heat transfer rate in the solar cooker.

2.6.2 Parabolic dish cookers with SHTES

Agrawal and Yadav [70] experimentally investigated a parabolic solar cooker with a storage cooking pot. The experimental setup was composed of a solar cooker that was made up of a hollow-concentric cylindrical pot with sensible heat storage materials, a parabolic dish collector, and an insulator box. Experiments were conducted using different sensible heat storage materials such as sand, stone pebbles, iron grits, and iron balls to determine the thermal performance of the sensible materials. After the solar cooker was charged, it was transferred to the insulated box and loaded with food. Results showed that the food was cooked properly using sand, stone pebbles, and iron grits, and it was partially cooked when iron balls were utilized.

Prasanna and Umanand [71] designed and optimized an energy transport system for a solar cooking application. The indirect system was composed of a paraboloid concentrating collector, and a heat storage tank that contained servo-thermal oil which was utilized as a storage medium and heat transfer fluid. Two pumps were used to circulate the heat transfer fluid during charging and discharging, and a heat exchanger was placed in the kitchen for cooking purposes. Simulations and experiments were performed using different pipe diameters to evaluate the overall energy transfer and the thermal performance of the proposed system. Results showed that cooking could be carried out at any time of the day, and the energy collected from the paraboloid concentrating collector was optimized by dynamically varying the flow rate. Mawire et al. [72] simulated the energy and exergy of the charging of an oil-pebble bed thermal energy storage system for a solar cooker. The proposed system was composed of a parabolic dish concentrator coupled with an absorber coil, and a storage tank that contained oil as a storage medium and heat transfer fluid. A load

coil was coupled with a cooking vessel used for cooking applications. Energy balance equations were used to model the indirect solar cooking system. Energy and exergy analyses were carried out to predict the performance of the solar cooking system. Results indicated that a greater degree of thermal stratification and energy stored was achieved by constant temperature charging compared to constant flow-rate charging. Discharging simulations of a thermal energy storage (TES) system for an indirect solar cooker were done by Mawire et al. [34]. The conceptual setup was presented in [72]. The models were validated by experimental results, and reasonably good agreement was obtained between simulation and experiment. Two methods were utilized for discharging the TES system. The first method discharged at a constant flow-rate, while the second method discharged the TES system by varying the flow-rate to acquire the desired constant discharging temperature. The results showed that discharging the TES system at a constant flow-rate resulted in a higher rate of heat utilization. An experiment on a portable solar cooker and a water heater was conducted by Badran et al. [73]. The experimental setup consisted of a parabolic dish collector, an absorber, a receiver, and a water storage tank as shown in Figure 2.5. The experimental setup had two modes of operation, which were the water heating mode and the cooking mode. During the water heating mode, the absorber was placed on the focal point of the dish to absorb heat and transport it to the storage tank. During the cooking mode, the collector was replaced by a cooking pot, and the pot lid was covered with polyurethane foam to reduce losses. Cooking and water heating experiments were done to determine the maximum efficiency and cooking power. Results showed that boiling of water was achieved under 1 h, and the maximum efficiency achieved was 77 %.



Figure 2.5: A photograph of the experimental setup of a portable solar cooker and water heater. The figure was reproduced from Ref. [73], with the permission of Elsevier Publishing.

An evaluation of the thermal performance of a heat exchanger unit for a parabolic solar cooker for off-place cooking was done by Murty et al. [74]. The inclined cylindrical heat exchanger system contained an SK14 parabolic solar cooker, a lower cylindrical absorber, and an upper cylindrical vessel that contained a cooking pot with a lid. Soya oil was used as the heat transfer fluid and storage medium. Cooking experiments were conducted using different types and masses of food. Results indicated that the inclined convective heat exchanger could be utilized during non-shine periods, and the highest temperature recorded for food was around 85 °C. An evaluation of the thermal efficiency of a solar cooking unit was done using food and water. Results showed that high solar insolation decreased the cooking time to a minimum period. Craig and Dobson [75] compared a heat pipe, and a direct copper tube using a parabolic solar cooker for cooking applications. This experiment was aimed at investigating and optimizing heat collection from a parabolic dish collector to a solar cooker using a heat pipe and direct spiral copper tubes. Shell S2 oil was used as the heat transfer fluid. Parameters such as the cooking time, boiling characteristics, and the overall heat utilization efficiencies were evaluated and analyzed. Results showed that both systems were satisfactory, but the spiral system was preferred to heat pipes because of the cost of production and the higher temperatures achieved when forced convection was employed. The spiral cooker took about 28 min to boil water, and the heat pipe took 30 min.

A parametric analysis of a parabolic solar cooking system with heat storage for indoor cooking was done by Mbodji and Hajji [76]. The experimental setup was an indirect solar cooking system composed of a concentrated solar parabolic dish, a receiver, a heat storage tank, a circulation pump, and a cooking section. Experiments and simulations were carried out to analyze the parameters of the solar cooking system. The results obtained showed that the daily maximum solar radiation increased the heat storage temperature by 4 °C. It was also found out that the maximum temperature on the surface of the plate was 81 °C which was sufficient for cooking.

Senthil and Cheralathan [77] analyzed the thermal performance of solid and liquid energy storage materials in a parabolic dish solar cooker. The objective of the experiment was to test different sensible heat storage media such as pebbles, sand, and iron grits, steel balls, sunflower oil, olive oil, and coconut oil that were filled inside a storage tank. Water heating

experiments were done to determine the thermal performance of each sensible heat storage medium. Results obtained indicated that sunflower oil was the best sensible heat storage material, as it showed better performance than the other sensible heat storage materials, and the temperatures it achieved were sufficient for cooking during non-shine periods. Nyahoro et al. [78] simulated the performance of thermal storage in a solar cooker. The proposed simulated system was an indirect solar cooker which consisted of a parabolic concentrator and a storage block that was coupled with a cooking pot. Mirrored reflectors were used to reflect sun rays to the bottom of a storage block which used granite and cast iron as the storage materials. A finite difference method was used to simulate the thermal performance of the thermal storage unit for solar cooking and cooking during non-shine periods. Results indicated that cast iron attained the highest temperature, and it also had shorter cooking periods and fewer heat losses compared to granite.

Lokeswaran and Eswaramoorthy [79] studied a solar parabolic dish cooker with porous media. The cooking utensil that contained metal copper chips was placed on the focal point. This experiment aimed to investigate the heat transfer enhancement of solar parabolic dish cookers using metal copper chips. Stagnation and cooking experiments were done with and without the metal copper chips. Results showed that the maximum temperature achieved was about 118 °C in 15 min with 85 g of eggs fried on the receiver with porous medium, whereas the temperature for the plain receiver was only 98 °C. Kedida et al. [80] analyzed the performance of a pebble bed thermal storage integrated with a concentrating parabolic solar collector for solar cooking. The experimental setup used air as the heat transfer fluid. The heat was transported from the receiver that was mounted on the parabolic dish to the thermal storage unit using the heat transfer fluid. A thermal storage unit was coupled with a cooking vessel. During the charging cycle, the cooking vessel was sealed with a cover plate to reduce heat losses, and during discharging a pot was placed on the cooking vessel. The experiment aimed to investigate the efficiency of a solar cooker using a 1D finite-difference computational model. Results obtained showed that during off-shine cooking periods, 5 L of water took 50 min to reach a temperature of 95 °.

The design and experimental investigation of a solar cooker with thermal energy storage was presented by Wollele and Hassen [81]. The experimental setup was composed of two joined parabolic dish collectors, and a solar cooker storage pot that was placed in between the

parabolic dish collectors. Rocks and engine oil were used as storage materials for the solar cooker storage pot. Charging and discharging experiments were conducted and water was used as the cooking load. The results showed that during discharging, the maximum temperature reached by water was 81.85 °C in under 40 min.

An energy and exergy thermal analysis of a solar bakery unit was done by Ayub et al. [82]. The experimental system was composed of a Scheffler reflector, secondary reflector, a receiver, a PV module, and a baking chamber. Rocks were used as sensible heat material, and they were placed in close contact with the receiver using air as the heat transfer fluid. Baking experiments were conducted using different food samples. Results showed that the baking temperature achieved was 180 °C, and it was also found out that the energy efficiency in the receiver increased with the baking time. The development and experimental analysis of a thermal oil-based roasting system were done by Raza et al. [83]. The continuous solar roaster was composed of a Scheffler concentrator, heat receiver, storage tank and a roasting unit. Heat was stored in the storage unit, and the thermal oil was used to transfer heat from the heat receiver to the roasting unit. Roasting experiments were carried out to investigate parameters such as feeding capacity, conveyor speed, and the thermal oil flow rate for achieving light, medium, and dark quality roasting of groundnuts. The results showed that the recommended time to roast light, medium and dark groundnuts was 14, 20 and 29 min, respectively, at an average temperature of 180 °C.

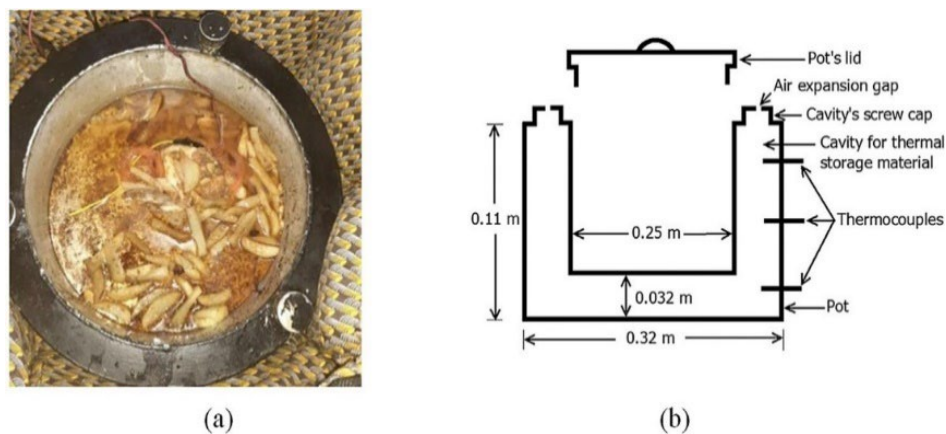


Figure 2.6: (a) A photograph of a solar cooker pot with cooked chicken and chips (b) A labelled diagram of a solar cooking storage pot. The figure was reproduced from Ref. [84], with the permission of Elsevier Publishing.

Figure 2.6 shows a photograph with cooked food and a schematic diagram of a storage cooking pot that was made of stainless steel presented by Mawire et al. [84]. The storage cooking pot had an internal cavity in which the storage material was placed. Experiments were performed to compare two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking. The experiment consisted of two solar storage cooking pots, parabolic dish collectors, and wonderbags. Two similar storage cooking pots were experimentally evaluated and compared using parabolic dish solar cookers for solar cooking and wonderbag cookers for off-sunshine cooking. One storage pot had sunflower oil as the sensible heat storage material, and the other had erythritol as the phase change material (PCM). The results obtained showed that the sunflower oil cooking pot performed better during solar cooking periods taking 1.8-5.6 h to cook with a maximum temperature range of 124-145 °C as compared to the erythritol PCM pot which took 3.8-6.6 h with a maximum temperature range of 118-140 °C. During off-shine periods, the erythritol PCM pot outperformed the sunflower oil pot, as it showed lower temperature drops of 0.1-9.7 °C compared to the sunflower oil pot that showed temperature drops between 4.8-14.3 °C because of its latent heat of storage.

A novel technique based on artificial intelligence for a solar bread cooker was presented by Nazari et al. [85]. A parabolic dish concentrator was used to reflect solar radiation to the solar cooker. The solar cooker was composed of a stand and cooking plate with an insulated lid. Experimental and numerical studies were carried out to analyze and evaluate the thermal performance of the experimental setup during baking periods. The results indicated that a dough ball weighing 200 g attained a temperature of 180 °C in period of 20-25 min. Table 2.2 shows a summary of different types of parabolic concentrators, and their applications related to cooking using different sensible heat storage materials.

Table 2.2: A summary of parabolic solar concentrating cookers with sensible heat thermal energy storage (SHTES)

Author	Type of concentrator	Application	Type of study	Storage material	Maximum cooking/storage temperature (°C)	Heat transfer fluid/ Working fluid	Test load
Mishra et al. [57]	Parabolic trough	Baking	Experimental	Duratherm 600	168	Duratherm 600	Dough
El Moussaoui et al. [58]	Parabolic trough	Frying	Experimental	Thermal oil	260	Thermal oil	Potato chips (Fries)
Asmelash et al. [59]	Parabolic trough	Cooking	Experimental	Soya bean oil	119	Soya bean oil	Water, eggs and potatoes
Dianda et al. [60]	Parabolic trough	Cooking and frying	Experimental	Vegetable oil	~110	Vegetable oil	Water, potato and mixed rice with ingredients
Mohan and Vasanthakumar [61]	Parabolic trough	Steam cooking	Experimental	Water	150	Water	Potatoes
Hassen et al. [62]	Parabolic trough	Baking	Experimental and Numerical	Shell Thermia-B oil	220	Shell Thermia-B	Injera (sour flatbread)
Goytom [63]	Parabolic trough	Baking	Numerical	Thermia-B oil	220	Thermia oil B	Injera (sour flatbread)
Yilmaz et al. [64].	Parabolic trough	Cooking and water heating	Experimental	Fuchs Renotherm 320	100	Fuchs Renotherm 320	Wheat
Arunachala et al. [65]	Compound parabolic collector	Cooking	Experimental and Numerical	Engine oil	110	Engine oil	Rice
Noman et al. [66]	Parabolic trough	Cooking	Numerical and Experimental	Water	53	Water	No test load
Akayleh et al. [29]	Parabolic trough	Baking	Experimental	None	85	None	Dough
Widjaja et al. [67]	Parabolic trough and compound parabolic concentrator	Process heating	Numerical	Water	75	Steam	Milk

Bade and Bandyopadhyay [68]	None	Cooking and frying	Numerical	Therminol 55	202	Therminol 55	Vegetables and roti
Abd-Elhady et al. [69]	Parabolic trough	Cooking	Experimental	Mobil-Therm 605	165	Mobil-Therm 605	None (double check)
Agrawal and Yadav [70]	Parabolic dish	Cooking	Experimental	sand, stone pebbles, iron grits and iron balls	117	None	Rice
Prasanna and Umanand [71]	Paraboloid concentrating collector	Cooking	Numerical	Servo-thermal oil	None	Servo-thermal oil	None
Mawire et al. [72]	Parabolic dish	Cooking	Numerical	Thermal oil	200	Thermal oil	None
Badran et al. [73]	Parabolic dish	Cooking	Experimental	Water	100	Water	Water
Murty et al. [74]	Parabolic dish	Cooking	Experimental	Soya oil	85	Soya oil	Oil, water and rice
Craig and Dobson [75]	Parabolic dish	Cooking and baking	Experimental	Shell S2 oil	100	Shell S2 oil	Water
Mbodji and Hajji [76]	Parabolic dish	Cooking	Experimental and Numerical	Synthetic oil SAE-40	~85	Synthetic oil SAE-40	None
Senthil and Cheralathan [77]	Parabolic dish	Cooking	Experimental	Sunflower oil, sand, stone pebbles, iron grits, steel balls, coconut oil and olive oil	100	None	Water

Nyahoro et al. [78]	Parabolic concentrator	Cooking	Numerical	Granite and cast iron	100	None	Water
Lokeswaran and Eswaramoorthy [79]	Parabolic dish	Cooking and frying	Experimental	Waste metal chips	118	None	Eggs and water
Kedida et al. [80]	Parabolic concentrator	Cooking	Experimental and Numerical	Pebbles	99	Air	Water
Wollele and Hassen [81].	Parabolic dish	Cooking	Experimental	Engine oil and rocks	82	None	Water
Ayub et al. [82].	Scheffler dish	Baking	Experimental and Numerical	Rocks	180	Air	Variety of food
Raza et al. [83]	Scheffler dish	Roasting	Experimental and Numerical	Shell S2 oil	180	Shell S2 oil	Groundnuts
Mawire et al. [84]	Parabolic dish	Cooking	Experimental	Sunflower oil	145	None	Variety of food
Nazari et al. [85]	Parabolic dish	Baking	Experimental and Numerical	None	146	None	Bread

2.7 Parabolic solar concentrating cookers with latent heat thermal energy storage (LHTES)

2.7.1 Parabolic trough cookers with LHTES

An experimental investigation of a solar cooker during sunshine and off-sunshine hours using a thermal energy storage unit based on a parabolic trough collector was done by Saini et al. [86]. The experimental setup was composed of a parabolic trough that reflected solar radiation to an absorber tube. The collected heat was transferred to the cooker using a thermosiphon cycle. Water and engine oil were used as heat transfer fluids separately, and acetanilide was incorporated with the cooker and used as the storage medium. The results showed that the maximum temperature of the food was 75.9 °C, and it took 2 h to cook the food fully.

Mussard and Nydal [87] experimentally investigated the charging of a heat storage tank coupled with a low-cost small-scale solar parabolic trough for cooking purposes as shown in Figure 2.7. The experimental setup was a self-circulating system that was composed of a parabolic trough and a storage tank. Two charging experiments were done using two different storage tank setups and TES materials. The main objective of the experiment was to store heat at the highest possible temperature to utilize it during off-shine periods for cooking purposes. The results obtained indicated that when the temperature was above 200 °C, it became difficult to collect heat energy without insulation on the receiver.



Figure 2.7: A photograph of a parabolic trough cooker integrated with LHTES. The figure was reproduced from Ref. [87], with the permission of Elsevier Publishing.

An experimental investigation on improving the heat transfer of cascaded thermal storage systems using different fins was done by Beemkumar et al. [88]. The parabolic trough collector was used as a solar collector, with three storage tanks that contained Therminol-66 as the heat transfer and storage fluid. Encapsulated balls used as fins were filled with three different PCM (d-mannitol, d-sorbitol, and paraffin wax) and welded on the storage tanks. An analysis of different encapsulation shapes (rectangular, annular, and pin fin) was done to determine the heat transfer rate. Results indicated that using an annular fin for encapsulation showed a higher heat transfer rate than the other shapes. The storage temperatures revealed that the solar cooking system had the potential of boiling and frying food.

Mussard et al. [89] performed an experimental study of a solar cooker using heat storage in comparison with direct heating. A comparative experimental study of two solar cookers was done, and the surface of the storage unit was combined with a flat plate meant for cooking purposes. The first solar cooker was a parabolic dish cooker, and the second solar cooker was a prototype of a solar parabolic trough using a nitrate salt mixture storage unit. Cooking experiments such as boiling and frying were conducted to compare the performance of these two methods of heat extraction. The results obtained showed that cooking with heat storage using an optimized surface contact area was found to be competitive with standard solar cookers or other cooking devices.

An experimental and numerical investigation of a solar flat plate cooking unit for domestic applications was done by Kumaresan et al. [90]. The experimental setup was composed of a solar parabolic trough collector (PTC), a thermal energy storage (TES) tank, a parabolic trough cooking unit, and a positive displacement pump. Therminol 55 was used as the heat transfer fluid, and D Mannitol was used as the phase change material. Cooking experiments were carried out, and dosa (an Indian pancake) was used as the cooking load. Parameters such as energy utilization, instantaneous heat transfer rate, and a detailed energy balance were analyzed and evaluated. Results showed that the maximum temperature reached was 167 °C, and it took 3.5 min to prepare 1 dosa.

The experimental analysis of a solar cooker with a parabolic trough enhanced with a PCM-based thermal storage unit was presented by Kumar and Pandian [91]. The main components of the indirect solar cooker were a storage tank that was used to store heat energy, a heat transfer fluid, a manual tracking system, a parabolic trough collector, and a semi-circular

cooking oven. Stearic acid was used as the PCM storage medium. A heat transfer analysis of the experimental setup was carried out using various mass flow rates. Results showed that using a mass flow rate of 0.45 kg/s gave better energy extraction that could be utilized for cooking applications. The highest temperature achieved was approximately 120 °C in 3 h. An evaluation of the thermal performance of a parabolic trough reflector with a PCM storage unit for different applications was presented by Abu-Hamdeh et al. [92]. The experimental components that were utilized were a parabolic trough reflector, a solar stove, an air blowing fan, and aluminium capsules that contained acetamide as a PCM. The PCM capsules were placed on the receiver of the parabolic solar reflector to absorb heat from the reflected sunlight. After the PCM melted completely, the capsules were removed from the receiver and transferred to the solar stove. Cooking experiments were done using rice, and the results showed that the cooking process took 60 min. The maximum cooking temperature achieved was approximately 90 °C with an airflow rate of 60 m³/h.

A parametric study of a solar parabolic trough collector was conducted by Manikandan et al. [93]. A novel solar system was proposed, and it consisted of a parabolic trough collector that was combined with a TES unit and a cooking unit. Therminol 55 was used as the heat transfer fluid. A thermal analysis was done on parameters such as the mass flow rate, efficiency, useful energy, the concentration ratio of the collector, and the heat removal factor. The results showed that performance parameters such as thermal efficiency and the useful energy gain rate increased as the solar insulation increased, and this was evidence that it can be utilized for cooking and heating applications. Beemkumar et al. [88] performed a comparative experimental study on a parabolic trough collector integrated with a thermal energy storage system by using different reflective materials. The parabolic trough collector system was composed of a parabolic trough collector, a storage tank that contained Therminol-66 oil which was used as the heat transfer fluid, D-mannitol, and a displacement pump to circulate Therminol-66 oil throughout the system. Two reflective materials (glass and stainless steel) were incorporated in the parabolic trough reflector. Experiments were conducted and various parameters were analyzed. Results obtained showed that the use of glass as reflective material showed better gain compared to stainless steel, and the maximum temperature achieved ranged from 220-230 °C.

An experimental and numerical study of a solar collector using phase change material as heat storage was done by Guerraiche et al. [94]. The aim of this experiment was to study the thermal performance of a solar collector combined with a thermal energy storage system. A small-scale parabolic trough was used to reflect solar radiation to the absorber; and the absorber contained a mixture of sodium nitrate and potassium nitrate that was used as PCM. Water was used as the heat transfer fluid, and it was stored in a storage tank. An experimental comparison of the absorber with and without PCM was done. The results showed that during heat retention the highest temperature achieved was 40 °C in a period of 1h:40 min to 2 h. The thermal performance evaluation of a coupled solar parabolic trough collector latent heat storage unit for solar water heating in large buildings was done by Lamrani et al. [95]. The experimental setup was composed of a shell and tube latent thermal energy storage system, a parabolic trough collector and a circulating pump. A dynamic thermal model was developed to evaluate thermal performance of the experimental system. Three phase change materials (RT-42, RT-55 and RT-65) were used as latent heat storage materials, and these were compared to determine the most suitable PCM. Results showed that using the mass flow rate of 1800 l/h, RT-55 showed better performance than RT-42 and RT-65. Furthermore, during daytime and night-time, the system was able to produce hot water ranging from temperatures of 36-85 °C and 38-63 °C.

The thermal analysis of a solar dryer equipped with a parabolic trough solar collector (PTSC) and PCM using experimental and numerical methods was presented by Alimohammadi et al. [96]. The thermal performance of four fluids (Nano-fluid, engine oil, glycerine, and water) used as heat transfer fluid was evaluated. Paraffin wax was used as the PCM, and air was used to transfer heat from the heat transfer fluid pipe to the drying chamber. Experiments and simulations were done using different heat transfer fluids. Results showed that engine oil reached around 80.4 °C, and it performed better compared to other heat transfer fluids.

2.7.2 Parabolic dish cookers with LHTES

The feasibility of incorporating phase change materials in a collapsible parabolic solar cooker was presented by Keith et al. [97]. The experimental setup consisted of a collapsible parabolic solar cooker with 12 panels, and a cooking vessel integrated with a PCM storage container. The PCM that was used was stearic acid. A comparison experiment with a commercial pot and a modified cooking vessel was done. Rice and pearled barley were used as the cooking

loads. The results obtained showed that the cooking vessel integrated with PCM reached a maximum average temperature of 57 °C for rice, and 59 °C for pearled barley, with cooking times of 131 and 161 min, respectively.

A solar-powered heat storage experiment for Injera baking in Ethiopia was presented by Tesfay et al. [98]. Two experimental setups were investigated, and solar salt was used as the PCM. The first experimental setup was an electric-based system that was composed of an electric heating element and a solar salt storage tank coupled with a cooking vessel. The second experimental setup was similar to the first experimental setup but the difference was the pipeline system and a parabolic dish that was used to reflect solar radiation to the absorber tube. The objective of this experiment was to investigate the heat loss, cooking times, cooking temperatures, and temperatures of the PCM storage. Cooking experiments were carried out with Injera, and nitrate salt mixtures were used as PCM. The results obtained showed that the useful latent energy and sensible heat stored were 374.4 kJ and 853 kJ, respectively. Results showed that cooking two Injeras and frying an egg took 32 min during non-shine periods. Bhave and Kale [99] developed a thermal energy storage type of solar cooker for high-temperature cooking using a mixture of sodium nitrate and potassium nitrate as the PCM. A parabolic dish concentrator was used to direct solar radiation to the solar receiver as shown in Figure 2.8. The solar receiver was integrated with a cooking cavity and a PCM storage unit. Cooking experiments were carried out, and the results showed that the solar cooker was able to store heat at the PCM melting point of 220 °C in 110 min, with 0.2 kg of potatoes being fried in 17 min at night. Malik et al. [100] designed and fabricated a solar thermal energy storage system using potassium alum as the PCM. The parabolic dish collector's inner surface was made up of small pieces of glass and fiber-glass. The heat transfer fluid (HTF) was composed of a mixture of ethylene glycol and water. Charging and discharging experiments were conducted and compared to simulation results. Results showed that thermal energy was stored for 7 h at a maximum temperature of 92 °C which was suitable for cooking and heating applications.

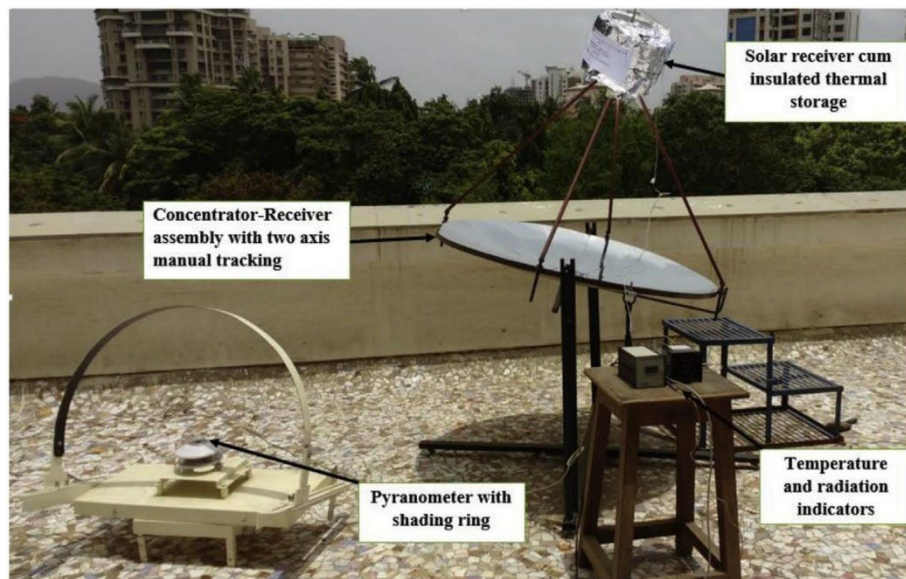


Figure 2.8: A photograph of an experimental setup of a parabolic dish cooker combined with an insulated solar receiver/thermal energy storage. The figure was reproduced from Ref. [99], with the permission of Elsevier Publishing.

An enhancement of the uniform temperature distribution of a concentrated solar receiver integrated with phase change material was done by Senthil [101]. The parabolic dish reflector was a Scheffler dish with multiple mirrors, and it was used to reflect sunlight to the receiver. The receiver was a cylindrical container that contained a cooking vessel and PCM storage. Sodium nitrate and potassium nitrate were used as the PCMs, and charging experiments were done using an insulated receiver and a receiver without insulation. After charging, water was used as the cooking load. The results obtained showed that the receiver was able to store 30 MJ of energy at a temperature of 300 °C with water completely evaporating.

Lecuona et al. [102] experimentally evaluated a portable parabolic dish cooker incorporating a heat storage unit based on PCMs. The experimental setup was composed of two cooking utensils that were combined with storage tanks, an insulated box used for off-shine periods, and a parabolic dish cooker that was used to reflect and direct sunlight to the cooking utensil. Erythritol and paraffin were suitable candidates that were chosen as PCMs because the melting temperatures are close to the boiling point of water. Results showed that the utensil was able to cook three meals for a family, and another finding was that at 100 °C, paraffin seemed to be better adapted for cooking than erythritol. A numerical study on coupling PCMs with a solar dish collector was done by Tao et al. [103]. The paraboloid solar collector was used to irradiate solar radiation to the receiver during sunshine periods. The receiver was composed of heat transfer tubes and PCM storage, and it was placed at the focal point of the

paraboloid solar collector. The PCM was 80.5%-lithium fluoride and 19.5 %-calcium fluoride. A Monte Carlo ray-tracing method (MCRTM) and finite volume methods (FVM) models were used to study the heat transfer problem. Results showed that enhancing the PCM thermal conductivity was an efficient way to achieve a more uniform temperature field distribution in the PCM. Senthil and Cheralathan [104] analyzed the effect of PCM in a solar receiver using a parabolic dish collector. A Scheffler parabolic dish solar concentrator was used to concentrate solar radiation to the receiver and improve heat transfer in the receiver. The receiver was made up of fins and a storage container filled with magnesium chloride hexahydrate as the PCM. Experiments were carried out to analyze heat transfer from the receiver to the heat transfer fluid with and without PCM. Results obtained showed that integrating PCM in the receiver improved the energy efficiency of the parabolic dish solar concentrator by about 60–65 % and decreased the time to reach the boiling point of water by about 20 % when compared with the receiver without PCM.

An enhancement of the productivity of a parabolic dish solar cooker integrated with PCM was done by Senthil and Cheralathan [105]. The thermal performance of the solar cooker with PCM integrated into a cylindrical pot was investigated to determine the thermal conductivity and storage capability enhancement. Results indicated that the productivity of the cooker during off-sunshine hours was improved with PCM, and water reached its boiling point in 130 min. Tesfay et al. [106] studied solar cookers with latent heat storage for intensive cooking applications. The solar cooking experimental setup was composed of a parabolic collector with a receiver, a storage system where the baking plate was embedded with stainless steel steam pipes, and aluminium fins. Water was used as the heat transfer fluid, and a nitrate salt mixture was used as the PCM. Baking experiments were carried out, and results indicated that Injera could be baked at lower temperatures (110–150 °C) than previously assumed (180–220 °C).

An experimental investigation of a solar cooker based on a parabolic dish collector with a PCM thermal storage unit in Indian climatic conditions was done by Chaudhary et al. [107]. The solar cooker system consisted of a parabolic dish collector combined with a flat surface absorber, a hollow-spaced solar cooker, and an insulated wood box filled with glass wool. Acetanilide was used as the PCM, and it was filled in between the hollow space of the inner and outer wall of the solar cooker. Cooking experiments were conducted, and water was used

as the cooking load. The results showed that during the discharging process, the maximum temperatures of cooking load achieved for an ordinary solar cooker, a solar cooker with the outer surface painted black, and for a solar cooker with the outer surface painted black along with glazing were 52.2 °C, 84. °C, and 88.4 °C, respectively.

Yadav and Yadav [108] performed an experimental investigation of a novel solar cooker with a dual thermal storage unit based on a parabolic dish collector. The experimental setup consisted of a solar cooker that was integrated with a sensible heat storage unit (sand) and a latent heat storage unit (acetamide). The objective of the experiment was to evaluate the thermal performance of the solar cooker based on a parabolic dish collector with acetamide and sand as dual thermal storage media for noon and evening cooking. Cooking was conducted during daytime as well as in the evening with different cooking loads. Results showed that the rate of evening cooking was approximately 1.5-2 times faster as compared to noon cooking, and the temperature of cooked food at 20:00 h was found to be in the range of 60.2-70.6 °C. An experimental design of a PCM-based solar cooker for both indoor and outdoor cooking applications was done by Rekha and Sukchai [109]. The experimental setup consisted of a parabolic dish collector used to reflect sunlight to the focal point, and a receiver that was made up of a cooking utensil combined with cylindrical tubes that contained PCM. The gap between the cooking utensil and cylindrical tubes of the receiver was filled with palm oil and salt hydrate was used as a phase change material. Performance parameters such as the heat loss factor, optical efficiency factor, and cooking power were calculated and analyzed with and without PCM in the receiver. The results obtained showed that the cooking power of the solar cooker with the PCM receiver was 125.3 W and 65.6 W without PCM in the receiver. The maximum temperature reached by the PCM solar cooker was approximately 100 °C .

Bhave and Thakare [110] developed a solar thermal storage cum cooking device using magnesium chloride hexahydrate powder as the PCM. A parabolic dish concentrator was used to reflect solar radiation to the receiver. The receiver was integrated with cylindrical PCM tubes and a cooking cavity. Taurus Therm 500 was used as the heat transfer fluid in the cooking experiments. Cooking experiments were conducted with rice as a cooking load. Results showed that it took 30 min to cook 50 g of rice with 100 ml of water, and the maximum storage temperature was 129 °C.

Veremachi et al. [111] designed a PCM heat storage unit charged with a double reflector solar system. The system was composed of a primary parabolic dish reflector, a secondary plane mirror reflector, and a PCM heat storage unit that contained a mixture of sodium nitrate and potassium nitrate. This experiment aimed to evaluate the thermal parameters of the system. Charging experiments were conducted, and the results showed that the PCM in the storage unit melted at around 220 °C which was suitable for cooking or frying applications. Floess [112] developed a solar resource map for a storage solar cooker. A solar cooker named the “Sun Bucket” was used both as a cooking utensil and a PCM storage container. A combination of potassium nitrate salt and sodium nitrate salt was used as the PCM. A parabolic dish collector was used to reflect solar radiation to the solar cooker. Charging experiments were done under different environmental conditions. Parameters such as the heat transfer coefficient and rate were analyzed. Results showed that the combined PCM melted at a temperature of 334 °C which was suitable to cook a full range of foods that an electric stove could cook. The performance analysis of a solar energy storage unit for cooking was presented by Sreepathi et al. [113]. The experimental setup was composed of a “butterfly” parabolic collector and a storage cooking utensil that contained PCM. Oxalic acid was used as the phase change material. The experiment was aimed at determining the peak temperature that could be attained. Water heating experiments and cooking experiments were conducted. Results obtained showed that the storage cooking utensil was able to store thermal energy for 3 h at a temperature of 65 °C. Panchal and Sadasivuni [114] investigated and performed an analysis of a Scheffler reflector solar cooking system integrated with sensible and latent heat storage materials. The experimental setup consisted of a Scheffler reflector, solar cooker, latent heat storage unit, a sensible heat storage unit, and an insulator box. Acetamide was selected as the latent storage material and rocks and sand were selected as the sensible storage material. A comparison experiment of acetamide-sand, acetamide-pebbles, and acetamide-iron balls was conducted to determine the thermal performance during off-shine periods. The results showed the maximum temperatures achieved by three materials were 95 °C, 82 °C, and 77 °C, respectively. The cooking process took 3 h achieving temperatures of 58 °C, 57 °C, and 56 °C.

Abreha et al. [115] carried out a study on numerical modelling and simulation of thermal energy storage for solar cooking using Comsol multiphysics software. A shell-and-tube heat

exchanger-type storage system coupled with a PCM mixture of potassium nitrate and sodium nitrate was used to conduct numerical experiments. 19 heat transfer tubes were selected and integrated with four longitudinal fins. A maximum average temperature of 230 °C was achieved with the total energy ranging from 4.29 MJ to 10.17 MJ. A numerical and experimental analysis of a solar Injera baking cooker coupled with PCM storage was performed by Tesfay et al. [116]. The main components of the experimental setup were a parabolic dish concentrator, a receiver, a tracking mechanism, and an insulated storage tank that contained a mixture of potassium nitrate and sodium nitrate. Water was used as the heat transfer fluid, and Injera was used as the cooking load. The study determined which baking surface was optimum for baking Injera. Results showed that one Injera was baked at temperatures in the range of 110-150 °C under 3 min.

Thermal performance evaluation of a solar cooker with a latent and sensible heat storage unit for evening cooking was done by Yadav et al. [117]. The main experimental components consisted of a parabolic solar dish collector, a storage solar cooking vessel, and an insulation box. A combination of latent and sensible heat was used in the storage solar cooker. Acetamide was selected as the PCM and sand, iron grits, stone pebbles, iron balls were the selected sensible heat materials. The storage solar cooker was charged throughout the day, and in the evening the storage solar cooker was placed with food in an insulated box. Results showed that a combination of PCM-sand and PCM-stone pebbles stored more energy compared to other combinations. The maximum cooking temperatures that were achieved were 70 °C and 60 °C for a cooking process that took 4 h. Hosseinzadeh et al. [118] performed an experimental study of a nanofluid-based indirect solar cooker. The indirect solar cooker consisted of a parabolic dish collector, a cooking unit, a storage tank, and a pump. Behran thermal oil was used as the heat transfer fluid. The experiment aimed to investigate and compare Behran thermal oil and three other Behran thermal oil-based nanofluids. The three Behran thermal oil-based nanofluids considered were; Silicon dioxide-Bهران thermal oil, Silicon carbide-Bهران thermal oil, and Titanium dioxide-Bهران thermal oil. The results obtained showed that Silicon carbide-Bهران thermal oil out-performed other candidates and it decreased the process of boiling 2 L of water by 17 min. An experiment on the effect of charging of PCMs in vertical and horizontal rectangular enclosures in a concentrated solar receiver was conducted by Senthil [119]. A parabolic concentrator was used to reflect the

sun's rays to the receiver. The insulated receiver was composed of fins and PCM used to store latent heat energy. Water was utilized as the heat transfer fluid, and it was used to transport latent energy from the receiver to the storage tank. A mixture of potassium nitrate and sodium nitrate was used as the PCM. An investigation on the effect of vertical and horizontal orientations was done. Results showed that after charging, the highest temperature achieved by the PCM receiver was approximately 315 °C for the vertical position and 297 °C for the horizontal position. An experimental investigation on thermal performance of a cavity receiver integrated with short-term thermal energy storage for a solar parabolic dish concentrator was done by Thirunavukkarasu et al. [120]. A Scheffler dish integrated with solar grade mirrors was used to reflect solar radiation to the receiver. The receiver was composed of a double layer walled vessel filled with a salt mixture PCM (sodium nitrate and potassium). Water was used as the heat transfer fluid, and it was circulated from the storage tank to the receiver to absorb the heat with the help of a centrifugal pump. The aim of this experiment was to test the effect of the salt mixture integrated with the receiver and the thermal efficiency of the experimental setup. The results showed that the total thermal efficiency was 24.3 % for an average solar radiation of around 429 W/m².

An experimental investigation of solar nitrate salts as solar TES materials for potential cooking applications was done by Gabisa and Aman [121]. Potassium sodium nitrate salts were used as the latent storage material, and an electrical heater was used to simulate solar radiation. The aim of the experiment was to determine the thermal characteristics of the PCM. Experiments were carried out using two local meals, and the results showed 2.38 kWh was required for cooking two meals for five families. Foong et al. [122] investigated a small-scale double-reflector solar concentrating system with high temperature heat storage. The main components of the experimental setup were a primary reflector (parabolic dish), a secondary reflector, and well insulated PCM heat storage unit. A combination of sodium nitrate and potassium nitrate was used as the storage material. Experiments were conducted to test and evaluate the thermal performance of the PCM heat storage during off-sunshine periods. Results showed that melting occurred after 2.5 h, and the maximum temperatures reached ranged from 230-260 °C. Table 2.3 shows a summary of parabolic concentrating collectors using latent heat storage for solar cooking applications.

Table 2.3: Summary of solar concentrating cookers with latent heat thermal energy storage (LHTES).

Author	Type of concentrator	Application	Type of study	Storage material	Maximum cooking/storage temperature (°C)	Heat transfer fluid/ working fluid	Test load
Saini et al. [88]	Parabolic trough	Cooking	Experimental	Acetanilide	76	Water and engine	Rice and pulse
Mussard and Nydal [89]	Parabolic trough	Cooking and frying	Experimental and Numerical	Potassium nitrate and sodium nitrate	200	Duratherm 630	Water and meat
Beemkumar et al. [90]	Parabolic trough	Heat storage	Experimental	D-mannitol, d-sorbitol, and paraffin wax	300	Therminol-66	None
Mussard et al. [91]	Parabolic trough and parabolic dish	Cooking And frying	Experimental	Potassium nitrate and sodium nitrate	130	Therminol-66	Meat
Kumaresan et al. [92]	Parabolic trough	Cooking	Experimental and Numerical	D-Mannitol	167	Therminol-66	Dosa (thick pancake)
Kumar and Pandian [93]	Parabolic trough	Cooking	Experimental	Stearic acid	120	Waste engine oil and water	None
Abu-Hamdeh et al. [94]	Parabolic trough	Cooking and water heating	Experimental	Acetamide	90	Air	Rice
Manikandan et al. [95]	Parabolic trough	Cooking	Experimental and Numerical	D-Mannitol	80	Therminol 55	None
Beemkumar et al. [96]	Parabolic trough	Heat storage	Experimental	D-mannitol, D-sorbitol and paraffin wax	~300	Therminol-66	None
Guerraiche et al. [97]	Parabolic trough	Heat storage	Experimental	Potassium nitrate and sodium nitrate	120	Water	None
Lamrani et al. [98]	Parabolic trough	Heat storage and water heating	Experimental	RT-55, RT-42 and RT-65	80	Water	None

Alimohammad i et al. [99]	Parabolic trough	Dryer	Experimental and Numerical	Paraffin was	80	Engine oil	Slices of banana
Keith et al. [100]	Parabolic dish	Cooking	Experimental and Numerical	Stearic acid	59	None	Rice, lentil and pearled barley
Tesfay et al. [101]	Parabolic dish	Cooking	Experimental	Potassium nitrate and sodium nitrate	~237	Steam	Eggs
Bhave and Kale et al. [102]	Parabolic dish	Cooking	Experimental	Potassium nitrate and sodium nitrate	180	None	Potatoes and rice
Malik et al. [103]	Parabolic dish	Cooking and heating	Experimental and Numerical	Potassium alum	92	Ethylene glycol and water	None
Senthil [104]	Scheffler dish	Cooking	Experimental	Potassium nitrate and sodium nitrate	300	None	Water
Lecuona et al. [105]	Parabolic dish	Cooking	Experimental and Numerical	Erythritol and paraffin	170	None	Water
Tao et al. [106].	Paraboloid solar collector	Heat storage	Numerical	Lithium fluorine And calcium fluoride	508	Not sure	None
Senthil and Cheralathan [107]	Scheffler dish	Heat storage	Experimental	Magnesium chloride hexahydrate	160	None	None
Senthil and Cheralathan [108]	Parabolic dish	Cooking	Experimental	Paraffin wax	90	None	Water
Tesfay et al. [109]	Parabolic collector	Cooking and baking	Experimental and Numerical	Potassium nitrate and sodium nitrate	150	Water	Injera
Chaudhary et al. [110].	Parabolic dish	Cooking	Experimental	Acetanilide	85	None	Water
Yadav and Yadav [111]	Parabolic dish	Cooking	Experimental	Acetamide	71	None	Water, rice and pulses
Rekha and Sukchai [112]	Parabolic dish	Cooking	Experimental	Salt hydrate	100	None	Not sure

Bhave and Thakare [113]	Parabolic dish	Cooking	Experimental	Magnesium chloride hexahydrate	129	Taurus Therm 500	Rice
Veremachi et al. [114]	Parabolic dish	Cooking and frying	Experimental	Potassium nitrate and sodium nitrate	220	None	None
Floess [115]	Parabolic dish	Cooking and frying	Experimental and Numerical	Potassium nitrate and sodium nitrate	334	None	Meat
Sreepathi et al. [116]	“Butterfly” parabolic collector	Cooking	Experimental	Oxalic acid	100	None	Water
Panchal and Sadasivuni [117]	Scheffler dish	Cooking	Experimental	Acetamide	57	None	Rice
Abreha et al. [118]	Parabolic dish	Cooking and heat storage	Numerical	Potassium nitrate and sodium nitrate	230	Thermal oil	None
Tesfay et al. [119]	Parabolic dish	Baking	Numerical	Potassium nitrate and sodium nitrate	150	Water	Injera
Yadav et al. [120]	Parabolic dish	Cooking	Experimental	Acetamide	70	None	Rice
Hosseinzadeh et al. [121]	Parabolic dish	Cooking	Experimental		95	Behran thermal oil	Water
Senthil [122]	Scheffler dish	Heat storage	Experimental	Potassium nitrate and sodium nitrate	315	Water	None
Thirunavukkarasu et al. [123]	Scheffler dish	Heat storage	Experimental	Potassium nitrate and sodium nitrate	~225	Water	None
Gabisa and Aman [124]		Cooking and heat storage	Experimental	Potassium nitrate and sodium nitrate	300	None	None
Foong et al. [125]	Parabolic dish	Heat storage, cooking and baking	Experimental and Numerical	Potassium nitrate and sodium nitrate	260	None	None

2.8 Conclusion

A comprehensive review of solar parabolic cookers incorporating thermal energy storage for off-sunshine cooking has been presented. This category of solar cookers includes both the parabolic trough solar cookers and the parabolic dish solar cookers. The main conclusions that may be drawn from this review are:

- There are more studies related to parabolic dish solar cookers with storage compared to those of parabolic trough solar cookers with storage indicating that the parabolic dish is a more versatile cooker.
- There are more studies on solar cookers incorporating latent heat storage as compared to sensible heat storage due to the lower energy storage density of sensible heat storage. However, very few research efforts have been geared towards combining both sensible and latent heat storage to utilize the advantages of both storage systems.
- Most studies presented on solar cookers are experimental, with limited numerical studies. Meanwhile, modelling reduces the cost of experimentation and ensures optimized designs.
- Most studies utilized aluminum as the material for the reflector (solar collector). Other materials should be investigated for potential competitive advantages.
- Larger-scale experimental setups for the end-users must be designed and tested.
- Very few studies have considered the techno-economic and socio-economic analyses of solar parabolic cookers as compared to conventional cooking methods. This is necessary in order to ensure that the solar cookers are economically competitive and viable, and to investigate the level of acceptability in intended communities.

The research gaps identified by this review for further future studies include modelling of the various types of solar cookers, the combination of both sensible and latent heat thermal energy storage materials for use in solar cookers, investigation of new materials for use as reflectors, investigation of more practical end-user experimental solar cooker prototypes, and techno-economic and socio-economic analyses of solar cookers. Other important aspects that may be considered for future work on parabolic solar cookers with TES include the choice of sensible or latent heat storage materials, environmental impact, types of food to be cooked, and social acceptance. The impact of the heat retention time, and the effect of clouds on heat

retention for solar cookers with and without storage also need to be investigated in future work as recently presented in [25].

Credit author contribution statement

Katlego Lentswe: Investigation, conceptualization, drafted original manuscript, reviewing and editing, formal analysis, interpreting the results. Ashmore Mawire: Conceptualization, methodology, supervision, reviewing and editing. Prince Owusu: Reviewing and editing. Adedamola Shobo: Reviewing, editing and supervision.

References

- [1] Aramesh, M., Ghalebani, M., Kasaeian, A., Zamani, H., Lorenzini, G., Mahian, O., & Wongwises, S. (2019). A review of recent advances in solar cooking technology. *Renewable Energy*, 140, 419-435.
- [2] Karekezi, S., & Kithyoma, W. (2002). Renewable energy strategies for rural Africa: is a PV-led renewable energy strategy the right approach for providing modern energy to the rural poor of sub-Saharan Africa? *Energy Policy*, 30, 1071-1086.
- [3] Demirbaş, A. (2006). Global renewable energy resources. *Energy Sources*, 28, 779-792.
- [4] Sukhatme, S.P., Nayak, J. Solar Energy, McGraw-Hill Education, India, 2017.
- [5] Khatri, R., Goyal, R., & Sharma, R. K. (2021). Advances in the developments of solar cooker for sustainable development: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 145, 111166.
- [6] Radabaugh, J. (1998). *Heaven's Flame: A Guidebook to Solar Cookers*. Joseph Radabaugh.
- [7] Schwarzer, K., & Da Silva, M. E. V. (2008). Characterisation and design methods of solar cookers. *Solar Energy*, 82, 157-163.
- [8] Telkes, M. (1959). Solar cooking ovens, *Solar Energy* 3, 1–11.
- [9] Wentzel, M., & Pouris, A. (2007). The development impact of solar cookers: a review of solar cooking impact research in South Africa. *Energy Policy*, 35, 1909-1919.
- [10] Muthusivagami, R. M., Velraj, R., & Sethumadhavan, R. (2010). Solar cookers with and without thermal storage—a review. *Renewable and Sustainable Energy Reviews*, 14, 691-701.
- [11] Ngala, G. M., Maina, M. B., & Tela, M. B. (2015). Design and construction of a high concentration solar cooker. *International Journal of Research in Mechanical Engineering*, 3, 01-07.
- [12] Indora, S., & Kandpal, T. C. (2018). Institutional and community solar cooking in India using SK-23 and Scheffler solar cookers: A financial appraisal. *Renewable Energy*, 120, 501-511.
- [13] Rao, A. N., & Subramanyam, S. (2005). Solar cookers—part-II—cooking vessel with central annular cavity. *Solar Energy*, 78, 19-22.
- [14] Zafar, H. A., Khan, M. Y., Badar, A. W., Tariq, R., & Butt, F. S. (2018). Introducing a novel design in the realm of box type solar cookers: An experimental study. *Journal of Renewable and Sustainable Energy*, 10, 043707.
- [15] Coccia, G., Aquilanti, A., Tomassetti, S., Ishibashi, A., & Di Nicola, G. (2021). Design,

- manufacture and test of a low-cost solar cooker with high-performance light-concentrating lens. *Solar Energy*, 224, 1028-1039.
- [16] Battocchio, C., Bruni, F., Di Nicola, G., Gasperi, T., Iucci, G., Tofani, D., ... & Venditti, I. (2021). Solar cookers and dryers: environmental sustainability and nutraceutical content in food processing. *Foods*, 10, 2326.
- [17] Anilkumar, B. C., Maniyeri, R., & Anish, S. (2021). Optimum selection of phase change material for solar box cooker integrated with thermal energy storage unit using multi-criteria decision-making technique. *Journal of Energy Storage*, 40, 102807.
- [18] Coccia, G., Di Nicola, G., Pierantozzi, M., Tomassetti, S., & Aquilanti, A. (2017). Design, manufacturing, and test of a high concentration ratio solar box cooker with multiple reflectors. *Solar Energy*, 155, 781-792.
- [19] Gama, F. Y., Azoui, B., Malek, A., Panwar, N. L., & Gama, A. (2015). Energetic and exergetic evaluation of solar box cooker in Algerian climatic conditions. *International Journal of Exergy*, 16, 337-357.
- [20] Collares-Pereira, M., Cavaco, A., & Tavares, A. (2018). Figures of merit and their relevance in the context of a standard testing and performance comparison methods for solar box–Cookers. *Solar Energy*, 166, 21-27.
- [21] Lahkar, P. J., Bhamu, R. K., & Samdarshi, S. K. (2012). Enabling inter-cooker thermal performance comparison based on cooker opto-thermal ratio (COR). *Applied Energy*, 99, 491-495.
- [22] Reddy, K. S., & Sendhil Kumar, N. (2009). Convection and surface radiation heat losses from modified cavity receiver of solar parabolic dish collector with two-stage concentration. *Heat and Mass Transfer*, 45, 363-373.
- [23] Yettou, F., Azoui, B., Malek, A., Panwar, N. L., & Gama, A. (2018). Generating Temperature Maps of a Solar Receiver for a Domestic Parabolic Concentrator for Cooking Purposes Under Algerian Environment. *Exergy for A Better Environment and Improved Sustainability 2: Applications*, 231-257.
- [24] Herez, A., Ramadan, M., & Khaled, M. (2018). Review on solar cooker systems: Economic and environmental study for different Lebanese scenarios. *Renewable and Sustainable Energy Reviews*, 81, 421-432.
- [25] Sagade, A. A., Samdarshi, S. K., Sagade, N. A., & Panja, P. S. (2021). Enabling open sun cooling method-based estimation of effective concentration factor/ratio for concentrating type solar cookers. *Solar Energy*, 227, 568-576.
- [26] Wimmer, R., Kang, M. J., Pokpong, C., & Mahdavi, A. (2017). Analysis of user needs for solar cooker acceptance. *Sustainability Through Innovation in Product Life Cycle Design*, 151-165.
- [27] Singh, H., Gagandeep, Saini, K., & Yadav, A. (2015). Experimental comparison of different heat transfer fluid for thermal performance of a solar cooker based on evacuated tube collector. *Environment, Development and Sustainability*, 17, 497-511.
- [28] Ahmed, S. M., Al-Amin, M. R., Ahammed, S., Ahmed, F., Saleque, A. M., & Rahman, M. A. (2020). Design, construction and testing of parabolic solar cooker for rural households and refugee camp. *Solar Energy*, 205, 230-240.
- [29] Akayleh, A. S., Al-Soud, M. S., & Al-Jufout, S. A. (2020). Design and development of a solar-based cooker with a mechanical sun tracking system. *International Journal of Ambient Energy*, 41, 808-812.
- [30] Prompuge, W., & Sirisamphanwong, C. (2018). Technical performance for heat storage of solar cooker using vegetable oil as working fluid. *Journal of Renewable*

- [31] Abou-Ziyan, H. Z. (1998). Experimental investigation of tracking paraboloid and box solar cookers under Egyptian environment. *Applied Thermal Engineering, 18*, 1375-1394.
- [32] Mohammed, I. L. (2015). Field testing and evaluation of a truncated pyramid solar thermal cooker. *International of Journal of Renewable Energy Environment Engineering, 3*.
- [33] Mawire, A., Ramokali, M., & Mothupi, M. (2020). A solar thermal experiment with parabolic dish solar cookers for developing countries. *European Journal of Physics, 41*, 055104.
- [34] Mawire, A., McPherson, M., & Van den Heetkamp, R. R. J. (2010). Discharging simulations of a thermal energy storage (TES) system for an indirect solar cooker. *Solar Energy Materials and Solar Cells, 94*, 1100-1106.
- [35] Riva, F., Rocco, M. V., Gardumi, F., Bonamini, G., & Colombo, E. (2017). Design and performance evaluation of solar cookers for developing countries: the case of M utoyi, B urundi. *International Journal of Energy Research, 41*, 2206-2220..
- [36] Mawire, A., Lentswe, K. A., Okello, D., Nyeinga, K., & Lugolole, R. (2018, December). Energy and exergy performance of three sensible heat storage systems during charging. In *2018 6th International Renewable and Sustainable Energy Conference*, 1-6.
- [37] Nkhonjera, L., Bello-Ochende, T., John, G., & King'onde, C. K. (2017). A review of thermal energy storage designs, heat storage materials and cooking performance of solar cookers with heat storage. *Renewable and Sustainable Energy Reviews, 75*, 157-167.
- [38] Omara, A. A., Abuelnuor, A. A., Mohammed, H. A., Habibi, D., & Younis, O. (2020). Improving solar cooker performance using phase change materials: A comprehensive review. *Solar Energy, 207*, 539-563.
- [39] Panchal, H., Patel, J., & Chaudhary, S. (2019). A comprehensive review of solar cooker with sensible and latent heat storage materials. *International Journal of Ambient Energy, 40*, 329-334.
- [40] Sharma, A., Chen, C. R., Murty, V. V. S., & Shukla, A. (2009). Solar cooker with latent heat storage systems: A review. *Renewable and Sustainable Energy Reviews, 13*, 1599-1605.
- [41] Fernández, A., Martínez, M., Segarra, M., Martorell, I., & Cabeza, L. F. (2010). Selection of materials with potential in sensible thermal energy storage. *Solar Energy Materials and Solar cells, 94*, 1723-1729.
- [42] Abdin, Z., & Khalilpour, K. R. (2019). Single and polystorage technologies for renewable-based hybrid energy systems. In *Polygeneration with Polystorage for Chemical and Energy Hubs*, 77-131.
- [43] Ferone, C., Colangelo, F., Frattini, D., Roviello, G., Cioffi, R., & Di Maggio, R. (2014). Finite element method modeling of sensible heat thermal energy storage with innovative concretes and comparative analysis with literature benchmarks. *Energies, 7*, 5291-5316.
- [44] Lahkar, P. J., & Samdarshi, S. K. (2010). A review of the thermal performance parameters of box type solar cookers and identification of their correlations. *Renewable and Sustainable Energy Reviews, 14*, 1615-1621.
- [45] Saxena, A., Pandey, S. P., & Srivastav, G. (2011). A thermodynamic review on solar

- box type cookers. *Renewable and Sustainable Energy Reviews*, 15, 3301-3318.
- [46] Panwar, N. L., Kaushik, S. C., & Kothari, S. (2012). State of the art of solar cooking: An overview. *Renewable and Sustainable Energy Reviews*, 16, 3776-3785.
- [47] Farooqui, S. Z. (2014). A review of vacuum tube based solar cookers with the experimental determination of energy and exergy efficiencies of a single vacuum tube based prototype. *Renewable and Sustainable Energy Reviews*, 31, 439-445.
- [48] Yettou, F., Azoui, B., Malek, A., Gama, A., & Panwar, N. L. (2014). Solar cooker realizations in actual use: An overview. *Renewable and Sustainable Energy Reviews*, 37, 288-306.
- [49] Harmim, A., Merzouk, M., Boukar, M., & Amar, M. (2014). Solar cooking development in Algerian Sahara: Towards a socially suitable solar cooker. *Renewable and Sustainable Energy Reviews*, 37, 207-214.
- [50] Iessa, L., De Vries, Y. A., Swinkels, C. E., Smits, M., & Butijn, C. A. A. (2017). What's cooking? Unverified assumptions, overlooking of local needs and pro-solution biases in the solar cooking literature. *Energy Research and Social Science*, 28, 98-108.
- [51] El Hage, H., Herez, A., Ramadan, M., Bazzi, H., & Khaled, M. (2018). An investigation on solar drying: A review with economic and environmental assessment. *Energy*, 157, 815-829.
- [52] Indora, S., & Kandpal, T. C. (2018). Institutional cooking with solar energy: A review. *Renewable and Sustainable Energy Reviews*, 84, 131-154.
- [53] Elsheikh, A. H., Sharshir, S. W., Abd Elaziz, M., Kabeel, A. E., Guilan, W., & Haiou, Z. (2019). Modeling of solar energy systems using artificial neural network: A comprehensive review. *Solar Energy*, 180, 622-639.
- [54] Arunachala, U. C., & Kundapur, A. (2020). Cost-effective solar cookers: A global review. *Solar Energy*, 207, 903-916.
- [55] Devan, P. K., Bibin, C., Gowtham, S., Hariharan, G., & Hariharan, R. (2020). A comprehensive review on solar cooker with sun tracking system. *Materials Today: Proceedings*, 33, 771-777.
- [56] Khatri, R., Goyal, R. and Sharma, R.K., 2021. Advances in the developments of solar cooker for sustainable development: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 145, 111166.
- [57] Mishra, A., Powar, S., & Dhar, A. (2019). Solar Thermal powered bakery oven. *Advances in Solar Energy Research*, 577-592.
- [58] El Moussaoui, N., Talbi, S., Atmane, I., Kassmi, K., Schwarzer, K., Chayeb, H., & Bachiri, N. (2020). Feasibility of a new design of a Parabolic Trough Solar Thermal Cooker (PSTC). *Solar Energy*, 201, 866-871.
- [59] Asmelash, H., Bayray, M., Kimambo, C. Z. M., Gebray, P., & Sebbit, A. M. (2014). Performance test of parabolic trough solar cooker for indoor cooking. *Momona Ethiopian Journal of Science*, 6, 39-54.
- [60] DIANDA, B., & Maurice, T. S. (2019). KY. parabolic trough cooker. *International Journal of Current Research Key Words*, 11, 1869-1874.
- [61] Mohan, B., & Vasanthakumar, D. (2015). Analysis of the effectiveness of solar assisted steam cooking using parabolic trough collector. *International Research Journal Engineering and Technology*, 2, 932-939.
- [62] Hassen, A. A., Amibe, D. A., & Nydal, O. J. (2011). Performance investigation of solar powered Injera Baking oven for indoor cooking. In *ISES Solar World Congress Proceedings, Kassel, Germany* (pp. 186-196).

- [63] Goytom, D. (2016). Finite difference modelling of solar thermal powered Injera baking oven. *International Advance Research Journal Science, Engineering and Technology*, 3, 124-131.
- [64] Yılmaz, İ. H., Söylemez, M. S., Hayta, H., & Yumrutaş, R. (2014). A process heat application using parabolic trough collector. In *International Congress on Energy Efficiency and Energy Related Materials (ENEFM2013) Proceedings, Antalya, Turkey, 9-12 October 2013* (pp. 137-141).
- [65] Arunachala, U. C., Jhalaria, A., & Sheikh, M. (2014). Design, fabrication and performance analysis of solar cooker for night cooking. *International Journal of Renewable Energy and Environmental Engineering*, 2.
- [66] Noman, M., Wasim, A., Ali, M., Jahanzaib, M., Hussain, S., Ali, H. M. K., & Ali, H. M. (2019). An investigation of a solar cooker with parabolic trough concentrator. *Case Studies in Thermal Engineering*, 14, 100436.
- [67] Widjaja, A. S., Löwe, K., & Costa, F. S. (2018). Design and simulation of a concentrated solar thermal system with an integrated concrete storage for continuous heat supply. *Energy Procedia*, 155, 121-135.
- [68] Bade, M. H., & Bandyopadhyay, S. (2015). Energy modelling of thermal oil based cooking system. *Energy Procedia*, 75, 1746-1751.
- [69] Abd-Elhady, M. S., Abd-Elkerim, A. N. A., Ahmed, S. A., Halim, M. A., & Abu-Oqual, A. (2020). Study the thermal performance of solar cookers by using metallic wires and nanographene. *Renewable Energy*, 153, 108-116.
- [70] Agrawal, H., & Yadav, A. (2015). Design and experimental testing of solar cooker with sensible heat storage. *Journal of Energy Research and Environmental Technology*, 2, 200-204.
- [71] Prasanna, U. R., & Umanand, L. (2011). Optimization and design of energy transport system for solar cooking application. *Applied Energy*, 88, 242-251.
- [72] Mawire, A., McPherson, M., & Van den Heetkamp, R. R. J. (2008). Simulated energy and exergy analyses of the charging of an oil-pebble bed thermal energy storage system for a solar cooker. *Solar Energy Materials and Solar Cells*, 92, 1668-1676.
- [73] Badran, A. A., Yousef, I. A., Joudeh, N. K., Al Hamad, R., Halawa, H., & Hassounah, H. K. (2010). Portable solar cooker and water heater. *Energy Conversion and Management*, 51, 1605-1609.
- [74] Murty, V. V. S., Gupta, A., Mandloi, N., & Shukla, A. (2007). Evaluation of thermal performance of heat exchanger unit for parabolic solar cooker for off-place cooking. *Indian Journal Pure Applied Physics*, 45, 745-748.
- [75] Craig, O. O., & Dobson, R. T. (2016). Parabolic solar cooker: Cooking with heat pipe vs direct spiral copper tubes. In *AIP Conference Proceedings*, 1734, 1.
- [76] Mbodji, N., & Hajji, A. (2017). Modeling, testing, and parametric analysis of a parabolic solar cooking system with heat storage for indoor cooking. *Energy, Sustainability and Society*, 7, 1-16.
- [77] Senthil, R., & Cheralathan, M. (2016). Thermal performance of solid and liquid energy storage materials in a parabolic dish solar cooker. *International Journal of Chemical Science*, 14, 1977-1983.
- [78] Nyahoro, P. K., Johnson, R. R., & Edwards, J. (1997). Simulated performance of thermal storage in a solar cooker. *Solar Energy*, 59, 11-17.
- [79] Lokeswaran, S., & Eswaramoorthy, M. (2012). Experimental studies on solar parabolic dish cooker with porous medium. *Applied Solar Energy*, 48, 169-174.

- [80] Kedida, D. K., Amibe, D. A., & Birhane, Y. T. (2019). Performance of a pebble bed thermal storage integrated with concentrating parabolic solar collector for cooking. *Journal of Renewable Energy*, 2019, 1-12.
- [81] Wollele, M. B., & Hassen, A. A. (2019). Design and experimental investigation of solar cooker with thermal energy storage. *AIMS Energy*, 7, 957-970.
- [82] Ayub, I., Munir, A., Amjad, W., Ghafoor, A., & Nasir, M. S. (2018). Energy-and exergy-based thermal analyses of a solar bakery unit. *Journal of Thermal Analysis and Calorimetry*, 133, 1001-1013.
- [83] Raza, A., Majeed, F., Munir, A., & Hensel, O. (2019). Development and experimental results of a thermal oil based roasting system for decentralized processing of groundnuts. *Applied Sciences*, 9, 4342.
- [84] Mawire, A., Lentswe, K., Owusu, P., Shobo, A., Darkwa, J., Calautit, J., & Worall, M. (2020). Performance comparison of two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking. *Solar Energy*, 208, 1166-1180.
- [85] Nazari, S., Karami, A., Bahiraei, M., Olfati, M., Goodarzi, M., & Khorasanizadeh, H. (2020). A novel technique based on artificial intelligence for modeling the required temperature of a solar bread cooker equipped with concentrator through experimental data. *Food and Bioprocesses Processing*, 123, 437-449.
- [86] Saini, G., Singh, H., Saini, K., & Yadav, A. (2016). Experimental investigation of the solar cooker during sunshine and off-sunshine hours using the thermal energy storage unit based on a parabolic trough collector. *International Journal of Ambient Energy*, 37, 597-608.
- [87] Mussard, M., & Nydal, O. J. (2013). Charging of a heat storage coupled with a low-cost small-scale solar parabolic trough for cooking purposes. *Solar Energy*, 95, 144-154.
- [88] Beemkumar, N., Karthikeyan, A., Yuvarajan, D., & Lakshmi Sankar, S. (2017). Experimental investigation on improving the heat transfer of cascaded thermal storage system using different fins. *Arabian Journal for Science and Engineering*, 42, 2055-2065.
- [89] Mussard, M., Gueno, A., & Nydal, O. J. (2013). Experimental study of solar cooking using heat storage in comparison with direct heating. *Solar Energy*, 98, 375-383.
- [90] Kumaresan, G., Santosh, R., Raju, G., & Velraj, R. (2018). Experimental and numerical investigation of solar flat plate cooking unit for domestic applications. *Energy*, 157, 436-447.
- [91] Babu Sasi Kumar, S., & Chinna Pandian, M. (2019). Experimental analysis of a solar cooker with a parabolic trough enhanced with PCM based thermal storage. In *IOP Conference Series: Materials Science and Engineering*, 574,1.
- [92] Abu-Hamdeh, N. H., & Alnefaie, K. A. (2019). Assessment of thermal performance of PCM in latent heat storage system for different applications. *Solar Energy*, 177, 317-323.
- [93] Manikandan, K. S., Kumaresan, G., Velraj, R., & Iniyan, S. (2012). Parametric study of solar parabolic trough collector system. *Asian Journal of Applied Sciences*, 5, 384-393.
- [94] Guerraiche, D., Bougriou, C., Guerraiche, K., Valenzuela, L., & Driss, Z. (2020). Experimental and numerical study of a solar collector using phase change material as heat storage. *Journal of Energy Storage*, 27, 101133.
- [95] Lamrani, B., Kuznik, F., & Draoui, A. (2020). Thermal performance of a coupled solar parabolic trough collector latent heat storage unit for solar water heating in large

- buildings. *Renewable Energy*, 162, 411-426.
- [96] Alimohammadi, Z., Akhijahani, H. S., & Salami, P. (2020). Thermal analysis of a solar dryer equipped with PTSC and PCM using experimental and numerical methods. *Solar Energy*, 201, 157-177.
- [97] Keith, A., Brown, N. J., & Zhou, J. L. (2019). The feasibility of a collapsible parabolic solar cooker incorporating phase change materials. *Renewable Energy Focus*, 30, 58-70.
- [98] Tesfay, A. H., Kahsay, M. B., & Nydal, O. J. (2014). Solar powered heat storage for Injera baking in Ethiopia. *Energy Procedia*, 57, 1603-1612.
- [99] Bhawe, A. G., & Kale, C. K. (2020). Development of a thermal storage type solar cooker for high temperature cooking using solar salt. *Solar Energy Materials and Solar Cells*, 208, 110394.
- [100] Malik, M. S., Iftikhar, N., Wadood, A., Khan, M. O., Asghar, M. U., Khan, S., ... & Rizvi, S. T. U. I. (2020). Design and fabrication of solar thermal energy storage system using potash alum as a pcm. *Energies*, 13, 6169.
- [101] Senthil, R., Rath, C., & Gupta, M. (2017). Enhancement of uniform temperature distribution on the concentrated solar receiver with integrated phase change material. *International Journal of Mechanical Engineering and Technology*, 8, 315-320.
- [102] Lecuona, A., Nogueira, J. I., Ventas, R., & Legrand, M. (2013). Solar cooker of the portable parabolic type incorporating heat storage based on PCM. *Applied Energy*, 111, 1136-1146.
- [103] Tao, Y. B., He, Y. L., Cui, F. Q., & Lin, C. H. (2013). Numerical study on coupling phase change heat transfer performance of solar dish collector. *Solar Energy*, 90, 84-93.
- [104] Senthil, R., & Cheralathan, M. (2017). Effect of the phase change material in a solar receiver on thermal performance of parabolic dish collector. *Thermal Science*, 21, 2803-2812.
- [105] Senthil, R. (2021). Enhancement of productivity of parabolic dish solar cooker using integrated phase change material. *Materials Today: Proceedings*, 34, 386-388.
- [106] Tesfay, A. H., Kahsay, M. B., & Nydal, O. J. (2015). Solar cookers with latent heat storage for intensive cooking application. In *ISES Proceedings of Solar World Congress, Daegu, Korea*, 8, 71-79.
- [107] Chaudhary, A., Kumar, A., & Yadav, A. (2013). Experimental investigation of a solar cooker based on parabolic dish collector with phase change thermal storage unit in Indian climatic conditions. *Journal of Renewable and Sustainable Energy*, 5.
- [108] Yadav, V., & Yadav, A. (2013). Experimental investigation of novel design of solar cooker with dual thermal storage unit based on parabolic dish-type collector. *International Journal of Energy for a Clean Environment*, 14.
- [109] Santhi Rekha, S. M., & Sukchai, S. (2018). Design of phase change material based domestic solar cooking system for both indoor and outdoor cooking applications. *Journal of Solar Energy Engineering*, 140, 041010.
- [110] Bhawe, A. G., & Thakare, K. A. (2018). Development of a solar thermal storage cum cooking device using salt hydrate. *Solar Energy*, 171, 784-789.
- [111] Veremachi, A., Cuamba, B. C., Zia, A., Lovseth, J., & Nydal, O. J. (2016). PCM heat storage charged with a double-reflector solar system. *Journal of Solar Energy*.
- [112] Floess, E. M. (2019). Developing a solar resource map for a stored solar cooker, Illinois, USA.

- [113] Sreepathi, L. K., Madhuvanthi, L. G., Sharadhi, T. S., & Chethan, G. S. (2017). Performance analysis of solar energy storage Unit for Cooking. *Journal of Engineering & Management*, 1, 65.
- [114] Panchal, H., & Sadasivuni, K. K. (2020). Investigation and performance analysis of Scheffler reflector solar cooking system integrated with sensible and latent heat storage materials. *International Journal of Ambient Energy*, 41, 1096-1105.
- [115] Abreha, B. G., Mahanta, P., & Trivedi, G. (2019, April). Numerical modeling and simulation of thermal energy storage for solar cooking using Comsol multiphysics software. In *AIP Conference Proceedings*, 2091,1.
- [116] Tesfay, A. H., Kahsay, M. B., & Nydal, O. J. (2019). Numerical and experimental analysis of solar Injera baking with a PCM heat storage. *Momona Ethiopian Journal of Science*, 11, 1-13.
- [117] Yadav, V., Kumar, Y., Agrawal, H., & Yadav, A. (2017). Thermal performance evaluation of solar cooker with latent and sensible heat storage unit for evening cooking. *Australian Journal of Mechanical Engineering*, 15, 93-102.
- [118] Hosseinzadeh, M., Sadeghirad, R., Zamani, H., Kianifar, A., Mirzababaei, S. M., & Faezian, A. (2021). Experimental study of a nanofluid-based indirect solar cooker: energy and exergy analyses. *Solar Energy Materials and Solar Cells*, 221, 110879.
- [119] Senthil, R. (2020). Effect of charging of phase change material in vertical and horizontal rectangular enclosures in a concentrated solar receiver. *Case Studies in Thermal Engineering*, 21, 100653.
- [120] Thirunavukkarasu, V., Nair, V. U., Tiwari, K., & Cheralathan, M. (2020). Experimental investigation on thermal performance of cavity receiver integrated with short-term thermal energy storage for a solar parabolic dish concentrator. *Journal of Thermal Analysis and Calorimetry*, 1-12.
- [121] Gabisa, E. W., & Aman, A. (2016). Characterization and experimental investigation of NaNO₃: KNO₃ as solar thermal energy storage for potential cooking application. *Journal of Solar Energy Engineering*, 2016 1-6.
- [122] Foong, C. W., Nydal, O. J., & Løvseth, J. (2011). Investigation of a small-scale double-reflector solar concentrating system with high temperature heat storage. *Applied Thermal Engineering*, 31, 1807-1815.

Chapter 3: Performance comparison of two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking

Overview and abstract

In this chapter, two similar storage cooking pots are experimentally evaluated and compared during solar cooking and storage off-sunshine cooking periods. This chapter consists of work that has been published in the Solar Energy journal ([Solar Energy 208 \(2020\)](#)).

One storage pot has sunflower oil as the sensible heat storage material, while the other has erythritol as the phase change material (PCM). To test their thermal performance during off-sunshine periods, the two pots are placed in insulated wonderbag slow cookers. Water and sunflower oil are used as the cooking fluids in the experimental tests. The sunflower oil cooking pot shows better performance during the solar cooking periods since it shows shorter cooking times (1.8-5.6 h) compared to the erythritol PCM pot (3.8-6.6 h). The sunflower oil pot also attains higher maximum storage temperatures (124-145 °C) compared to the erythritol PCM pot (118-140 °C). Storage efficiencies for the sunflower oil pot (3.0-7.1%) are also greater than those of the PCM pot (2.5-3.7%). During the storage cooking periods, the erythritol based phase change material cooking pot shows better performance as evidenced by the lower temperature drops (0.1-9.7 °C) from the maximum cooking temperatures compared to 8.3 to 34 °C for the sunflower oil pot. The heat utilisation efficiencies for the erythritol pot (4.8-14.3%) are also greater compared to the sunflower oil pot (3.7-6%).

3.1 Introduction

Solar cookers are environmentally friendly devices that use energy from the sun to cook food. Recent comprehensive reviews on solar cookers have presented different designs, applications and approaches for the evaluation of cookers to improve their efficiency [1,2,3,4,5,6,7]. The four main types of solar cookers are oven solar cookers (box type), panel cookers, concentrating cookers (e.g. parabolic dish solar cookers) and indirect type of solar cookers (e.g. evacuated tube solar cookers with thermal energy storage). Recent work on solar cookers has focussed on improvements of the design of these cookers to achieve higher operating temperatures by using reflectors and changes in the design of the solar cookers and

cooking pots, improving the efficiency of solar cookers [8,9, 10, 11, 12, 13,14]. The efficiency improvement, however, does not guarantee operation during non-sunshine periods, for example, at night to cook dinner. Oven and panel cookers have lower efficiency, achieve lower temperatures, and take a longer time to cook food compared to concentrating solar cookers and indirect solar cookers, although they are cheaper and easier to construct [7]. On the other hand, the indirect type of solar cookers alleviate the problem of cooking when the sun is not available by using thermal energy storage (TES) but are rather expensive for mass production compared to the concentrating type of solar cookers [7].

A widely available and highly efficient type of concentrating solar cooker is the parabolic dish solar cooker [15,16,17]. Different studies have been done recently, improving, characterising, and evaluating its thermal performance. An eco-friendly concentrating solar cooker for extraction of cashew nutshell oil and household cooking was presented by Mohod et al. [18]. The parabolic concentrating solar cooker (SK-14) was evaluated for cooking and generation of heat for cashew nutshell liquid (CNSL) extraction. A no-load temperature of 320 °C was achieved inside the extractor, and the average oil recovery efficiency was reported to be 55-70%. Panwar et al. [19] presented an experimental investigation of energy and exergy efficiencies of a domestic sized parabolic dish solar cooker. The heat output of the cooker varied between 46.67 and 653.33 W, whereas its exergy output varied between 7.37 and 46.46 W.

An experimental study of solar cooking using heat storage in comparison with direct heating was done by Mussard et al. [20]. For the SK14 direct solar cooker, the cooking pot was placed on the focal point of a parabolic dish. The system was compared to a parabolic trough system where heat was transported from an absorber to a storage unit using a self-circulation loop filled with thermal oil. The system with heat storage was slower than the SK14 cooker for boiling water even with a standard pot. However, the quality of the heat transfer could be significantly improved with an amelioration of the contact surface of the heat storage unit. The thermal analysis of a solar parabolic dish cooker with back reflection was presented by Kedar et al. [21]. The thermal performance of this type of solar cooker was better than a solar box cooker.

The design, modelling, energy, and exergy analysis of a parabolic cooker for Nigerian conditions was presented by Onokwai et al. [22]. The solar cooker was fabricated using

inexpensive, and locally available materials in Nigeria. The average energy and exergy efficiencies of the parabolic cooker were about 39 % and 44 %, respectively. The major problem with the parabolic dish solar cooker, as with all solar cookers, is that it cannot be used at night or during cloudy periods.

In order to cater for the mismatch between the supply and demand of solar energy for cooking purposes, TES systems can be integrated with solar thermal solar cookers and other solar thermal devices [23, 24, 25, 26, 27, 28, 29, 30, 31]. A recent comprehensive review by Omara et al. [32] highlighted the advantages and draw-backs of using solar cookers based on latent heat storage using phase change materials (PCMs), and they concluded that organic PCMs were the most commonly used in solar cookers due to the lower cost and high latent heat capacity as compared to other PCMs. Latent heat storage based on PCMs has recently been used in solar cookers to cook during non-sunshine periods due to the associated high thermal energy storage densities and quasi-isothermal storage and release of thermal energy [33, 34, 35, 36, 37, 38, 16, 31]. The parabolic dish solar cooker offers reasonably good thermal performance at a relatively low cost and can be fabricated with locally available materials at reasonable costs, as recently investigated by Ahmed et al. [39] who fabricated cheap parabolic dish solar cookers for refugee camps and rural households. However, as already highlighted, this type of cooker cannot be used to cook food during non-sunshine hours. To alleviate the problem of cooking during non-sunshine hours, recent works have investigated using TES indirectly combined with parabolic solar cookers [40, 41, 42, 43, 44, 45]. These are rather expensive and inefficient methods with more components required and result in additional heat losses from piping that is required for transporting heat to the storage system. Integration of the cooking pot directly with thermal energy storage (TES) has recently been developed, which is cheaper and more efficient than indirect methods.

Lecuona et al. [46] investigated a standard concentrating parabolic dish cooker that incorporated a daily TES utensil. This utensil was formed by two conventional coaxial cylindrical cooking pots consisting of an internal one and a larger external one. The space between the two coaxial pots was filled with PCM forming an intermediate jacket. The results indicated that retaining the utensil inside an insulating box indoors allowed it to be used to cook food in the evening, whilst also retaining enough heat to cook breakfast the next morning. An experimental investigation of a parabolic solar cooker with a receiver

incorporating a PCM storage unit was carried out by Chaudhary et al. [47]. During the day, acetanilide (PCM) stored solar heat, and during the evening, the solar cooker was kept in the insulator box where the phase change material delivered heat to the food. To enhance the performance of the solar cooker, three cases were considered namely, an ordinary solar cooker, a solar cooker with the outer surface painted black, and a solar cooker with the outer surface painted black and with glazing. It was observed that the solar cooker with the outer surface painted black with glazing performed better compared to the other cases. It was also found out that the PCM in the solar cooker with the outer surface painted black stored 26.8 % more heat as compared to the PCM in the ordinary solar cooker. In addition, the PCM in the solar cooker with the outer surface painted black with glazing stored 32.3 % more heat in comparison to the PCM in the ordinary solar cooker.

The design of a PCM based domestic solar cooking system for both indoor and outdoor cooking applications was presented by Rekha and Sukchai [48]. The receiver was formed as a hollow concentric cylinder, with heat transfer oil filling the gap between the cylinders. The outer layer of the receiver was surrounded by vertical cylindrical PCM tubes. The optical efficiency factor of the solar cooker with the PCM receiver was double that of the receiver without PCM. The results also concluded that the design of the PCM solar cooking system could expand the applicability of solar cookers as a compatible cooking solution for cooking applications instead of using fossil fuel-based cooking systems.

Bhave and Thakare [49] carried out an experimental investigation of a concentrating type of solar cooker using magnesium chloride hexahydrate as the thermal storage material designed for the boiling type of cooking. The time required to cook 50 g of rice with 100 ml of water was approximately 30 min, and the heat utilization efficiency above 100 °C was 32.66 %. The thermal performance evaluation of a solar cooker with a latent and sensible heat storage unit for evening cooking was evaluated by Yadav et al. [50]. The research presented an investigation of the thermal performance of PCM in combination with different sensible heat storage materials (SHSMs) in a solar cooker based on a parabolic dish collector for evening cooking. During sunshine hours, the storage cooking pot was placed on the focal region of the parabolic dish to store heat. In the evening, the solar cooking storage pot was placed inside an insulated box and loaded with food. Heat transferred from the PCM was used to cook the food. It was found that the PCM-Sand

and PCM-Stone pebble cases stored 3 to 3.5 times more heat compared to the PCM-Iron grits and PCM-Iron ball cases. The PCM assisted in cooking while the outer sensible heat material assisted the PCM to maintain its performance.

The work by Choudhari and Shende [51] investigated a solar cooking pot with acetanilide as the PCM. In order to evaluate the internal behaviour of the PCM, a one-dimensional heat balance model was developed, and it was compared with the experimental results. The results obtained demonstrated that the PCM could absorb solar radiation throughout daytime periods and use the heat in evening cooking. Nayak et al. [52] experimentally investigated acetanilide and stearic acid as PCMs for a storage cooking pot charged up with an evacuated tube solar collector. The circumference of the cooker was integrated with a heat exchanger, and the annulus area of the cooking unit was embedded with PCMs. The results revealed that the cooker was efficiently utilised for cooking during evenings due to the use of PCM. The results showed that acetanilide was superior to stearic acid in terms of thermal performance with a cooker utilisation efficiency of 31 % compared to 25 % for stearic acid.

Senthil and Cheralathan [53] presented the enhancement of the thermal energy storage capacity of a parabolic dish concentrated solar receiver using phase change materials. A parabolic dish collector with a reflector aperture area of 16 m² was used to test the performance of the solar receiver. Sugar alcohols were used as the PCMs. The average energy and exergy efficiencies of the receiver with multiple PCMs were 66.7 % and 13.8 %, respectively, for the heat transfer fluid (HTF) flowrate of 80 kg/h. The solar receiver acted as a thermal battery for meeting thermal needs even after sunset. Keith et al. [54] conducted a feasibility study of a collapsible parabolic solar cooker incorporating phase change materials. This research proposed a collapsible parabolic solar cooker with 12 panels, and a PCM-incorporated cooking pot as a viable alternative to firewood. The PCM allowed food cooked during the daytime to be kept warm and subsequently consumed as an evening meal.

Bhave and Kale [55] recently developed a thermal storage unit for a solar parabolic dish using a solar salt which was embedded with the receiver. The TES unit was able to successfully store heat at its melting point of 220 °C with a charging time of 110 min. Frying temperatures of 170-180 °C using oil were easily obtained during indoors cooking, and 0.25 kg of potato

chips were fried in 17 mins from one heat charging cycle. A portable solar box cooker coupled with an erythritol-based PCM storage system was recently reported Coccia et al. [56]. The TES unit was a double-walled stainless-steel vessel, with the annular volume filled with 2.5 kg of erythritol. Results showed that equipping the portable solar box cooker with the erythritol-based TES allowed extending the average load cooling time, in the range of 125-100 °C, to around 351.16 %.

A recent innovation in cooking is the slow cooking wonderbag, which has been used to retain heat and cook food that has been initially slightly pre-cooked using electric cookers and liquefied petroleum gas (LPG) [57]. It is a stand-alone, non-electric insulated bag designed to reduce the amount of fuel required in the cooking of food in developing countries. Food is only brought up to the cooking temperature and then placed inside the wonderbag cooker instead of cooking for the whole period. Thermal insulation in the wonderbag retains the heat, so that cooking continues slowly without the need for additional heat. One of the few scientific studies on wonderbag slow cookers carried out by Islam and Salehin [57] revealed that the wonderbag reduced a significant amount of energy consumption in the induction cooker and the LPG stove. The tests showed a range of energy savings from 22 to 48 % for different food items. The wonderbag also helped to reduce the carbon footprint and reduced carbon-dioxide emissions by 45-189 g per kg of different foods. The food cooked during the tests was tasted, and it was found that the texture of the food cooked using the wonderbag was improved. The wonderbag was primarily designed for slow cooking in conjunction with electric cookers, biomass, and LPG. However, to reduce the use of electrical energy, biomass, and LPG for cooking, it can be combined with solar cooking pots with energy storage especially in rural areas of developing countries where there is no electrical grid connection.

We are not aware of research into wonderbag together with solar cookers and storage cooking pots in recent literature searches, and so we will be disseminating novel and interesting research to the solar cooking and energy utilisation communities. Using the wonderbag with solar storage cooking pots can be a sustainable cooking solution for people in rural areas in the developing countries where there is an abundance of solar energy. However, the performance of solar storage pots and wonderbags could be limited by the amount of solar radiation available at a particular location and the prevailing weather conditions.

It is clear from the literature review that limited work has been done on solar cooking storage vessels or pots, and more work needs to be done in terms of improving the storage efficiency, finding suitable storage materials, and improving heat retention properties. In addition to this, solar cooking pots need an insulating container for them to retain heat that will be used for cooking later effectively. This paper thus presents a novel study that will evaluate the performance of solar cooking pots with TES combined with wonderbag slow cookers for cooking during non-sunshine hours. This study has never been done and will assist developing countries who have limited electricity supplies for cooking, where biomass is the major source of energy for cooking, but which presents hazards to the environment and to human beings.

The two main viable storage options for solar cookers are latent heat storage using PCMs and sensible heat storage; thus, two storage cookers will be compared. Sensible heat storage has the advantage of being less expensive than latent heat storage but has lower energy density for TES applications. Two solar cooking storage pots will be compared in this work. One storage cooker uses sunflower oil as the sensible heat storage material. Sunflower oil has been reported by recent studies to be a viable storage medium since it is food grade, inexpensive and readily available, non-toxic and has comparable performance to other heat transfer oils [58, 59, 60]. The other storage cooker uses erythritol as the PCM which is affordable, food-grade, non-toxic and a readily available PCM that has been proposed recently for solar cooking TES applications [46, 61, 62, 56, 63]. Preliminary cooking experimental results are presented using the two storage cooking pots heated up with solar parabolic dish solar cookers combined with wonderbag slow cookers for off-sunshine cooking. This study will add invaluable information on solar cooking storage pots and wonderbag slow cookers where limited previous research has been reported on these two devices.

3.2 Materials and method

3.2.1 Parabolic dish solar cooker

A photograph of the parabolic dish solar cooker used in the experiments is shown in Figure 3.1. It has a diameter of around 1.2 m and a manual tracking mechanism to allow proper focusing of solar radiation on to a stand where the pot is placed. It is relatively inexpensive costing about R1500 (~USD 85) and is purchased locally in South Africa from SunFire Solutions [64]. The performance of this parabolic dish solar cooker has recently been evaluated using

different non-heat storage cooking pots and fluids, and it was found to perform reasonably well [65].



Figure 3.1: A photograph of the parabolic dish solar cooker used in the cooking tests.

3.2.2 Solar cooking pot and storage materials

Different views of the storage cooking pot are shown in Figure 3.2. The storage cooking pot is made with stainless steel, and it has an internal cavity in which the storage material is placed. The pot is painted black in order to increase its absorbance of solar radiation, as shown in Figure 3.2(c). A standard cooking pot lid fits on the top of the storage pot and is closed to increase its efficiency during cooking tests. The top of the pot has three air vents to allow for thermal expansion of the storage materials. Three K-type thermocouples are embedded on the sides of the pot to measure the temperature of the storage material, as shown in Figure 3.2(b). A K-type thermocouple is also placed inside the cooking pot to measure the cooking temperature. The K-type thermocouples all have an accuracy of ± 2.2 °C. The properties of two cooking pots used in the experiments are shown in Table 3.1. The masses of the erythritol and the oil cooking pots are nearly the same.

Figure 3.3 shows a schematic diagram indicating the dimensions of the storage pot presented in Table 3.1. The three thermocouples are placed at vertical distances of 0.024 m, 0.06 m, and 0.09 m from the base of the storage. Thermophysical properties of the two storage materials, erythritol and sunflower oil, are shown in Table 3.2. Erythritol was purchased locally in South Africa from Faithful to Nature, and sunflower oil was purchased locally from Shoprite. These are local supermarket stores in South Africa. Sunflower oil was poured in the cavity of the storage pot in its liquid form, whereas erythritol first had to be melted to be poured into

the storage pot. Nearly equal volumes of sunflower oil and erythritol were poured into the cavities; 3.750 and 3.780 L, respectively. It was opted to use equal volumes rather than equal masses to measure the temperatures in the storage cavity more accurately.



Figure 3.2: Photographs of the storage cooking pot; (a) plan view, (b) side view and (c) the storage cooker painted black in a solar cooking experiment.

Table 3.1: Properties of the cooking pots

Property	Value
Material of pots	Stainless steel
Thickness of stainless steel used for the pot(m)	0.003
Mass of oil pot (kg)	1.915
Mass of erythritol pot (kg)	2.020
External pot diameter (m)	0.320
Internal pot diameter (m)	0.250
Internal pot depth (m)	0.078
Outer pot depth (m)	0.110

Equal masses would have resulted in the top thermocouple of the erythritol pot being exposed to ambient conditions since its mass would have occupied a smaller volume because of its larger density. Erythritol has a larger density; thus, its storage mass of 5.438 kg was

larger as compared to 3.438 kg for sunflower oil. Erythritol also shows a reasonably higher thermal conductivity both in the liquid and solid states compared to sunflower oil. The thermocouples connections had rubber seals connected to the ferrules to prevent any sort of leakages during heating of the pots. Each pot was electrically heated on a hot plate to maximum temperatures of up to 300 °C to test for leakages and the thermal expansion capability. No visible leakages through the thermocouples and the thermal expansion air vents were observed in either pot after electrical heating.

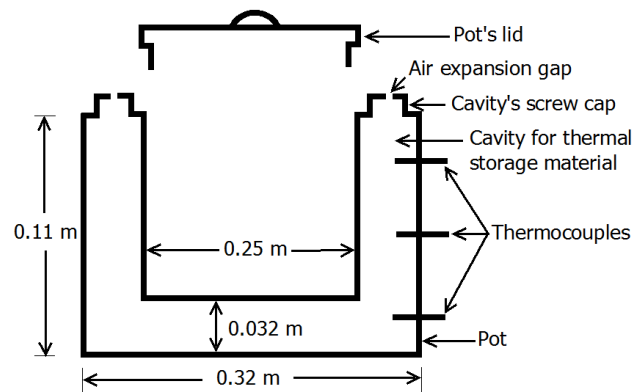


Figure 3.3: Schematic of the storage cooking pot showing the dimensions.

Table 3.2: Thermophysical properties of the two storage materials used in this study.

Property	Erythritol	Sunflower Oil
Melting Temperature (°C)	118.4 – 122.0 [66]	N/A
Specific Heat Capacity (kJ/kgK)	1.38 (20 °C), 2.76 (140 °C) [67]	$c = 2.115 + 0.00131T$ (Mawire, 2016)
Phase change enthalpy (kJ/kg)	310.6 [66]	N/A
Density (kg/m ³)	1480 (20 °C), 1300 (140 °C) [68]	$\rho = 930.62 - 0.65T$ (Mawire, 2016)
Thermal conductivity (W/mK)	0.733 (20 °C), 0.326 (140 °C) [68]	0.17 (Hoffmann et al., 2018)
Volume of storage material in the pot (litres)	3.780	3.750
Mass of storage material in the pot (kg)	5.438	3.438

3.2.3 Wonderbag cookers

The wonderbag insulated slow cooker used for the off-sunshine cooking experiments is shown in Figure 3.4. The wonderbag is a stand-alone, non-electric insulated bag mainly designed to reduce the amount of fuel required in the cooking of food. Instead of placing a pot on electrical, fossil fuel-based or biomass stoves for the duration of the cooking period, food is instead only heated to up to a hot enough temperature and then transferred to the wonderbag.



Figure 3.4: A photograph of the insulating wonderbag slow cooker used for heat retention cooking tests.

It then uses the principle of thermal insulation to continue cooking and keeps food warm without needing additional fire or heat. The wonderbag is estimated to save up to 30% of the total fuel costs associated with cooking with kerosene (paraffin) alone. In developing countries, there are numerous advantages for the product, as it immediately helps ease deforestation of natural reserves, and it frees up those who would spend their time gathering extra wood for fire fuel. The wonderbag consists of an inner layer of insulation containing recycled polystyrene balls, with an outer drawstring covering of polyester-cotton blended textiles [57]. The polystyrene balls have a low thermal conductivity of 0.03 W/mK making them a good insulator. The dimensions of the wonderbag and the other technical details are shown in Table 3.3. The properties of the wonderbag used in the experiments are very similar to those reported by Islam and Salehin [57]. The storage cooking pots are placed in the wonderbag so that the stored heat can be transferred to the food placed inside the pots. The top cover is closed during the non-sunshine cooking experiments. Heat is conducted from the storage cavity to the food during the non-sunshine cooking experiments. Medium-sized wonderbags with capacities of up to 6 L are used in the experiments. The wonderbags are

manufactured locally in South Africa and are inexpensive devices costing about R350 (~USD 20) per unit.

Table 3.3: Properties of the wonderbag cookers

Property	Value
Mass of empty wonderbag (kg)	1.7
Capacity (m ³)	0.008
External height without pot (m)	0.200
Internal height without pot (m)	0.140
Diameter fully open (m)	0.910
Diameter with pot inside (m)	0.500
Base diameter (m)	0.400
Thickness of insulation (m)	0.126
Thermal insulation	Polystyrene
Thermal conductivity (W/mK)	0.030

3.2.4 Experimental method

Temperatures in storage cooking pots, and the direct solar radiation were monitored during each test. Figure 3.5 shows the two storage pots in a solar cooking experiment using the parabolic dish solar cookers in an open space with no obstruction from trees and buildings. K-type thermocouples with an accuracy of ± 2.2 °C were used to monitor the temperature in the solar heating experiments. An Eppley normal incidence pyroheliometer with a solar tracker was used to measure the direct normal incidence (DNI) radiation [69]. It has a single point measurement uncertainty of less than ± 5 W/m², and a 95% response time of 5 s. The ambient temperature was also measured with a K-type thermocouple during each experiment period. The minimum period for each experiment was at least 3 h in Mahikeng, South Africa as previously established by Mawire et al. [65]. This minimum cooking period was deemed adequate for high enough temperatures to be achieved inside three different cooking pots without storage. The cookers used manual tracking based on shading of the pots, and the cookers were adjusted every 15 min, so that maximum solar radiation was incident on the pots with minimal shading.



Figure 3.5: Experimental testing of the two storage cooking pots with two parabolic dish solar cookers.

The experimental tests were carried out at the same time under similar ambient conditions. A total of eight tests were carried out with different types of foods. The first four experiments, indicated in Appendix A, considered solar water heating experiments with the same load of 2.0 kg to store energy in the storage materials. Cooking experiments were then carried out with different types of food after water heating with the 2.0 kg load. The other four experiments are the main contents of this paper, which investigated solar and storage cooking using the same type and amount of food. Two cooking experiments were performed using water as the cooking fluid, and another two were performed using sunflower oil as the cooking fluid for both storage pots. The same amount and type of food, as indicated in Tables 3.5 and 3.6 was put in the storage cooking pots in each experimental test during the solar and storage cooking phases. The thermocouples and the pyrheliometer were connected to an Agilent 34970 A data logger [70] which logged the data to a computer every 10 s for each experimental cooking period. The wind speed was also measured manually every 30 mins with a handheld anemometer to get an idea of the prevailing wind speed conditions which affected the performance of the solar cookers [71]. The measurement interval was made 30 mins due to the manual nature of the wind speed measurement since only estimated values were required, and a detailed analysis of the wind speed effects was beyond the scope of this study.

Table 3.4: Details of the instrumentation.

Name	Parameter	Range	Accuracy	Resolution
Eppley pyrhelimeter	Direct solar radiation	0–10 mV(0–1250 W/m ²) – Sensitivity 8 μ V/(W/m ²)	Single point, ± 5 W/m ² , Daily and Hourly Average, $\pm 1\%$	1 W/m ²
K-type thermocouple	Temperature	–200–1260 °C	± 2.2 °C	0.1 °C
Benetech anemometer	Wind speed	0–30 m/s	$\pm 5\%$	0.1 m/s
Agilent 34970A Datalogger	K-type of thermocouple	–100–1200 °C	± 1.0 °C	0.1 °C
Agilent 34940A Datalogger	Voltage (Pyrhelimeter)	0–100 mV	$\pm 0.009\%$	0.001 mV
Mass balance	Mass	0–5.000 kg	± 0.001 kg	± 0.001 kg

Table 3.5: A summary of the experimental conditions during the solar cooking periods.

Test no. and Date	Average Solar radiation and standard deviation (W/m ²)	Average wind speed and standard deviation (m/s)	Average ambient temperature and standard deviation (°C)	Total solar cooking period (h)	Total mass of food cooked (kg)
1-28/02/20	642 $\pm$ 377	1.9 $\pm$ 0.8	31.9 $\pm$ 2.0	6.6	0.9
2-09/03/20	887 $\pm$ 198	0.9 $\pm$ 0.9	29.2 $\pm$ 1.7	4.8	0.9
3-24/03/20	837 $\pm$ 252	1.1 $\pm$ 0.4	26.6 $\pm$ 2.0	3.8	0.5
4-25/03/20	837 $\pm$ 252	1.6 $\pm$ 0.4	30.3 $\pm$ 1.4	4.2	0.5

The details of the instruments and sensors used in the experiments are shown in Table 3.4. The windspeed anemometer shows the lowest accuracy, and the datalogger is able to measure the voltage signal from the pyrhelimeter and temperature signals from K-type thermocouples with a good degree of accuracy. In terms of the wind speed measurement, the maximum uncertainty of ± 0.2 m/s is obtained using its accuracy for a maximum wind speed of 3.1 m/s in the experimental tests. The average hourly solar radiation during the experimental tests ranges from 642 W/m² to 919 W/m², and the uncertainty is estimated to be in the range of ± 6 W/m² to ± 9 W/m² according to the accuracy of the pyrhelimeter.

Table 36: A summary of the experimental test conditions during the storage cooking periods.

Test No and Date	Total Storage Cooking Period(h)	Total mass of food cooked (kg)	Cooking fluid	Type of food cooked
1-28/02/20	1.7	0.9	Water	Potatoes/rice
2-09/03/20	1.5	0.9	Water	Rice/chicken
3-24/03/20	1.0	0.5	Sunflower oil	Chicken/fries
4-25/03/20	1.2, 1.3	0.5, 0.3	Sunflower oil	Chicken/fries/ tomatoes, Chicken



Figure 3.6: Wonderbag cookers with the storage pots placed inside them during the heat retention off sunshine cooking experiments.

From the temperature range of 25 °C to 150 °C in the experimental tests and using the uncertainty of the K-type thermocouple, the average percentage uncertainty in the temperature readings is around 2.5 %. The maximum percentage uncertainties in the measured values are at most 5 %; therefore, the measured readings are deemed to be acceptable and reasonably accurate. For the off-sunshine cooking experiments, the two cooking pots were loaded with the same amount of food as in the solar cooking experiments immediately after solar cooking for maximum utilisation of the stored heat. The repeated use of the stored heat after a storage cooking test was also investigated to find out if extended use of the stored heat was possible. The cooking pots were placed in wonderbag slow cookers which were closed with the top covers, as shown in Figure 3.6. Drawstrings were tightened once the pots were inside the wonderbags so that the stored heat could effectively

cook food. The storage cooking tests were carried out indoors. As with the solar cooking tests, the off-sunshine tests were carried out two times each with water and sunflower oil as the cooking fluids. Each heat retention cooking test was carried out for a minimum duration of one hour deemed to be adequate for cooking food as established by Chaudhary et al. [47] who performed similar tests with a storage cooking pot. The storage and cooking temperatures were monitored every 10 s from the start to the end of the cooking experiments. Table 3.5 shows a summary of the experimental conditions and dates for the solar cooking periods. The first two tests were performed with water, while the last two tests were performed with sunflower oil. The tests with water were carried out with larger food masses as compared to those with sunflower oil. Generally, for the majority of tests, the average solar radiation was above 800 W/m². The first test was under very cloudy conditions; thus, the average solar radiation was lower at 642 W/ m² with a very high standard deviation of around 58 % of the average solar radiation value. This test thus had the longest duration of 6.6 h. The best test conditions were seen during test 4, with the highest average solar radiation and the lowest standard deviation in the average solar radiation. The average ambient temperatures were greater than 26 °C for all the tests. The average wind speed was less than 2 m/s for all the tests. Test 2 and test 3 had lower average wind speed conditions. A summary of the test conditions for the storage cooking periods immediately after the solar cooking tests is presented in Table 3.6. The same types and amount of food were used as in the solar cooking tests. Test 4, with the best solar cooking conditions, had two consecutive storage cooking periods, and the total cooking period was 2.5 h. As with the solar cooking tests, the experimental tests with water used a larger mass of water and food. Test 1 had the longest cooking period due to the type of food which was cooked.

3.2.5 Experimental thermal analysis

The total solar energy incident on the dish aperture area for the solar cooking period can be estimated as [55];

$$Q_{inc} = \sum I_{av} A_c \Delta t \quad (3.1)$$

where I_{av} is the cumulative moving average solar radiation at each time interval during the solar period to cater for fluctuations in the solar radiation, A_c is the dish aperture (~1.12

m^2 , estimated from the diameter of the dish, $d = 1.19 \text{ m}$) and Δt is the data logging time interval of 10 s. The cumulative moving average solar radiation is calculated as;

$$I_{av} = \sum_{i=1}^N \frac{I_i}{N} \quad (3.2)$$

where N is the number of samples taken during the measurement interval. The total energy stored during the solar cooking period is estimated as [55];

$$Q_{ust} = \sum mc_s \Delta T \quad (3.3)$$

where m is the mass in the storage pot, c_s is the specific heat capacity of the storage material and ΔT is the moving average temperature between the next and previous time step interval Δt . A cumulative moving temperature is evaluated in a similar manner to the solar radiation as;

$$T_{av} = \sum_{i=1}^N \frac{T_i}{N} \quad (3.4)$$

to account for up and down fluctuations of the temperature due to the variable wind speed and solar radiation conditions. The solar energy storage efficiency is thus given by the ratio total energy stored to the total solar incident energy as [55].

$$\eta_{storage} = \frac{Q_{ust}}{Q_{inc}} \quad (3.5)$$

During the storage cooking period, the total heat utilisation can be estimated by considering the total heat delivered to the cooking fluid and the total heat delivered to each type of food, and it is expressed as [55];

$$Q_{ust} = \sum m_l c_l \Delta T + \sum m_{f1} c_{f1} \Delta T + \sum m_{f2} c_{f2} \Delta T + \sum m_{f3} c_{f3} \Delta T \quad (3.6)$$

where m_l is the mass of the cooking fluid, c_l is the specific heat capacity of the cooking fluid, m_f is the mass of food, c_f is the specific heat capacity of the food. The subscripted value, 1, 2, 3 on the mass and specific heat capacities of the foods indicate the number of foods cooked, which in this case is three. For two types of food, the last term in Eq. (3.6) will not appear. The heat utilisation efficiency can be estimated from the ratio of the total heat utilisation to the total energy stored, and it is given as [55];

$$\eta_{uti} = \frac{Q_{ust}}{Q_{inc}}. \quad (3.7)$$

The specific heat capacity of sunflower oil (one of the storage and cooking fluid) is temperature-dependent, and it can be expressed as [59];

$$c_{av}(\text{J/kgK}) = 2115.00 + 3.13T_{av} \quad (3.8)$$

where T_{av} is the moving average temperature calculated from the number of samples measured. The other specific heat capacity of the other storage material, erythritol is also temperature-dependent, and it is given as [67];

$$c_{av}(\text{J/kgK}) = 1269 + 4.10T_{av} \quad (3.9)$$

The specific heat capacities of the other cooking fluid (water), and foods (rice, potatoes, chicken and tomatoes) are assumed constant. The specific heat capacities are taken to be 4.187, 0.370, 3.430, 3.220 and 3.980 kJ/kgK, respectively, for water, rice, potatoes, chicken, and tomatoes as obtained from the online Engineering ToolBox [72]. To estimate the uncertainties in the mean solar energy incident, mean energy stored, mean heat utilisation, mean storage efficiency and mean storage heat utilisation efficiency for each experimental test, a propagation of error method of the whole solar cooking period is considered according to Eqs. ((3.1), (3.3), (3.5), (3.6), (3.7)), and the propagation of error method was implemented as reported by Mawire et al. [73]. The uncertainties in the measured variables are obtained from Table 3.4, and the error in the specific heat capacity is $\delta_{cav} = \pm 21$ kJ/kgK [73]. The percentage errors vary from 1.5 to 5.5% of the calculated values, which is deemed acceptable.

3.3 Results and discussion

Figure 3.7 shows the results of the cooking experiment performed on an overcast day on 28 February 2020 using the two storage cooking pots (one with erythritol as the PCM, and the

other one with sunflower oil). Solar and storage cooking were done with a total cooking mass of 0.9 kg (0.4 kg of potatoes/rice and 0.5 kg of water). The test day was cloudy and windy with the solar radiation and wind speed fluctuating up and down. The solar cooking period was just over 6.5 hrs, and the average solar radiation and wind speed were around 642 W/m^2 and 1.9 m/s , respectively. Even with these poor weather conditions, the temperatures of the storage pots are seen to rise to cooking temperatures above 70°C (Figure 3.7 (b)). T_{OILST} is the oil storage temperature at the bottom of the pot that is close to the temperature of the food in the oil cooking pot represented by T_{OILF} . Similarly, T_{PCMST} is the PCM storage temperature at the bottom of the PCM pot exposed to the majority of solar radiation, and T_{PCMF} is the food temperature inside the cooking pot. The oil cooking pot shows higher temperatures during the solar cooking period due to its lower thermal mass compared to the erythritol PCM pot. All temperatures in the storage pots fluctuate up and down to maximum values during the solar cooking period due to the variable solar radiation and wind speed conditions. The solar radiation seems to have more influence on the fluctuations as seen by corresponding drops of the temperature profiles during the low solar radiation periods.

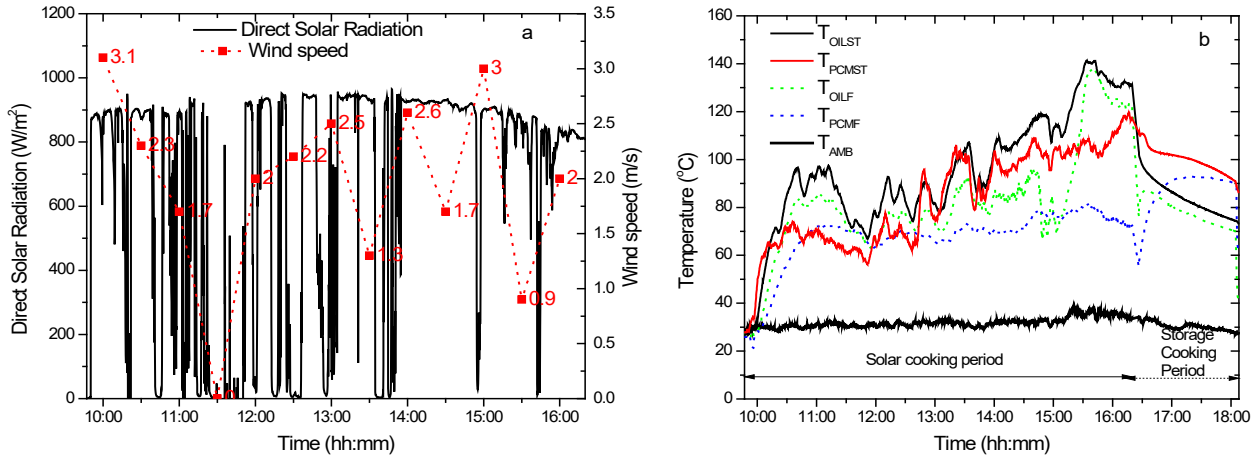


Figure 3.7: (a) Direct solar radiation, wind speed profiles and, (b) temperature profiles of the two storage pots on 28 February 2020.

The food in the oil pot was cooked earlier, as determined by physically tasting it, in comparison to the PCM pot, and this is shown by the drop of T_{OILF} around 14:45 h where food was removed from it. It took about 5 h to cook food using the oil storage pot because of the very cloudy conditions. After removing food inside the oil storage pot, the temperature inside the pot quickly rose to a peak value of around 140 °C, which was very close to the oil storage temperature. On the other hand, the food in the heavier PCM storage pot was cooked about 1 h:45 mins later. The maximum storage temperature in the PCM pot was around 120 °C at the end of the solar cooking period, which was not adequate to induce phase change fully in erythritol. The maximum food temperature in the PCM storage pot was around 80 °C, and it fluctuated to a lesser extent than the food temperature in the oil cooking pot. During the storage cooking period, the PCM storage pot shows better thermal performance with a maximum temperature of around 93 °C that drops marginally to around 89 °C at the end of the cooking period. On the other hand, even with the higher initial oil storage temperature, the food cooked with the oil cooking pot achieved a maximum temperature of only around 87 °C, and it dropped to around 69 °C at the end of the cooking period. This is attributed to the higher thermal conductivity of erythritol both in the liquid and the solid phase combined with its larger thermal mass. Heat conduction from the storage medium to the food is the main form of heat transfer in the wonderbag slow cookers. It is also important to note that even without the phase change process due to lower temperatures achieved in the PCM storage pot, it still outperforms the oil storage pot. The oil storage temperature drops more rapidly when compared to the PCM storage temperature indicating better heat utilisation with the PCM storage pot.



Figure 3.8: Rice and potatoes cooked with water using the wonderbags combined with (a) the oil storage cooking pot and (b) the erythritol storage cooking pot on 28 February 2020.

Figure 3.8 shows photographs of the cooked food on 28 February 2020 after 100 mins using the wonderbags and the storage pots. The potatoes and the rice were well cooked with both pots; however, the heat utilisation of the PCM storage pot was more effective. In principle, both storage cooking pots could be used for off sunshine cooking when combined with the insulated wonder slow cookers. Results of another cooking test performed on 9 March 2020 on a slightly cloudy day with the two cooking pots are shown in figure 3.9. The average solar radiation and wind speed were about 887 W/m² and 0.9 m/s, respectively, which were better weather conditions for solar cooking than in the previous test.

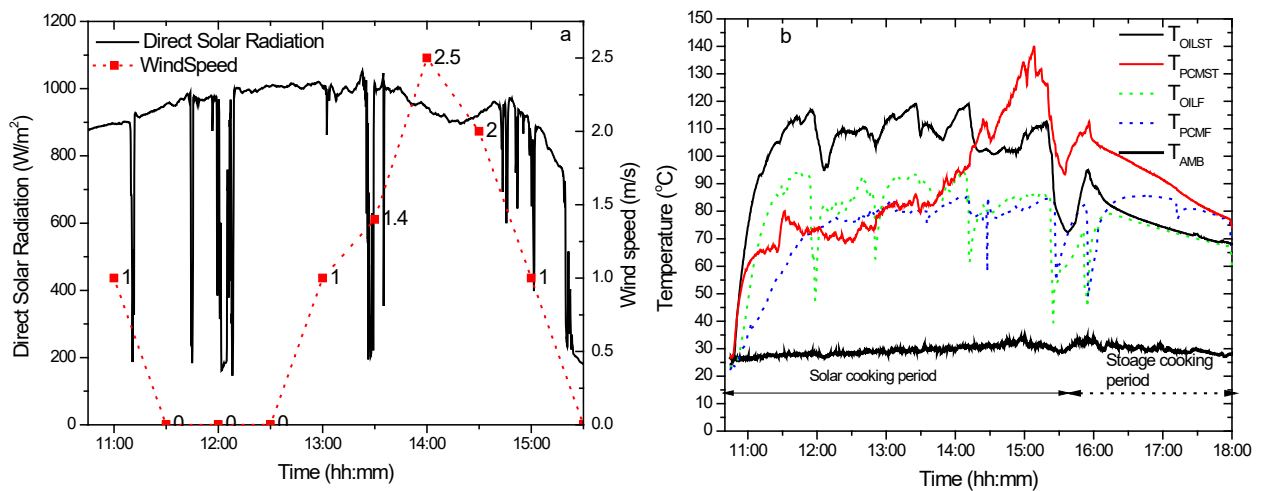


Figure 3.9: (a) Direct solar radiation, wind speed profiles and, (b) temperature profiles of the two storage pots on 9 March 2020.

In this test, also 0.9 kg of food was cooked during the solar and storage cooking periods (0.5 kg of water and 0.4 kg of rice/ chicken). As with the other cooking case, the oil pot temperatures are generally higher than the PCM pot temperatures for most of the solar cooking period. The PCM storage temperature shows an accelerated rise from about 14:15 h to around 15:15 h, becoming higher than oil storage temperature. This may be attributed to localised heating of the PCM pot at the bottom as manual solar tracking was used in the experiments and it was difficult to achieve perfect uniform heating of the storage material in some instances. However, the oil storage temperature is higher than the PCM storage temperature for most of the duration of solar cooking. Fluctuations of the food temperature due to the external physical conditions are less evident in the PCM storage pot as compared to the oil storage pot. The maximum solar cooking temperature achieved in the oil storage pot is around 95 °C, whereas in the PCM storage pot it is around 85 °C. The cooking time (10:40–14:15 h, 3 h:25mins) for the oil storage pot during solar cooking is also shorter than

the cooking time using the PCM storage pot (10:40–15:30 h, 4 h:50 mins) as with the previous cooking test using water. However, in this test, water was added after cooking food for the oil storage pot; thus, the temperature inside the pot did not rise drastically. The storage cooking period shows higher temperatures and more effective heat utilisation was achieved in the PCM storage pot with the maximum food temperature of around 86 °C, whereas it was 79 °C for the oil storage pot. The final storage temperatures were around 77 °C and 68 °C for the PCM pot and the oil pot, respectively. Food cooked with the oil storage pot was partially cooked as a result of these lower temperatures, whereas the PCM pot cooked the food well during this experimental test in a duration of 1.3 h.

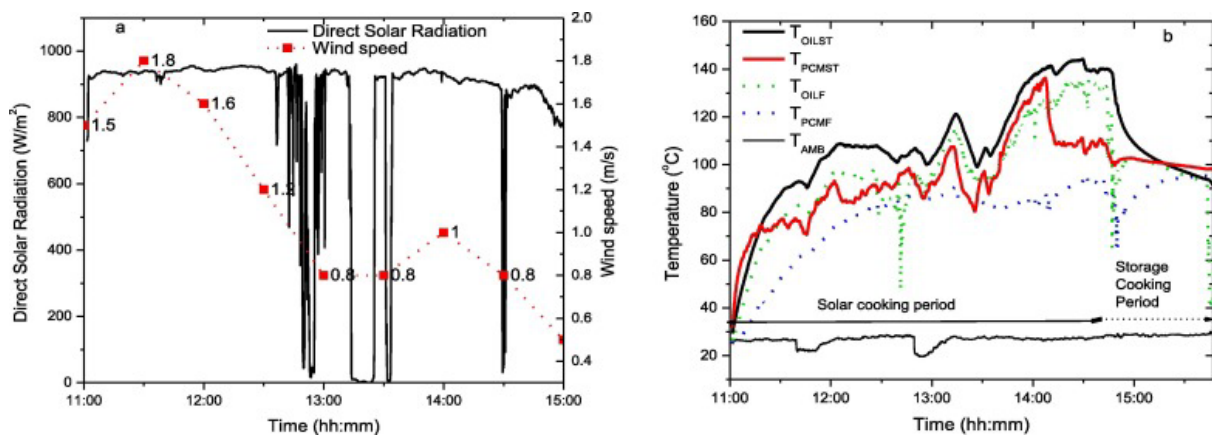


Figure 3.10: (a) Direct solar radiation, wind speed profiles and, (b) temperature profiles the two storage pots on 24 March 2020.

Test results using sunflower oil as the cooking fluid for a cooking test performed on 24 March 2020 are shown in Figure 3.10. In this test, the mass of the food and the cooking fluid was 0.5 kg (0.1 kg of cooking oil and 0.4 kg of chicken/potato chips (fries)). It was generally a slightly cloudy day with three cloudy periods in the duration of the experiment. The average solar radiation and wind speed were around 837 W/m^2 and 1.1 m/s , respectively. These conditions were better than the first experimental test and slightly worse compared to the second test. Generally, higher storage temperatures are achieved using sunflower oil compared to the other two previous tests, and the test duration for solar cooking is less. This is as a direct result of using a lower thermal mass of sunflower oil which causes the temperature to rise more. Even though the melting temperature of erythritol is exceeded, no clear phase change transition is seen during the temperature rise period. The only sort of phase change phenomenon is seen between 14:15–14:45 h where the PCM shows an almost constant

temperature of 110 °C after peaking. This probable phase change temperature is lower than erythritol's stipulated phase change range which is 118-120 °C, possibly due to impurities in the purchased sample or the transformation to a semi-amorphous state. The localised heating of the PCM in the storage pot due to imperfect manual tracking could also explain why the temperature rises very fast during heating with no observed phase change phenomenon. It should also be stated that the parabolic dish solar cooker is quite cheap, and it comes with imperfections since it is designed for developing countries. As with the previous tests, the fluctuations of the food temperature in the PCM storage pot are less than those in the oil storage pot. The solar cooking period for the oil pot is about 1 h:45 mins, whereas for the PCM pot it is almost 2 h more (~3h:45 mins). The maximum solar cooking temperature for the oil storage pot (135 °C) is much greater than for the PCM storage pot (95 °C). For the storage cooking period, it is also observed that the oil storage pot shows a more rapid drop in the oil storage temperature compared to the PCM storage pot indicating poor storage heat utilisation. The oil storage temperature drops from around 140 °C to just above 90 °C, while the PCM storage shows a smaller drop from about 105 °C to just below 100 °C. The food temperature in the PCM storage pot rises more steadily, and effective cooking is possible with the stored heat from it, even though lower storage temperatures are attained during solar cooking. Both pots cook the food well using the stored heat; however, more heat is retained after the cooking process in the PCM storage pot.

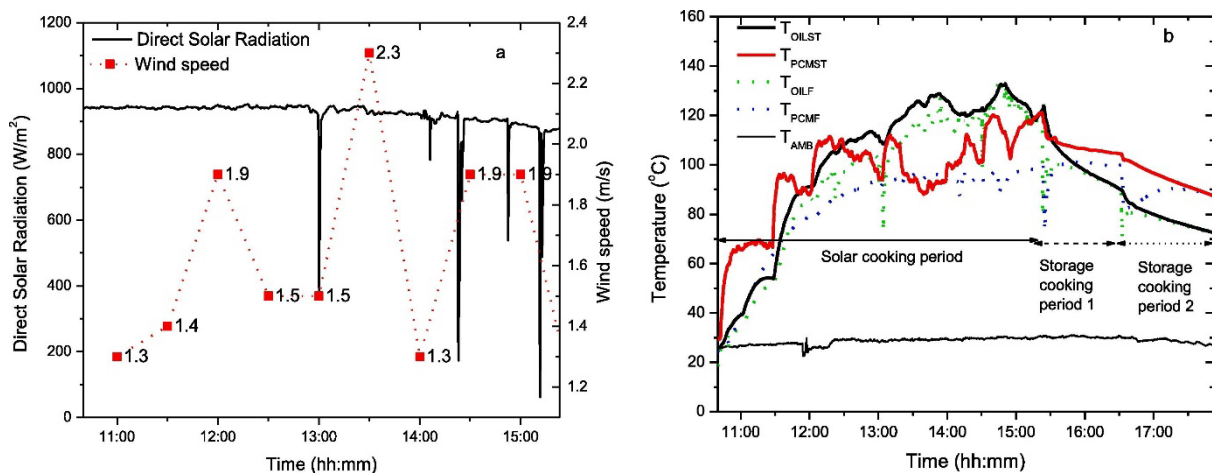


Figure 3.11: (a) Direct solar radiation, wind speed profiles and, (b) temperature profiles the two storage pots on 25 March 2020.

The results for a cooking test using sunflower oil done on 25 March 2020 are shown in Figure 3.11. In this test, the solar cooking load was 0.5 kg (0.1 kg of sunflower oil and 0.4 kg of

chicken/chips), and two storage cooking loads were used for two consecutive storage cooking periods. The load in first storage period was 0.5 kg (0.1 kg of sunflower oil and 0.4 kg of chicken/chips/tomatoes), while in the second storage period it was 0.3 kg (0.05 kg of sunflower oil and 0.25 kg of chicken). It was a slightly cloudy day, and the average solar radiation was around 919 W/m^2 , and it was the best average solar radiation in all the tests. This test had the second-highest average wind speed of 1.6 m/s , which reduced the rate of temperature rise due to heat losses. During the solar cooking period, the initial fastest temperature rise is seen with the PCM storage temperature from the start of the experiment to around 12:30 h. This can be explained with the higher initial storage temperature and manual tracking resulting in more localised heating of the PCM storage pot during the initial periods. However, the oil storage cooking pot shows higher storage and food temperatures after this higher initial temperature rise of the PCM storage pot. As with the other cases, the food is cooked faster during solar cooking with the oil storage pot. It takes only 2 h:10 mins for the oil cooking pot when compared to around 4 h:10 mins for the PCM storage pot, which is almost double the time.

For storage cooking period 1, both the storage and food temperatures for the oil storage pot drop rapidly during the cooking process. Unlike the oil storage pot, the PCM storage temperature drops very slowly, and it seems to be delivering storage latent heat in the temperature range between 105°C and 110°C . The food temperature also rises quickly to 100°C , and this temperature is maintained for the whole of storage cooking period 1. The food cooked with the PCM storage cooking pot is slightly more well-cooked as compared to the food cooked with oil storage pot. The second storage cooking period also shows better thermal performance with the PCM storage cooking with a maximum food temperature of around 90°C compared to 81°C for the oil storage cooking pot. The food temperature only drops by 3°C at the end of the cooking period for the PCM storage pot indicating the potential for another extra cooking period. In contrast to this, the oil storage pot food temperature drops by around 8°C and cooking food in another storage period is really not possible. The chicken cooked with the PCM storage pot during storage cooking period was well-cooked, while it was partially cooked during the same period using the oil storage cooking pot.

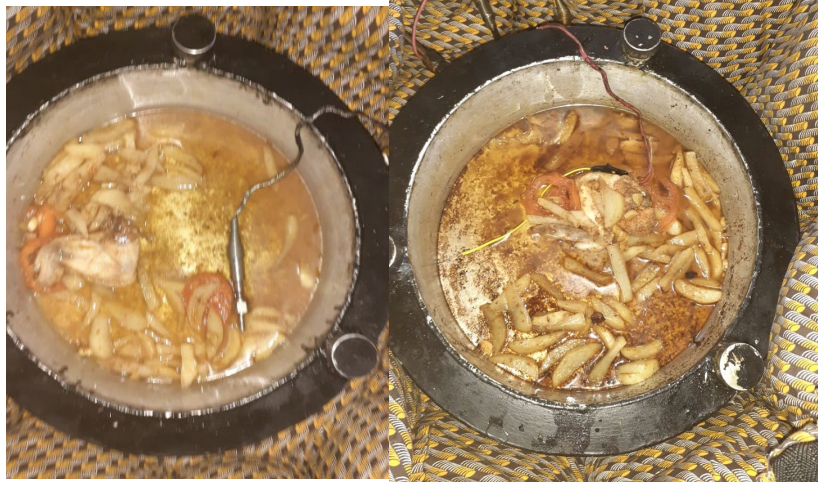


Figure 3.12: Chicken, tomatoes and chips (fries) cooked with sunflower oil using the wonderbags combined with (a) the oil storage cooking pot and (b) the erythritol storage cooking pot on 25 March 2020 during the first cooking period.

Figure 3.12 shows the food cooked on 25 March 2020 during the first storage cooking period using the two pots. The food cooked with the PCM storage cooking pot is browner and crispier, indicating that it is cooked better compared to the oil storage cooking pot. Figure 3.13 shows the solar cooking and storage cooking times dependence on the total combined mass of the food cooked. The thermal mass is considered since different foods have different specific heat capacities. It is clear that both the solar and storage cooking times increase with the increase in the thermal mass of the food being cooked. Storage cooking durations were identical for both cooking fluids since the wonderbags were closed and opened at the same time since there was no way of observing the cooking processes once the wonderbags were closed. The storage cooking time is also less for all cases when compared to solar cooking indicating better cooking efficiency. Case 3 (Sunflower oil, chicken, fries) shows the shortest solar and storage cooking since it has the lowest thermal mass, and the longest cooking duration is seen with Case 1 (Water, potatoes, rice) which has the largest thermal mass. The solar cooking times for the sunflower oil storage pot are less than the erythritol storage pot for all foods cooked due to the smaller storage mass of sunflower oil. An almost linear variation in the solar cooking time is observed with an increase in the thermal mass for cases 2, 3 and 4. However, a sharp increase in the solar cooking time is observed from case 2 to case 1 possibly due to the lower average solar radiation conditions for case 1 (642 W/m^2) compared to above 800 W/m^2 for the other three cases as shown in Table 3.5. The storage cooking time also shows the same variation as depicted by the solar cooking time.

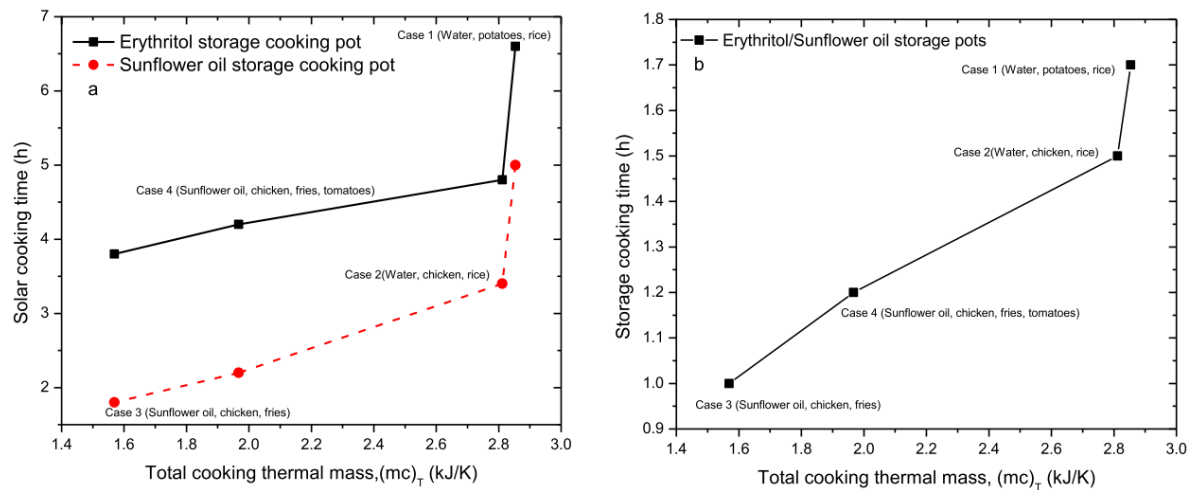


Figure 3.13: Solar cooking (a) and storage cooking times (b) for different thermal masses of food.

A summary of the temperatures attained using the wonderbags during the storage cooking periods for the two pots is presented in Table 3.7. It is seen that higher initial cooking temperatures are seen with the oil storage cooking pot due to the higher temperatures attained during solar cooking. The PCM storage cooking pot generally shows higher final storage and cooking temperatures showing that cooking using this pot is more effective during the storage cooking periods. Cases 3 and 4 using sunflower oil as the cooking fluid also show higher cooking temperatures for both cooking pots.

Table 3.7: A summary of storage cooking temperatures attained using the wonderbag

Cooking pot	Cooking time (mins)	Initial storage temperature (°C)	Final storage temperature (°C)	Maximum food temperature (°C)	Final food temperature (°C)
Erythritol					
Case 1	100	117.1	90.1	92.9	89.4
Case 2	90	100.3	77.0	85.6	75.9
Case 3	60	100.7	98.2	95.8	95.7
Case 4	70, 80	121.1, 103.0	103.0, 87.5	101.2, 90.2	93.2, 87.5
Sunflower Oil					
Case 1	100	140.0	74.3	87.1	69.0
Case 2	90	79.5	68.3	79.1	67.1
Case 3	60	137.5	91.0	103.1	69.0
Case 4	70, 80	122.3, 89.2	89.2, 72.6	105.1, 80.6	78.6, 72.3

Table 3.8 shows a summary of the solar cooking period test results. Generally, food is well cooked using both storage cooking pots, although the cooking periods for the sunflower oil pot are lower than those of the erythritol storage cooking pot. The storage efficiencies are higher for the sunflower oil pot compared to those of the erythritol pot. However, the efficiencies of both pots are quite low, possibly due to the low efficiency of the parabolic dish solar cooker which has been recently reported to achieve maximum water and sunflower oil heating efficiencies of 0.15 and 0.22, respectively, when using black non storage cooking pots [65]. A larger, more efficient dish will improve the storage efficiency, as well as an optimised and more efficient storage cooking design as reported recently by Bhawe and Kale [55]. The storage efficiencies for frying potatoes and cooking rice as reported by Bhawe and Kale [55] are also reasonably low at 11.34 and 13.51 % respectively, even with an optimised storage cooking pot and a better solar concentrator resulting in higher operational temperatures. These storage efficiencies are not exceptionally higher than the ones obtained in this study which range from 2.5 to 3.7 % for the erythritol storage cooking pot, and from 3.0 to 7.1 % for the sunflower storage cooking pot. Two efficiencies are shown for the sunflower oil storage pot. These efficiencies signify the efficiency at the end of the solar cooking process for the sunflower oil storage pot, and the efficiency at the end of the experimental test when both pots have cooked the food. The solar cooking period for the sunflower oil pot is shorter compared to the erythritol pot; thus, the first storage efficiencies shown in Table 3.8 are higher than the second storage efficiencies for sunflower oil. It is also important to state that improvements in the efficiency of solar collection and storage will result in increased costs, which will render the designed product too expensive for use in the developing world where there are very limited resources. Future work will look at storage pot design improvement.

Table 3.8: A summary of the solar cooking period experimental results.

Cooking pot	Cooking food	Cooked load(kg)	Cooking time(hrs)	Cooking results	Storage efficiency (%)
Erythritol					
Case 1(Water-0.5 kg)	Potatoes/rice	0.4(0.2,0.2)	6.6	Boiled, well cooked	3.7
Case 2(Water-0.5 kg)	Rice/chicken	0.4(0.2,0.2)	4.8	Boiled, well cooked	2.5
Case 3(Sunflower oil-0.1 kg)	Chicken/fries	0.4(0.2,0.2)	3.8	Fried and slightly crispy, well cooked	3.2
Case 4(Sunflower oil-0.1 kg)	Chicken/fries/tomatoes	0.5(0.2,0.2,0.1)	4.2	Fried and slightly crispy, well cooked	2.8
Sunflower Oil					
Case 1(Water-0.5 kg)	Potatoes/rice	0.4(0.2,0.2)	5.0	Boiled, well cooked	3.6*(End of solar cooking period), 0.032 (End of experimental test)
Case 2(Water-0.5 kg)	Rice/chicken	0.4(0.2,0.2)	3.4	Boiled, well cooked	4.6*, 3.2
Case 3(Sunflower oil-0.1 kg)	Chicken/fries	0.4(0.2,0.2)	1.8	Fried and very crispy, well cooked	7.1*, 4.1
Case 4(Sunflower oil-0.1 kg)	Chicken/fries/tomatoes	0.5 (0.2, 0.2, 0.1)	2.2	Fried and very crispy, well cooked	4.2*, 3

A summary of storage cooking results is shown in Table 3.9. The erythritol storage cooking pot uses the stored heat more effectively as all the tests showed that the food is well cooked, and the heat utilisation efficiencies are higher than those for the sunflower oil pot. The erythritol storage cooking pot also shows more effective heat utilisation when cooking foods with higher thermal masses (Cases 1 and 2) as compared to the lower thermal masses (Case 3 and 4). This is in agreement with the work by Islam and Salehin [57] where larger amounts of food resulted in better thermal performance when wonderbag slow cookers were used. For the sunflower oil storage cooking, there seems to be no clear relationship between the cooking thermal mass and the utilisation efficiency, possibly due to the inefficient heat transfer mechanisms in this pot. As already mentioned, the use of fins and other heat transfer improvements as well as cooking larger amounts of food can improve the efficiency of heat utilisation, which varied between 4.8 and 14.3 % for the erythritol storage cooking pot, and for the sunflower oil storage cooking pot. A comparison with other related works with optimised finned storage cooking pots achieving higher operating temperatures shows

considerably higher heat utilisation efficiencies of 32.38 %, 32.82 % and 30.28 %, respectively [55, 49]. The efficiencies were higher also due to the latent heat contributions considered, and the thermal performance evaluations, which assumed step responses from the initial temperature to the final cooking temperature which is not the case in reality. Table 3.10 compares the cooking temperatures achieved with the two storage cooking pots with recent work that has been published on solar cooking storage pots.

Table 3.9: A summary of the storage cooking period experimental results.

Cooking pot	Cooking food	Cooked load(kg)	Cooking time(hrs)	Cooking results	Heat utilisation efficiency (%)
Erythritol					
Case 1(Water-0.5 kg)	Potatoes/rice	0.4(0.2,0.2)	1.7	Well cooked, rice and potatoes soft.	14.3
Case 2(Water-0.5 kg)	Rice/chicken	0.4(0.2,0.2)	1.5	Well cooked, both foods soft.	10.2
Case 3(Sunflower oil-0.1 kg)	Chicken/fries	0.4(0.2,0.2)	1.0	Well cooked, food crispy	8
Case 4(Sunflower oil-0.1 kg)	Chicken/fries/toma toes	0.5(0.2,0.2,0.1)	1.2, 1.3	Well cooked, food crispy. Chicken well cooked in second test.	4.8*(First test)
Sunflower Oil					
Case 1(Water-0.5 kg)	Potatoes/rice	0.4(0.2,0.2)	1.7	Well cooked, rice and potatoes soft.	3.7
Case 2(Water-0.5 kg)	Rice/chicken	0.4(0.2,0.2)	1.5	Partially cooked, rice a bit hard.	6
Case 3(Sunflower oil-0.1 kg)	Chicken/fries	0.4(0.2,0.2)	1.0	Well cooked, food less crispy.	5.9
Case 4(Sunflower oil-0.1 kg)	Chicken/fries/ tomatoes	0.5 (0.2, 0.2, 0.1)	1.2, 1.3	Well cooked, food less crispy. Chicken partially cooked in second test.	4.3*(First test)

Table 3.10: A comparison of recent work on storage cooking pots.

Author	Storage material	Storage mass(kg)	Cooking fluid and combined mass of food (kg)	Maximum temperature achieved in cooking vessel (°C)	Time taken to achieve the maximum cooking temperature (mins)
Mawire et al. (2020)-This work	Erythritol	5.438	Water, 0.900	92.9	53
Mawire et al. (2020)-This work.	Sunflower oil	3.438	Water, 0.900	87.1	13
Mawire et al. (2020)-This work.	Erythritol	5.438	Sunflower oil , 0.500	95.8	60
Mawire et al., (2020)-This work.	Sunflower oil	3.438	Sunflower oil, 0.500	103.1	11
Bhave and Kale, (2020)	Solar salt	2.230	Water, 0.325	100.0	20
Bhave and Kale, (2020)	Solar salt	2.230	Ground nut oil, 0.409	180.0	17
Chaudhary et al., (2013)	Acetanilide	2.500	Water, 2.000	84.3	90
Lecuona et al., (2013)	Paraffin wax	5.416	Water, 4.000	90.0	240

Limited previous work has been reported that clearly evaluates solar cooking storage pots, thus only five authors are used for the comparison. The maximum cooking temperatures and the times for achieving maximum cooking temperatures are slightly better than the work presented by Lecuona et al. [46], Yadav et al. [50] and Chaudhary et al. [47], bearing in mind that some of these authors used larger water thermal masses and different storage materials. Bhave and Kale [54] and Bhave and Thakare [48] presented very optimised designs with fins, a better parabolic dish concentrator and one PCM had a higher melting temperature resulting in higher temperatures and faster temperature rises. Their storage cooking masses were also generally lower; however, the intention in the near future is to optimise the design of the cooking pots so that faster solar and storage cooking times can be achieved.

3.4 Future work

In general, the solar cooking pots showed reasonably good thermal performance considering that they were used with a relatively low efficiency parabolic dish solar cooker, and the pots were not of an optimised and efficient design. More future work needs to be done to enhance the heat transfer of the storage material with the use of fins, nanoparticles and an optimised

pot design. A better and more efficient parabolic dish solar concentrator needs to be used to achieve higher cooking and storage temperatures. A thermal model of the cooking vessel needs to be developed to optimise the design of the pot and also to investigate the integration of the wonderbag. The thermal model will be validated with experimental results presented in this work, and optimisation design changes (shape, fins, materials, etc.) to increase the heat transfer efficiency will be performed with a parametric study. The PCM storage material showed good storage cooking characteristics, but the phase change process needs to be improved to shorten the solar cooking period, which was rather too long. Sunflower oil showed good solar cooking characteristics, but its thermal conductivity needs to be enhanced for it to be more useful during the storage cooking period. Future work will also look at combining both PCM and sensible heat storage material in a single cooking pot to enhance the performance of the pot for both solar and storage cooking periods as reported by Yadav et al. [50] The effect of different loads of water and sunflower oil on the storage and heat utilisation efficiencies also needs to be studied experimentally and numerically in future work. A thermo-economic and payback analysis of the designed system also needs to be investigated to find out if is affordable for developing countries.

3.5 Conclusion

Two similar solar cooking storage pots were compared experimentally during solar and storage cooking periods. One storage pot had sunflower oil as the sensible heat storage material, while the other one had erythritol as the phase change material. To test their thermal performance during off-sunshine periods, the two pots were placed in insulated wonderbag slow cookers. The major conclusions of the study were;

1. The sunflower oil storage cooking pot showed faster cooking times (1.8-5.0 h) and higher maximum storage temperatures (124-145 °C), compared to 3.8-6.6 h and 118–140 °C, respectively, for the erythritol PCM pot during the solar cooking period due to its smaller thermal mass. The storage efficiencies for the sunflower oil pot (3.0-7.1%) were higher compared to the erythritol pot during the solar cooking period (2.5-3.7%). For both cooking pots, the cooking period increased with an increase in the total combined thermal mass of cooked food.
2. The erythritol PCM storage pot out-performed the oil storage pot during off-sunshine periods by achieving lower temperature drops during the storage cooking periods

even though it had lower initial storage temperatures. The temperature drops from the maximum cooking temperatures ranged from 0.1 to 9.7 °C for the PCM storage pot, while those of the sunflower oil pot were significantly higher, ranging between 8.3 and 34 °C. This was due to its larger thermal storage mass, the release of stored latent heat and higher thermal conductivity during the storage cooking period. The heat utilisation efficiencies of the erythritol pot (4.8-14.3 %) were greater than those of the sunflower pot (3.7-6.0 %). The heat utilisation efficiencies of the erythritol storage pot were generally greater for larger thermal masses as previously investigated by Islam and Salehin [57].

3. The use of sunflower oil as a cooking fluid instead of water shortened the solar cooking period, and higher temperatures were obtained. The effectiveness of storage cooking was also improved using sunflower oil as higher maximum storage cooking temperatures ranging from 95.8 to 105.1 °C were obtained, compared to 79.1 to 92.9 °C for water.
4. The performance of the storage cooking pots during the heat utilisation processes was comparable to or slightly better than most of the previously reported works (Chaudhary et al. [47], Lecuona et al. [46], Yadav et al., [50]) although optimised storage cooking pot designs by Bhawe and Thakare [48] and Bhawe and Kale [54] showed better heat utilisation characteristics.

Credit author contribution statement

Ashmore Mawire: Drafted original manuscript, formal analysis, funding, and conceptualization. Katlego Lentswe: Investigation, conceptualization, formal analysis, methodology, reviewing and editing. Prince Owusu: Investigation, reviewing and editing. Adedamola Shobo: Reviewing and editing and supervision. Jo Darkwa: Reviewing, editing and funding. John Calautit: Reviewing, editing and funding. Mark Worall: Reviewing, formal analysis and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to acknowledge, the University of Nottingham for funding to carry out this research under the internal Global Challenges Research Fund (GCRF) scheme, GCRF Interdisciplinary Research Project Award 2019, SALEC: Safe and Affordable Low Energy Cooking Solutions for Namibia and South Africa (RIS 2483754/RIS 2147131).

Appendix A

Table A1 shows the experimental tests for solar water heating with a water load of 2.0 kg to store heat to be used for cooking. The average solar radiation varies between 509 and 716 W/m² in the experimental tests; the average wind speeds vary between 1.3 and 1.7 m/s and the average ambient temperatures between 26.9 and 29.7 °C. The solar water heating periods range between 4.0 and 6.8 hrs, and it was observed that storage efficiencies are slightly lower for the PCM storage pot. Although the efficiencies are lower for the PCM pot, they are comparable to the sunflower oil pot. The variable cloudy conditions with high standard deviations in the average solar radiation induce different solar water heating periods to attain high temperatures suitable for storage cooking purposes.

Table A2 shows the storage cooking results after heating water loads of 2.0 kg. Food cooked with the PCM storage pot is well cooked in all cases, whereas the food cooked using water for the oil storage pot is partially cooked. The heat utilisation efficiencies for the PCM storage pot are very high when using water (24.2-28.1 %) as the cooking fluid compared to when using sunflower oil (4.9-7.1 %). On the other hand, the sunflower oil pot shows comparable efficiencies for both cooking fluids (10.4–16.7 %). This suggests that larger loads should be used for PCM storage pot whereas it makes no significant difference to increase the load in the oil storage pot. Solar heating with larger loads also assists in achieving higher heat utilisation efficiencies in both pots.

Table A1 A summary of solar storage heating experiments using a water load of 2 kg.

Cooking pot	Average solar radiation and standard deviation (W/m ²)	Average ambient temperature and standard deviation (°C)	Average wind speed and standard deviation (m/s)	Cooking time (hrs)	Storage efficiency (%)
Erythritol					
Case 1(13/02/2020)	607 ± 286	27.0 ± 1.3	1.3 ± 0.6	6.8	2.1
Case 2(04/03/2020)	509 ± 348	26.9 ± 1.5	2.0 ± 0.7	5.6	3.8
Case 3(19/03/2020)	716 ± 352	28.4 ± 1.7	1.4 ± 0.5	5.6	3.8
Case 4(20/03/2020)	657 ± 331	29.7 ± 1.2	1.7 ± 0.7	4.0	2.9
Sunflower Oil					
Case 1(13/02/2020)	607 ± 286	27.0 ± 1.3	1.3 ± 0.6	6.8	2.7
Case 2(04/03/2020)	509 ± 348	26.9 ± 1.5	2.0 ± 0.7	5.6	4.9
Case 3(19/03/2020)	716 ± 352	28.4 ± 1.7	1.4 ± 0.5	5.6	4.4
Case 4(20/03/2020)	657 ± 331	29.7 ± 1.2	1.7 ± 0.7	4.0	4.8

Table A2 A summary of storage cooking experiments after solar storage heating with a water load of 2 kg.

Cooking pot	Cooked food	Cooked load (kg)	Cooking time (hrs)	Cooking results	Heat utilisation efficiency (%)
Erythritol					
Case 1 (Water – 0.5 kg)	Potatoes	0.5	2.2	Well cooked potatoes soft.	24.2
Case 2 (Water – 0.5 kg)	Rice/ potatoes	0.5(0.1, 0.4)	2.0	Well cooked, both foods soft.	28.1
Case 3 (Sunflower oil-0.1 kg)	Chicken/fries	0.4 (0.2, 0.2)	2.0	Well cooked, food crispy	4.9
Case 4 (Sunflower oil-0.1 kg)	Chicken	0.5	0.8	Well cooked, chicken slightly crispy.	7.1
Sunflower Oil					
Case 1 (Water-0.5 kg)	Potatoes	0.5	2.2	Partially cooked, potatoes not too soft.	16.6
Case 2 (Water-0.5 kg)	Rice/ potatoes	0.5 (0.1, 0.4)	2.0	Reasonably well cooked, rice and potatoes not too hard.	14.9
Case 3 (Sunflower oil-0.1 kg)	Chicken/fries	0.4 (0.2, 0.2)	2.0	Well cooked, food crispy	10.4
Case 4 (Sunflower oil-0.1 kg)	Chicken	0.4	0.8	Well cooked, chicken slightly crispy.	16.7

References

- [1] Muthusivagami, R. M., Velraj, R., & Sethumadhavan, R. (2010). Solar cookers with and without thermal storage—a review. *Renewable and Sustainable Energy Reviews*, 14, 691-701.
- [2] Saxena, A., Pandey, S. P., & Srivastav, G. (2011). A thermodynamic review on solar box type cookers. *Renewable and Sustainable Energy Reviews*, 15, 3301-3318.
- [3] Cuce, E., & Cuce, P. M. (2013). A comprehensive review on solar cookers. *Applied Energy*, 102, 1399-1421.
- [4] Yettou, F., Azoui, B., Malek, A., Gama, A., & Panwar, N. L. (2014). Solar cooker realizations in actual use: An overview. *Renewable and Sustainable Energy Reviews*, 37, 288-306.
- [5] Nkhonjera, L., Bello-Ochende, T., John, G., & King'onde, C. K. (2017). A review of thermal energy storage designs, heat storage materials and cooking performance of solar cookers with heat storage. *Renewable and Sustainable Energy Reviews*, 75, 157-167.
- [6] Herez, A., Ramadan, M., & Khaled, M. (2018). Review on solar cooker systems: Economic and environmental study for different Lebanese scenarios. *Renewable and Sustainable Energy Reviews*, 81, 421-432.
- [7] Aramesh, M., Ghalebani, M., Kasaeian, A., Zamani, H., Lorenzini, G., Mahian, O., & Wongwises, S. (2019). A review of recent advances in solar cooking technology. *Renewable Energy*, 140, 419-435.
- [8] Esen, M. (2004). Thermal performance of a solar cooker integrated vacuum-tube collector with heat pipes containing different refrigerants. *Solar Energy*, 76, 751-757.
- [9] Saxena, A., Goel, V., & Karakilcik, M. (2018). Solar food processing and cooking methodologies. *Applications of Solar Energy*, 251-294.
- [10] Saxena, A., & Agarwal, N. (2018). Performance characteristics of a new hybrid solar cooker with air duct. *Solar Energy*, 159, 628-637.
- [11] Guidara, Z., Souissi, M., Morgenstern, A., & Maalej, A. (2017). Thermal performance of a solar box cooker with outer reflectors: Numerical study and experimental investigation. *Solar Energy*, 158, 347-359.
- [12] Saxena, A., Cuce, E., Tiwari, G. N., & Kumar, A. (2020). Design and thermal performance investigation of a box cooker with flexible solar collector tubes: Experimental research. *Energy*, 206, 118144.
- [13] Sagade, A. A., Samdarshi, S. K., Lahkar, P. J., & Sagade, N. A. (2020). Experimental determination of the thermal performance of a solar box cooker with a modified cooking pot. *Renewable Energy*, 150, 1001-1009.
- [14] Khallaf, A. M., Tawfik, M. A., El-Sebaei, A. A., & Sagade, A. A. (2020). Mathematical modeling and experimental validation of the thermal performance of a novel design solar cooker. *Solar Energy*, 207, 40-50.
- [15] Panwar, N. L., Kaushik, S. C., & Kothari, S. (2012). Experimental investigation of energy and exergy efficiencies of domestic size parabolic dish solar cooker. *Journal of Renewable and Sustainable Energy*, 4, 023111.

- [16] Kumar, S., Kumar, A., & Yadav, A. (2018). Experimental investigation of a solar cooker based on evacuated tube collector with phase change thermal storage unit in Indian climatic conditions. *International Journal of Renewable Energy Technology*, 9, 310-336.
- [17] Kumar, A., Shukla, S. K., & Kumar, A. (2018). Heat loss analysis: An approach toward the revival of parabolic dish type solar cooker. *International Journal of Green Energy*, 15, 96-105.
- [18] Sagade, A. A., Samdarshi, S. K., & Panja, P. S. (2018). Enabling rating of intermediate temperature solar cookers using different working fluids as test loads and its validation through a design change. *Solar Energy*, 171, 354-365.
- Panwar, N. L., Kaushik, S. C., & Kothari, S. (2012). Experimental investigation of energy and exergy efficiencies of domestic size parabolic dish solar cooker. *Journal of Renewable and Sustainable Energy*, 4, 023111.
- [19] Mohod, A. G., Khandetod, Y. P., & Sengar, S. (2010). Eco-friendly utilization of parabolic concentrating solar cooker for extraction of cashew nut shell oil and household cooking. *International Journal of Sustainable Energy*, 29, 125-132.
- [20] Mussard, M., Gueno, A., & Nydal, O. J. (2013). Experimental study of solar cooking using heat storage in comparison with direct heating. *Solar Energy*, 98, 375-383.
- [21] Kedar, S. A., Sonawale, P., Valve, P., Khujat, P., & Talekar, P. (2017). Thermal analysis of parabolic solar cooker with back reflection. *Materials Today: Proceedings*, 4, 8035-8039.
- [22] Onokwai, A. O., Okonkwo, U. C., Osueke, C. O., Okafor, C. E., Olayanju, T. M., & Samuel, O. D. (2019). Design, modelling, energy and exergy analysis of a parabolic cooker. *Renewable Energy*, 142, 497-510.
- [23] Esen, M., & Ayhan, T. (1996). Development of a model compatible with solar assisted cylindrical energy storage tank and variation of stored energy with time for different phase change materials. *Energy Conversion and Management*, 37, 1775-1785.
- [24] Esen, M., Durmuş, A., & Durmuş, A. (1998). Geometric design of solar-aided latent heat store depending on various parameters and phase change materials. *Solar Energy*, 62, 19-28.
- [25] Esen, M. (2000). Thermal performance of a solar-aided latent heat store used for space heating by heat pump. *Solar Energy*, 69, 15-25.
- [26] Schwarzer, K., & Da Silva, M. E. V. (2003). Solar cooking system with or without heat storage for families and institutions. *Solar Energy*, 75, 35-41.
- [27] Mawire, A., McPherson, M., & Van den Heetkamp, R. R. J. (2008). Simulated energy and exergy analyses of the charging of an oil-pebble bed thermal energy storage system for a solar cooker. *Solar Energy Materials and Solar Cells*, 92, 1668-1676.
- [28] Mawire, A., McPherson, M., & Van den Heetkamp, R. R. J. (2010). Discharging simulations of a thermal energy storage (TES) system for an indirect solar cooker. *Solar Energy Materials and Solar Cells*, 94, 1100-1106.
- [29] Kumaresan, G., Sridhar, R., & Velraj, R. (2012). Performance studies of a solar parabolic trough collector with a thermal energy storage system. *Energy*, 47, 395-402.

- [30] Saxena, A., & Karakilcik, M. (2017). Performance evaluation of a solar cooker with low cost heat storage material. *International Journal of Sustainable Green Energy*, 6, 57-63.
- [31] Cuce, P. M., Kolayli, S., & Cuce, E. (2020). Enhanced performance figures of solar cookers through latent heat storage and low-cost booster reflectors. *International Journal of Low-Carbon Technologies*, 15, 427-433.
- [32] Omara, A. A., Abuelnuor, A. A., Mohammed, H. A., Habibi, D., & Younis, O. (2020). Improving solar cooker performance using phase change materials: A comprehensive review. *Solar Energy*, 207, 539-563.
- [33] Buddhi, D., Sharma, S. D., & Sharma, A. (2003). Thermal performance evaluation of a latent heat storage unit for late evening cooking in a solar cooker having three reflectors. *Energy Conversion and Management*, 44, 809-817.
- [34] Chen, C. R., Sharma, A., Tyagi, S. K., & Buddhi, D. (2008). Numerical heat transfer studies of PCMs used in a box-type solar cooker. *Renewable Energy*, 33, 1121-1129.
- [35] Hussein, H. M. S., El-Ghetany, H. H., & Nada, S. A. (2008). Experimental investigation of novel indirect solar cooker with indoor PCM thermal storage and cooking unit. *Energy Conversion and Management*, 49, 2237-2246.
- [36] El-Sebaei, A. A., Al-Amir, S., Al-Marzouki, F. M., Faidah, A. S., Al-Ghamdi, A., & Al-Heniti, S. (2009). Fast thermal cycling of acetanilide and magnesium chloride hexahydrate for indoor solar cooking. *Energy Conversion and Management*, 50, 3104-3111.
- [37] Saxena, A., Lath, S., & Tirth, V. (2013). Solar cooking by using PCM as a thermal heat storage. *MIT International Journal of Mechanical Engineering*, 3, 91-95.
- [38] Ahmed, S. M., Al-Amin, M. R., Ahammed, S., Ahmed, F., Saleque, A. M., & Rahman, M. A. (2020). Design, construction and testing of parabolic solar cooker for rural households and refugee camp. *Solar Energy*, 205, 230-240.
- [39] Prasanna, U. R., & Umanand, L. (2011). Optimization and design of energy transport system for solar cooking application. *Applied Energy*, 88, 242-251.
- [40] Mussard, M., & Nydal, O. J. (2013). Comparison of oil and aluminum-based heat storage charged with a small-scale solar parabolic trough. *Applied Thermal Engineering*, 58, 146-154.
- [41] Kumaresan, G., Vigneswaran, V. S., Esakkimuthu, S., & Velraj, R. (2016). Performance assessment of a solar domestic cooking unit integrated with thermal energy storage system. *Journal of Energy Storage*, 6, 70-79.
- [42] Saini, G., Singh, H., Saini, K., & Yadav, A. (2016). Experimental investigation of the solar cooker during sunshine and off-sunshine hours using the thermal energy storage unit based on a parabolic trough collector. *International Journal of Ambient Energy*, 37, 597-608.
- [43] Mbodji, N., & Hajji, A. (2017). Modeling, testing, and parametric analysis of a parabolic solar cooking system with heat storage for indoor cooking. *Energy, Sustainability and Society*, 7, 1-16.
- [44] El Moussaoui, N., Talbi, S., Atmane, I., Kassmi, K., Schwarzer, K., Chayeb, H., & Bachiri, N. (2020). Feasibility of a new design of a Parabolic Trough Solar Thermal Cooker (PSTC). *Solar Energy*, 201, 866-871.

- [45] Lecuona, A., Nogueira, J. I., Ventas, R., & Legrand, M. (2013). Solar cooker of the portable parabolic type incorporating heat storage based on PCM. *Applied Energy*, 111, 1136-1146.
- [46] Chaudhary, A., Kumar, A., & Yadav, A. (2013). Experimental investigation of a solar cooker based on parabolic dish collector with phase change thermal storage unit in Indian climatic conditions. *Journal of Renewable and Sustainable Energy*, 5, 023107.
- [47] Santhi Rekha, S. M., & Sukchai, S. (2018). Design of phase change material based domestic solar cooking system for both indoor and outdoor cooking applications. *Journal of Solar Energy Engineering*, 140, 041010.
- [48] Bhawe, A. G., & Thakare, K. A. (2018). Development of a solar thermal storage cum cooking device using salt hydrate. *Solar Energy*, 171, 784-789.
- [49] Yadav, V., Kumar, Y., Agrawal, H., & Yadav, A. (2017). Thermal performance evaluation of solar cooker with latent and sensible heat storage unit for evening cooking. *Australian Journal of Mechanical Engineering*, 15, 93-102.
- [50] Choudhari, K. S., & Shende, M. D. (2015). Solar cooker using PCM material. *Journal Basic Applied Engineering Research*, 2, 1449-1453.
- [51] Nayak, N., Abu Jarir, H., & Al Ghassani, H. (2016). Solar cooker study under Oman conditions for late evening cooking using stearic acid and acetanilide as PCM materials. *Journal of Solar Energy*, 2016, 2305875.
- [52] Senthil, R., & Cheralathan, M. (2019). Enhancement of the thermal energy storage capacity of a parabolic dish concentrated solar receiver using phase change materials. *Journal of Energy Storage*, 25, 100841.
- [53] Keith, A., Brown, N. J., & Zhou, J. L. (2019). The feasibility of a collapsible parabolic solar cooker incorporating phase change materials. *Renewable Energy Focus*, 30, 58-70.
- [54] Bhawe, A. G., & Kale, C. K. (2020). Development of a thermal storage type solar cooker for high temperature cooking using solar salt. *Solar Energy Materials and Solar Cells*, 208, 110394.
- [55] Coccia, G., Aquilanti, A., Tomassetti, S., Comodi, G., & Di Nicola, G. (2020). Design, realization, and tests of a portable solar box cooker coupled with an erythritol-based PCM thermal energy storage. *Solar Energy*, 201, 530-540.
- [56] Islam, A.M.K.S., Salehin, S., 2014. Performance Test of Wonder Bag: A Pathway to Reduce Cooking Energy Consumption and CO₂ Emission. GIZ Technical Report 2014; 1–44. https://energypedia.info/images/a/af/Report_Performance_Test_of_retained_heat_cooker_%28WonderBag%29_GIZ.pdf (website accessed 20 June 2020).
- [57] Hossain, A. K., & Davies, P. A. (2010). Plant oils as fuels for compression ignition engines: A technical review and life-cycle analysis. *Renewable Energy*, 35, 1-13.
- [58] Mawire, A. (2016). Performance of Sunflower Oil as a sensible heat storage medium for domestic applications. *Journal of Energy Storage*, 5, 1-9.
- [59] Hoffmann, J. F., Vaitilingom, G., Henry, J. F., Chirtoc, M., Olivès, R., Goetz, V., & Py, X. (2018). Temperature dependence of thermophysical and rheological properties of seven vegetable oils in view of their use as heat transfer fluids in concentrated solar plants. *Solar Energy Materials and Solar Cells*, 178, 129-138.

- [60] Mawire, A., Lentswe, K. A., & Shobo, A. (2019). Performance comparison of four spherically encapsulated phase change materials for medium temperature domestic applications. *Journal of Energy Storage*, 23, 469-479.
- [61] Anish, R., Mariappan, V., Joybari, M. M., & Abdulateef, A. M. (2020). Performance comparison of the thermal behavior of xylitol and erythritol in a double spiral coil latent heat storage system. *Thermal Science and Engineering Progress*, 15, 100441.
- [62] Mawire, A., Lefenya, T. M., Ekwomadu, C. S., Lentswe, K. A., & Shobo, A. B. (2020). Performance comparison of medium temperature domestic packed bed latent heat storage systems. *Renewable Energy*, 146, 1897-1906.
- [63] SunFire Solutions. <https://www.sunfire.co.za/> (website accessed 31 May 2020).
- [64] Mawire, A., Ramokali, M., & Mothupi, M. (2020). A solar thermal experiment with parabolic dish solar cookers for developing countries. *European Journal of Physics*, 41, 055104.
- [65] Shobo, A. B., & Mawire, A. (2017). Experimental comparison of the thermal performances of acetanilide, meso-erythritol and an In-Sn alloy in similar spherical capsules. *Applied Thermal Engineering*, 124, 871-882.
- [66] Gunasekara, S. N., Mao, H., Bigdeli, S., Chiu, J. N., & Martin, V. (2018). Thermodynamic assessment of binary erythritol-xylitol phase diagram for phase change materials design. *Calphad*, 60, 29-36.
- [67] Agyenim, F., Eames, P., & Smyth, M. (2010). Heat transfer enhancement in medium temperature thermal energy storage system using a multitube heat transfer array. *Renewable Energy*, 35, 198-207.
- [68] Eppleylab. <http://www.eppleylab.com/instrument-list/normal-incidence-pyrheliometer/> (website accessed 31 May 2020).
- [69] Agilent 34970 A datalogger. <http://www.farnell.com/datasheets/64296.pdf> (website accessed 31 May 2020).
- [70] Benetech anemometer. <https://vctec.co.kr/web/product/benetech/img/GM816.pdf> (website accessed 31 May 2020).
- [71] Engineering ToolBox. https://www.engineeringtoolbox.com/specific-heat-capacityfood-d_295.html (website accessed 23 July 2020).
- [72] Mawire, A., Lefenya, T. M., Ekwomadu, C. S., & Shobo, A. B. (2020). Performance of a medium temperature eutectic solder packed bed latent heat storage system for domestic applications. *Journal of Energy Storage*, 28, 101294.

Chapter 4: Performance of two solar cooking storage pots using parabolic dish solar concentrators during solar and storage cooking periods with different heating loads.

Overview and abstract

In this chapter, a comparative experimental study on the effect of different cooking loads for two solar cooking pots incorporated with different thermal energy storage (TES) materials is presented during solar and storage cooking periods. This chapter consists of work that has been published in the Results in Engineering journal ([Results in Engineering 13 \(2022\)](#)).

Two pots have cavities in their walls for placing TES materials and are designed to be used with parabolic solar cookers. One pot is filled with erythritol as the TES material in the cavity, while the cavity of the other pot is filled with sunflower oil as the TES material. During the solar cooking period, the storage pots are heated up with solar energy, and cooking occurs as well as storage of thermal energy in the cavities of the pots. During the storage cooking period, the pots are placed in wonderbag slow cookers for off-sunshine cooking using the stored heat in the cavities. Water and sunflower oil with masses of 0.5, 1.0, 1.5, 2.0, and 2.5 kg, respectively, are used as the cooking loads during both solar and storage cooking periods. The effect of the load is evaluated in terms of storage and heat utilisation efficiencies. The storage efficiencies marginally increase with the increase in the load when water is used as the heating load. The sunflower oil pot shows slightly higher storage efficiencies (3.2-4.4 %) compared to the erythritol pot (2.5-3.9 %) with water as the cooking load. Storage efficiencies using sunflower oil as the cooking load show slightly greater values compared to when using water and follow no particular trend with the increase in the mass of the load. Heat utilisation efficiencies increase with the load for both storage cooking pots and both cooking fluids. However, water shows higher heat utilisation efficiencies (erythritol-13-49 %, sunflower oil-17-46 %) compared to sunflower oil (erythritol-9.2-19 %, sunflower oil-9.4-28 %) during the heat utilisation experiments. The erythritol storage pot shows higher heat utilisation efficiencies compared to the sunflower pot when using water as the heating fluid. However, when using sunflower oil as the heating fluid, the sunflower oil pot shows higher heat utilisation efficiencies.

4.2 Introduction

To alleviate the negative impact on the environment by fossil fuel-based cookers, different types of solar cookers have been designed and implemented in recent years as discussed comprehensively in the reviews by Cuce and Cuce [1], Nkhonjera et al. [2], Herez et al. [3], Aramesh et al. [4], Omara et al. [5] and Arunachala and Kundapur [6]. The four major types of solar cookers are oven solar cookers (box type), panel solar cookers, concentrating solar cookers (e.g. parabolic dish solar cookers), and indirect types of solar cookers (e.g. evacuated tube solar cookers with thermal energy storage). The incorporation of thermal energy storage (TES) systems with solar cookers will enable them to operate during non-sunshine periods [5]. Indirect solar cookers are the most expensive to fabricate for mass production when compared to the other types of solar cookers [4,6]. Although box solar cookers and panel cookers are less expensive to design and manufacture, they achieve lower temperatures which may not be sufficient for high-temperature cooking processes such as frying or roasting [5]. As highlighted by Senthil [8], end users are concerned with the duration of any cooking solution, and the parabolic solar cookers are faster in cooking compared to other solar cookers. The high cooking temperatures achievable by parabolic solar cookers are advantageous in killing food-borne bacteria.

Ebersviller and Jetter [9] reported that best pasteurization is achieved when the internal temperature of foods reaches about 74 °C or higher in less than 2 h. The efficiency of a solar cooker largely depends on the performance of the parabolic reflector which collects and directs solar radiation to focus it on the cooking pot. In a recent study by Ahmed et al. [10], it was reported that the use of Mylar tape as the reflective material on the parabolic reflector is more advantageous in terms of cost and performance compared to aluminium foil and stainless steel. The efficiency of parabolic solar cookers is also improved by the incorporation of a tracking system which ensures that the solar reflector captures solar radiation more efficiently to focus it on the cooking vessel [11,12]. Automated tracking is more user-friendly compared to manual tracking; however, the cost of the whole system becomes very expensive especially for applications in the developing world [13]. Besides improving the reflector and employing a tracking mechanism, the cheapness of manufacturing [6,14], heat transfer enhancement mechanisms [15,16], and novel

performance evaluation parameters [17-19] should be considered when evaluating parabolic solar cookers. All these mentioned aspects, however, do not guarantee the usage of parabolic solar cookers during non-sunshine periods like at night for preparing dinner.

Concentrating solar cookers are ideal for high-temperature cooking processes, and they can be combined directly and indirectly with TES systems to enhance their usefulness during non-sunshine hours [7]. TES can assist in enhancing the usefulness of solar cookers during non-sunshine periods, by combining them indirectly to TES units. Indirect TES systems have been incorporated with parabolic solar cooking systems to make off-sunshine cooking possible [20-25]. These systems also permit cooking of food to be done inside the house making the cost of the systems quite high due to the heat transfer systems required from the TES to the cooking vessel. These systems are not too economically viable in developing countries due to the high costs of design, manufacturing, and maintenance. The heat retention capability of a cooking vessel has been reported to also be a crucial component that influences the efficiency of a solar cooking system [6,7]. Both sensible and latent heat storage media have been used to improve the heat retention ability of cooking vessels directly. Studies by Lecuona et al. [26], Chaudhary et al. [27], Rekha and Sukchai [28], Bhavne and Thakare [29], Yadav et al. [30], Keith et al. [31], Choudhari and Shende [32], Bhavne and Kale [33], Mawire et al. [34] and Rekha et al. [35] have presented cooking pots with cavities in their walls for heat storage. The cavities in the walls of the pots were filled with heat storage materials. This design not only improves the heat retention capabilities of the pots while being used when there is sunshine, but it also enables cooking with the stored heat after sunset. These types of pots also require good insulation for higher heat retention during storage or off-sunshine usage. Cooking pots have been placed in the wonderbag which reduced heat losses from the pots and allowed slow cooking of foods [34,36].

Limited studies have reported the effects of the load on the solar heat storage and heat utilisation efficiencies for cooking pots with embedded thermal energy storage. These types of storage cooking pots are economically viable for developing countries. Ebersviller and Jetter [9] suggested that reduction of the vaporization of the water content of foods being cooked by solar cookers will help to conserve heat in the pots. A measure of the mass difference of the food cooked is thus also an important factor that accounts for the efficiency

of a solar cooker. It is also important to evaluate the efficiencies of these cooking vessels from the perspective of the evaporated water content of food cooked. The aim of this paper is to evaluate the effects of the cooking load on the storage and heat utilisation efficiencies of two similar heat-storage pots using different heat storage media. Additionally, the mass evaporated during solar and storage cooking periods will also be evaluated. The performances of two heat-storage cooking pots using erythritol (a phase change material (PCM)) and sunflower oil (a sensible heat storage material) respectively, as the storage materials, are compared experimentally using five different cooking loads (0.5, 1.0, 1.5, 2.0, 2.5 kg). Water and sunflower oil are used as the cooking loads in these experiments. The major novelty of the work is the evaluation of heat storage and utilisation efficiencies of solar storage cooking pots under variable cooking loads which has been rarely reported including the rate of evaporation with variable cooking loads. The results presented in this paper will be useful in the design of heat-storage cooking pots in the future. Numerical models to be developed in the future will also be validated with experimental results presented in this paper.

4.2 Materials and methods

The basic experimental components are shown in Figure 4.1, which is composed of a parabolic solar cooker (Figure 4.1(a)) and a wonderbag (Figure 4.1(b)). The experimental tests were done at North-West University, Mahikeng, South Africa. The parabolic dish solar cooker consists of a 1.2 m diameter parabolic dish with a heat-storage pot which is painted black outside and placed at the focal region of the dish. The parabolic dish uses a manual tracking mechanism. The wonderbag (Figure 4.1(b)) is an insulating bag in which the heat storage pot is placed after being charged so that the stored heat may be used to also cook. The properties of the wonderbag have been reported in more detail in Ref. [34]. Figure 4.2 (a) shows a photograph of one of the heat-storage pots used in the experiments.

Figure 4.2 (b) shows a section of the heat-storage pot with its dimensions. The cavity of one of the pots was filled with about 3.75 L of liquid erythritol while the cavity of the other pot was filled with about 3.75 L of sunflower oil. The two pots with their contents were allowed to attain equilibrium with the ambient temperature before the start of the experiments. The properties of these two heat storage materials are presented in Table 4.1. To measure the temperature inside the storage material, three K-type thermocouples were placed at

distances of 0.024 m, 0.06 m and 0.09 m, respectively from the outer base of the pots. The temperature inside each pot during cooking was measured with another K-type thermocouple. The direct solar radiation, the temperatures in the pots, and the wind speed were monitored in each experimental test. Two experiments were carried out each with water heating loads of 0.5, 1.0, 1.5, 2.0 and 2.5 kg, respectively, in the two pots making a total of 10 experiments to investigate the effect of the water cooking load. Similarly, two experiments were also carried with oil cooking loads of 0.5, 1.0, 1.5, 2.0 and 2.5 kg, respectively, in the two pots (10 experiments in total) to investigate the effect of the oil cooking load.

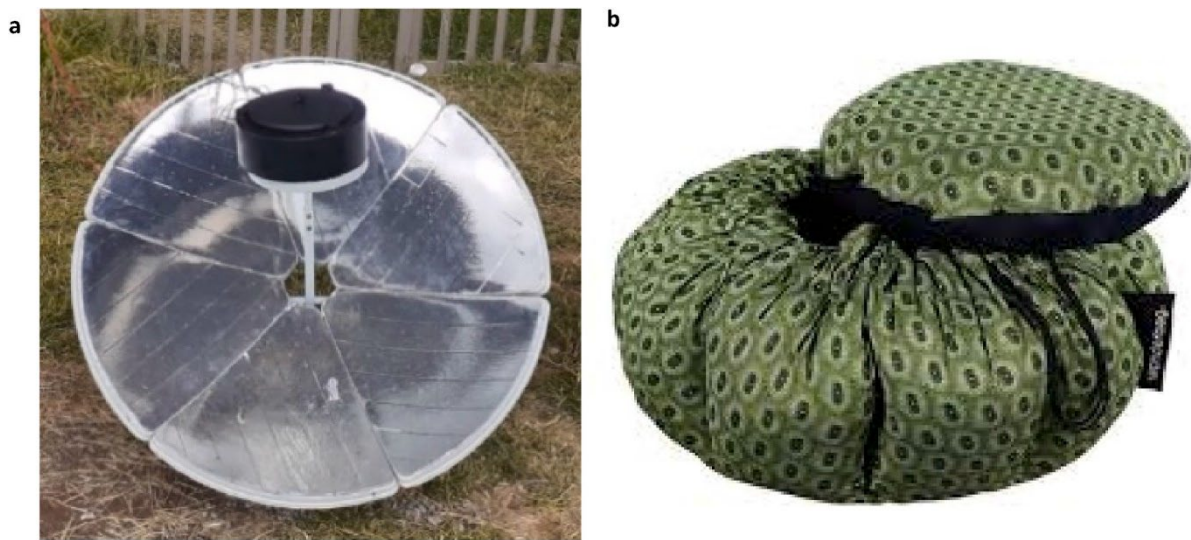


Figure 4.1: Photographs of (a) the parabolic dish solar cooker used in solar cooking tests, and (b) the wonderbag slow cooker used in off-sunshine storage cooking tests.

The solar cooking period was the period when concentrated solar radiation was used to simultaneously heat the cooking load in the pot and store thermal energy in the TES material within the walls of the pot. The storage cooking period was the period when the thermal energy stored in the TES material within the walls of the pot was used for heating the cooking load while the pot was put in an insulated wonder bag. It is important to note that each storage cooking test was done immediately after the preceding solar cooking test with the same load. It was also possible to use this stored heat to cook in the evening or at night since the pots were placed in the insulated bags.

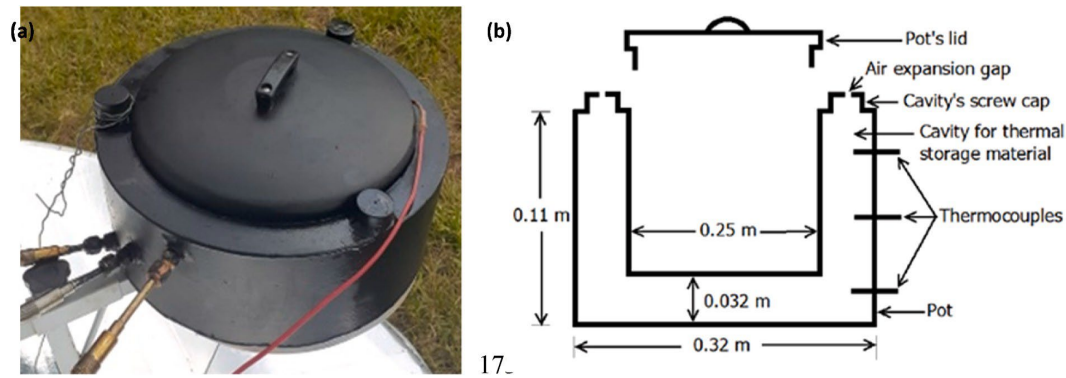


Figure 4.2: (a) A photograph and (b) schematic diagram of the solar storage cooking pot.

Table 4.1: Thermophysical properties of the two storage materials used in this study [34].

Property	Erythritol	Sunflower Oil
Melting Temperature (°C)	118.4–122.0	N/A
Specific Heat Capacity (kJ/kgK)	$c = 1.263 + 0.00410T$	$c = 2.115 + 0.00313T$
Phase change enthalpy (kJ/kg)	310.6	N/A
Density (kg/m ³)	1480 (20 °C), 1300 (140 °C)]	$c = 930.62 + 0.65T$
Thermal conductivity (W/mK)	0.733 (20 °C), 0.326 (140 °C)	0.17
Volume of storage material in the pot (litres)	3.780	3.750
Mass of storage material in the pot (kg)	5.438	3.438
Flashpoint (°C)	339-331	315

The experiments were carried out mainly in May 2020, and the test conditions on the different dates of the experiments are given in Table 4.2. The average solar radiation in Mahikeng varied between 630 and 962 W/m²; the average wind speed varied between 0 and 1.6 m/s, while the average ambient temperatures ranged between 17.3 and 26.6 °C. The experimental solar cooking period (total solar heating period) ranged between 3.8–4.2 h. The test conditions when sunflower oil was used as the cooking load are shown in Table 4.3. These tests were performed in Mahikeng mainly in June and July 2020. The average solar radiation varied between 764 and 902 W/m², while the average wind speed varied between 0.2 and 2.2 m/s. The average ambient temperature ranged between 20.9 and 28.3 °C. The solar cooking was between 3.8 and 4.0 h, while the storage cooking periods ranged between 1.8 and 1.9 h.

Table 4.2: Test conditions using water as the cooking load.

Test No. and Date	Average solar radiation and standard deviation (W/m ²)	Average wind speed and standard deviation (m/s)	Average ambient temperature and standard deviation during solar heating (°C)	Total solar heating period (h)	Total storage heating period (h)	Average ambient temperature and standard deviation during storage heating (°C)	Heated load (kg)
1-22/05/20	630 ± 318	0.1 ± 0.4	25.0 ± 3.1	4.1	1.9	23.4 ± 1.4	0.5
2-27/05/20	944 ± 34	0.5 ± 0.9	17.3 ± 2.6	3.8	1.8	16.6 ± 1.1	0.5
3-28/05/20	945 ± 33	0.4 ± 0.9	23.3 ± 1.6	3.8	1.7	21.0 ± 1.0	1.0
4-29/05/20	916 ± 33	0.6 ± 0.7	24.4 ± 2.2	4.0	1.8	23.0 ± 1.1	1.0
5-11/05/20	743 ± 234	0.0 ± 0.0	22.8 ± 1.1	4.1	1.8	24.2 ± 0.7	1.5
6-12/05/20	848 ± 40	0.2 ± 0.5	25.6 ± 1.9	4.0	1.8	24.7 ± 1.1	1.5
7-14/05/20	962 ± 27	0.9 ± 2.3	26.6 ± 2.3	4.0	1.8	25.0 ± 1.5	2.0
8-15/05/20	916 ± 28	1.6 ± 2.0	24.0 ± 2.0	4.1	1.8	24.1 ± 0.8	2.0
9-20/05/20	892 ± 26	0.7 ± 1.1	25.7 ± 2.4	4.2	1.8	25.1 ± 1.4	2.5
10-21/05/20	872 ± 23	1.0 ± 1.2	24.2 ± 2.3	4.2	1.8	22.8 ± 1.5	2.5

Table 4.3: Test conditions using sunflower oil as the cooking load.

Test No. and Date	Average solar radiation and standard deviation (W/m ²)	Average wind speed and standard deviation (m/s)	Average ambient temperature and standard deviation during solar heating (°C)	Total solar heating period (h)	Total storage heating period (h)	Average ambient temperature and standard deviation during storage heating (°C)	Heated load (kg)
1-02/06/20	857 ± 44	0.8 ± 1.1	28.3 ± 2.6	3.8	1.8	26.5 ± 1.9	0.5
2-04/06/20	878 ± 25	1.6 ± 1.0	25.9 ± 1.9	3.8	1.8	23.9 ± 1.1	0.5
3-15/06/20	902 ± 25	1.6 ± 1.4	20.9 ± 1.7	3.8	1.9	19.4 ± 1.2	1.0
4-23/06/20	853 ± 33	0.3 ± 0.4	22.4 ± 2.1	4.0	1.9	20.9 ± 1.1	1.0
5-22/07/20	764 ± 69	0.9 ± 1.3	25.0 ± 1.2	3.9	1.8	23.2 ± 0.7	1.5
6-27/07/20	806 ± 24	1.9 ± 0.8	22.6 ± 1.9	3.8	1.9	22.3 ± 1.3	1.5
7-28/07/20	801 ± 25	2.2 ± 0.6	21.2 ± 2.1	4.0	1.9	20.9 ± 1.3	2.0
8-29/07/20	806 ± 61	0.9 ± 0.7	21.2 ± 2.0	4.0	1.8	20.9 ± 1.3	2.0
9-30/07/20	845 ± 38	0.6 ± 0.9	24.0 ± 1.9	4.0	1.8	23.3 ± 1.1	2.5
10-31/07/20	806 ± 76	0.8 ± 1.2	27.1 ± 2.2	4.0	1.8	26.0 ± 1.1	2.5

4.3 Experimental thermal analysis

The experimental analysis follows the methods presented in a previous study by the authors [34] thus, a summarized version of thermal analysis is presented here. During the solar cooking period, the incident solar energy during a cooking period is given as;

$$Q_{inc} = \sum I_{ac} A_o \Delta t \quad (4.1)$$

where I_{ac} is the cumulative moving average solar radiation at each time interval during the solar period to cater for fluctuations in the solar radiation, A_o is the dish aperture area, and Δt is the data logging time interval of 10 s. The total stored energy during a solar cooking period is estimated as;

$$Q_s = \sum m_s c_s (\Delta T) s \quad (4.2)$$

where m_s is the mass in the storage pot, c_s is the specific heat capacity of the storage material and $(\Delta T)s$ is the moving average temperature difference between the next and previous time step interval Δt in the storage material. The solar thermal energy storage efficiency is given by the ratio of total thermal energy stored to the total solar incident energy as;

$$\eta_s = \frac{Q_s}{Q_{inc}} \quad (4.3)$$

For the storage cooking period, the total heat utilisation can be estimated by considering the total heat delivered to the cooking fluid, and it is expressed as:

$$Q_{uti} = \sum m_l c_l (\Delta T) l \quad (4.4)$$

where m_l is the mass of the cooking fluid, c_l is the specific heat capacity of the cooking fluid, and $(\Delta T)l$ is the temperature difference in the cooking fluid during heat utilisation. The heat utilisation efficiency can be estimated from the ratio of the total heat utilisation to the total energy stored, and it is given as;

$$\eta_{uti} = \frac{Q_{uti}}{Q_s}. \quad (4.5)$$

The specific heat capacity of sunflower oil (one of the storages and cooking fluid) is temperature-dependent, and it can be expressed as;

$$c_{av}(\text{kJ/kgK}) = 2115.00 + 3.13T_{av} \quad (4.6)$$

where T_{av} is the moving average temperature calculated from the number of samples measured. The other specific heat capacity of the other storage material, erythritol is also temperature-dependent, and it is given as;

$$c_{av}(\text{kJ/kgK}) = 1.269 + 0.00410T_{av}. \quad (4.7)$$

The percentage mass loss due to evaporation during cooking periods is given as;

$$m_{loss}\% = \frac{m_f}{m_{ini}} \times 100\% \quad (4.8)$$

where m_{ini} is the initial mass of the cooking fluid at the start of the experiment and m_f is the final mass of the cooking fluid at the end of the experiment.

4.4 Results and discussion

Figure 4.3 (a) shows the variations in solar radiation and the wind speed (in 30 min intervals) profiles on May 29, 2020 while the experiments were performed. The solar radiation is around 950 W/m² at the start of the experimental period (11:10 h), and it drops relatively slowly to be about 850 W/m² at the end of the experimental period (~15:15 h). Fluctuations in the wind speed can be observed from the start of the experiment up until about 14:00 h with the maximum wind speed being about 1.5 m/s at about 12:00 h. The wind seems to cease after 14:00 h as the speed was undetectable by the anemometer. The temperature profiles of the two different cooking pots with 1 kg of water used as the cooking load during both solar and storage cooking periods are shown in Figure 4.3 (b). The solar cooking period was about 4 h while the storage cooking period was about 2 h. The temperatures of the water inside of and in the storage compartment of the pot utilizing sunflower oil as storage material (T_{POTOIL} and T_{STOIL}) were higher than those of the pot which utilized erythritol during solar cooking. This was as a result of the lower thermal mass of sunflower oil as compared to that of erythritol. A maximum temperature of about 118 °C was attained in the storage chamber of the sunflower oil pot, whereas the erythritol pot only attained a maximum temperature of just above 100 °C in its storage chamber. This temperature is below the melting temperature of erythritol thus, latent heat was not stored in the PCM. The water inside the two pots also shows similar temperature trends as with the TES materials with the water in the

sunflower oil pot attaining higher temperatures than that in the erythritol pot. The erythritol pot had more fluctuations in its temperature profiles due to non-uniform heating of erythritol in the storage compartment. However, there was a greater drop in the temperatures in the sunflower storage than the erythritol storage during the storage cooking period. This indicates that there is more effective heat utilisation in the erythritol pot than in the sunflower oil pot.

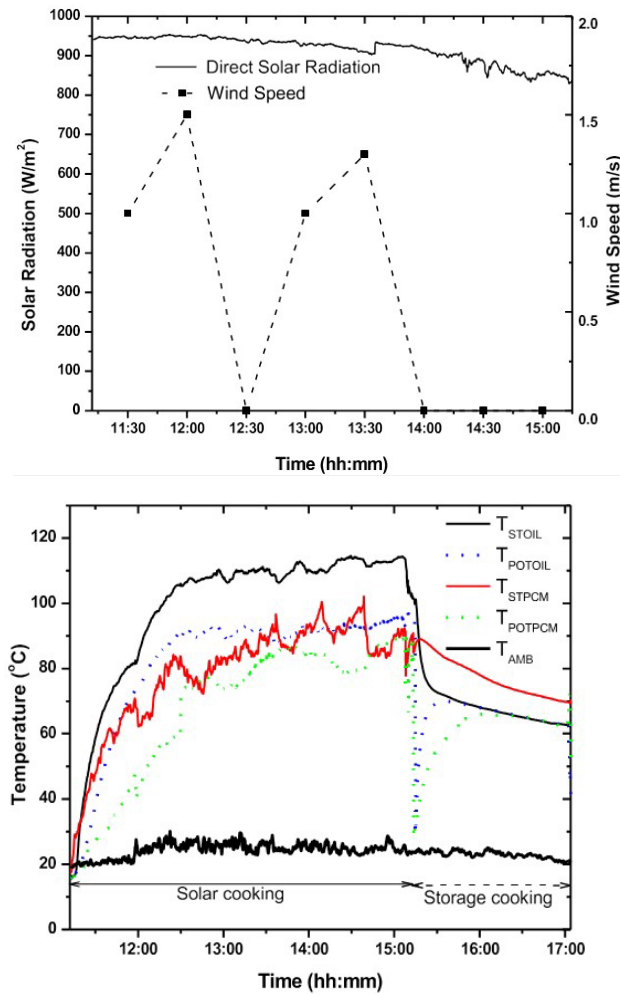


Figure 4.3: (a) Solar radiation and wind speed during the solar cooking period, and (b) temperature profiles of the two pots during solar and storage cooking periods for 1 kg load of water on May 29, 2020.

Experimental test results using 1 kg of sunflower oil as the cooking load on June 23, 2020 are shown in Figure 4.4. Solar radiation varied from about 880 W/m² at the start of the solar cooking period to about 750 W/m² at end of the solar cooking period, with an average value of about 820 W/m².

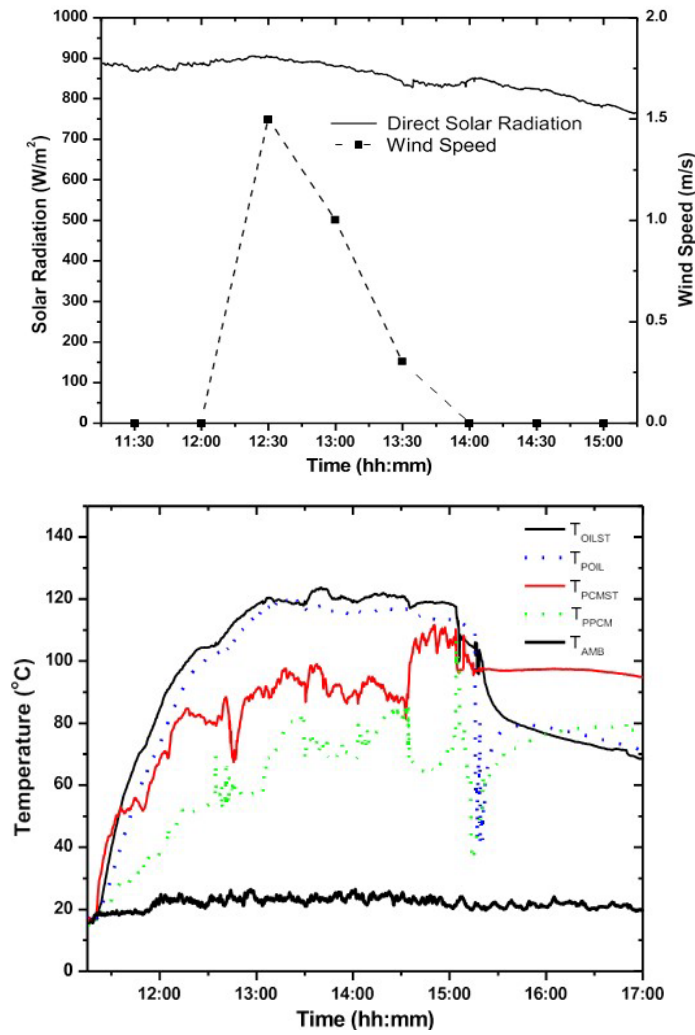


Figure 4.4: (a) Solar radiation and wind speed during the solar cooking period, and (b) temperature profiles of the two pots during solar and storage cooking periods for a 1 kg load of oil on June 23, 2020.

The wind speed had a peak value of about 1.5 m/s at 12:30 h, after which it gradually drops to zero. Higher storage and cooking temperatures can be observed with the sunflower oil pot compared to those when using water as the heating load (Figure 4.3(b)). This is because of the lower thermal mass of the sunflower oil in the pot. The temperature difference between storage and cooking temperatures is lower when using sunflower oil as the load. Slightly higher storage temperatures are also seen in the erythritol storage pot but fluctuations due to non-uniform heating are evident as explained earlier. The load temperature in the PCM storage pot shows lower temperatures compared to water (Figure 4.3 (b)) for the initial stages of charging as a direct result of non-uniform heating and manual tracking. For the storage cooking period, the erythritol storage shows an almost constant storage temperature

of 95 °C for the whole period, whereas there is a big drop in the storage temperature from around 110 °C to just below 70 °C for the sunflower oil storage pot. As a result of this drop, the erythritol storage pot shows higher cooking temperatures in the second hour of storage cooking compared to the oil storage pot. Higher cooking temperatures are seen when using sunflower oil as the cooking load compared to when using water as the cooking load (Figure 4.3(b)) due to the lower thermal mass of the cooking load. The maximum temperatures for the sunflower oil pot and the erythritol pot are around 78 °C and 80 °C, respectively, during the storage cooking period when using sunflower oil as the heating load.

Results of the cooking tests with a larger cooking load of 2.5 kg of water are shown in Figure 4.5. The maximum solar radiation during this test is just above 900 W/m², and the wind speed fluctuates during the test with a maximum value of about 2.8 m/s at 11:00 h. The storage and cooking temperatures during cooking with the larger load were slightly lower compared to having a smaller load inside the oil storage pot (Figure 4.3 (b)). For the erythritol storage pot with the larger thermal of storage material, the storage and cooking temperatures during the solar cooking period are significantly lower during the initial stages of cooking compared to having a smaller cooking load of 1 kg (Figure 4.3(b)). The larger load is a larger heating thermal mass which causes the temperature rise to be slower. As with the other tests, the erythritol storage pot shows lower temperatures compared to the oil storage pot during the solar cooking period. For the storage cooking period, both storage pots show significantly lower cooking temperatures compared to the smaller cooking load of 1 kg. The larger heating load has the effect of dropping the storage temperatures more rapidly from about 100 °C to just above 50 °C for both storage cooking pots. The maximum cooking temperatures are about 50 °C and 47 °C, respectively, for the sunflower oil and erythritol pots during the storage cooking periods.

The effect of increasing the cooking load of sunflower to 2.5 kg can be observed in Figure 4.6. The average solar radiation and wind speed were about 840 W/m² and 1.5 m/s, respectively for this test. The temperature difference between the storage and cooking temperatures became larger for the sunflower oil pot as compared to when it had a smaller cooking load (Figure 4.4 (b)). This is because the larger thermal mass absorbs heat at a lesser rate than the lower thermal mass.

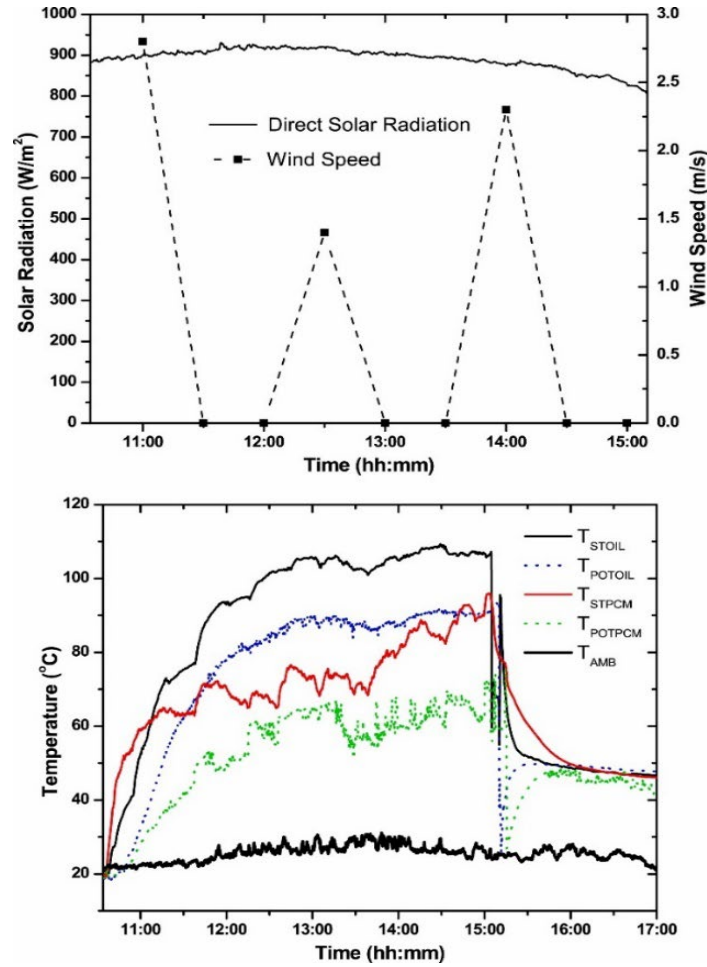


Figure 4.5: (a) Solar radiation and wind speed during the solar cooking period, and (b) temperature profiles of the two pots during solar and storage cooking periods for a 2.5 kg load of water on May 20, 2020.

With the erythritol storage pot having a bigger load of 2.5 kg, lower storage temperatures were attained than when it has a smaller cooking load indicating better thermal performance (1.0 kg) with the smaller load. This is due to the lower rate of heat absorption with the larger thermal mass. The storage cooking temperatures also attained values lower than those with a smaller cooking load. Maximum cooking temperatures achieved during the storage cooking period were about 70 °C and 65 °C for the sunflower oil and erythritol storage pots respectively.

The solar radiation and temperatures depicted in Figures 4.3-4.6, and in the other experimental tests together with Equations (4.3) and (4.5) were used to calculate the storage and heat utilization efficiencies of the two pots. The initial and final masses of the cooking fluid were used to determine the percentage mass evaporated after each experiment using Equation (4.8).

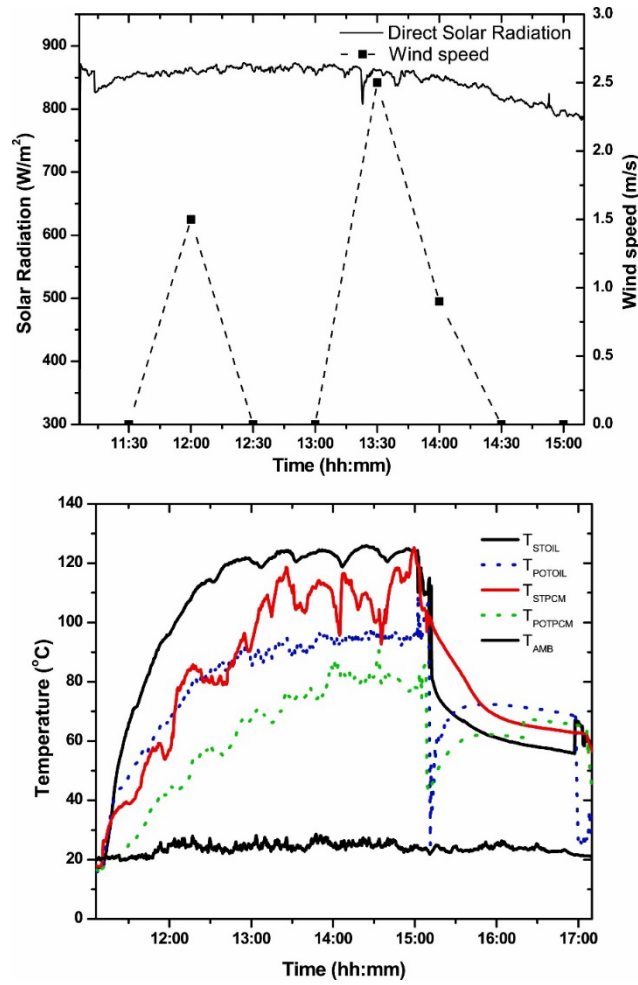


Figure 4.6: (a) Solar radiation and wind speed during the solar cooking period, and (b) temperature profiles of the two pots during solar and storage cooking periods for a 2.5 kg load of oil on July 30, 2020.

Table 4.4 presents a summary of the effect of different loads of water on storage and heat utilization efficiencies for the two storage cooking pots. The average storage efficiencies for both storage cooking pots decrease marginally with the increase in the load. The storage efficiency decreases from 3.9 to 2.5 % for a load increase of 0.5-2.5 kg for the erythritol pot, whereas the corresponding decrease for the sunflower pot is 4.4-3.2 %. The sunflower pot shows slightly higher storage efficiencies due to the higher temperatures attained as a result of its lower thermal mass. The decrease in the storage efficiency with an increase in the load is due to the larger loads which reduce the temperature rise during the solar charging phase. The heat utilization efficiencies for both storage pots increase with the increase in the load. This is consistent with the work reported by Islam and Salehin [36], and this suggests that heavier loads are more suitable for effective heat utilization of the stored energy. The

erythritol pot shows higher heat utilization efficiencies which range from 13 to 49 % compared to 17-46 % for the sunflower oil pot. This is a direct result of the larger thermal storage mass for the erythritol pot although higher storage temperatures are seen with the sunflower oil pot.

Table 4.4: A summary of the solar heating and storage heat utilization experimental results using water as the load.

Cooking pot	Average solar heating time (h)	Heated load (kg)	Average storage heating time (h)	Average evaporated % mass during solar heating	Average evaporated % mass during storage heating	Average storage efficiency (%)	Average heat utilisation efficiency (%)
Erythritol							
Case 1	3.95	0.50	1.85	41	4.9	3.9	13
Case 2	3.90	1.00	1.75	12	3.0	3.2	29
Case 3	4.05	1.50	1.80	17	2.1	2.9	44
Case 4	4.05	2.00	1.80	8.9	2.4	2.8	47
Case 5	4.20	2.50	1.80	17	5.8	2.5	49
Sunflower oil							
Case 1	3.95	0.50	1.85	71	8.9	4.4	17
Case 2	3.90	1.00	1.75	65	3.2	4.3	21
Case 3	4.05	1.50	1.80	69	2.4	4.1	29
Case 4	4.05	2.00	1.80	48	3.7	3.8	35
Case 5	4.20	2.50	1.80	36	2.8	3.2	46

The percentage mass loss due to evaporation is seen to generally decrease with an increase in the heating load for both storage cooking pots during the solar cooking period. However, for an increase in the load from 1 kg to 1.5 kg the percentage mass loss is slightly greater for the 1.5 kg case. This is possibly due to the lower average wind speed conditions depicted in Table 4.2 for 1.5 kg which induce fewer heat losses for higher temperatures to be attained, resulting in more mass loss due to evaporation. The mass evaporated for the sunflower oil storage pot is very high, and it varies between 71 and 36 % for the increase in the load from 0.5 to 2.5 kg, whereas for the erythritol pot it varies in the range of 41-17 %. Higher temperatures achieved in the sunflower oil pot cause this higher percentage of mass loss. The high mass losses suggest that evaluation of the performance should not be done with the mass of water as the cooking fluid since the mass that evaporated was not negligible. This has also been pointed out by Ebersiviller and Jetter [9] in their recent study. For the storage cooking period, the average percentage mass loss is lower for both pots compared to the solar cooking period. This is a direct result of the solar radiation heating conditions during the solar cooking period. The mass loss also generally decreases with the load, however, the decrease is not very pronounced compared to the solar cooking period. The mass loss for the

sunflower oil is more, and it ranges from 2.4 to 8.9 % compared to 2.1–5.8 % for the erythritol pot. The loaded mass during the heat utilisation period can be used to evaluate the cooking performance since the mass loss is not too large.

Table 4.5 shows a summary of the experimental results using different sunflower oil cooking loads.

Table 4.5: A summary of the solar heating and storage heat utilisation experimental results using sunflower oil as the load.

Cooking pot	Average solar heating time (h)	Heated load (kg)	Average storage heating time (h)	Average evaporated % mass during solar heating	Average evaporated % mass during storage heating	Average storage efficiency (%)	Average heat utilisation efficiency (%)
Erythritol							
Case 1	3.80	0.50	1.80	2.7	1.9	3.6	9.2
Case 2	3.90	1.00	1.90	2.4	1.3	3.8	14
Case 3	3.90	1.50	1.90	2.6	3.2	4.0	16
Case 4	4.00	2.00	1.90	2.2	2.0	3.5	18
Case 5	4.00	2.50	1.80	1.6	1.6	4.3	19
Sunflower oil							
Case 1	3.80	0.5	1.80	3.6	1.8	5.3	9.4
Case 2	3.90	1.00	1.90	2.0	2.0	5.2	13
Case 3	3.90	1.50	1.90	2.2	1.3	5.1	21
Case 4	4.00	2.00	1.90	2.0	1.7	3.9	32
Case 5	4.00	2.50	1.80	5.3	2.1	5.4	28

Using sunflower oil as the heating load, the average storage efficiencies are almost independent of the load and there is no predictable trend. Some cooking loads show almost the same storage cooking efficiencies. The sunflower oil pot as in the case with water load shows slightly higher average storage efficiencies (3.9-5.4 %) during the solar cooking periods compared to the erythritol pot (3.6-4.3 %). The storage efficiencies using sunflower oil as the cooking fluid are slightly greater than those depicted in Table 4.4 using water as the cooking fluid. This is a result of the lower thermal mass of sunflower oil compared to water which results in higher cooking temperatures above the boiling point of water. The heat utilisation efficiencies of the two storage pots also increase with the load as with the case when using water as the load (Table 4.4). However, the heat utilisation efficiencies of the erythritol pot (9.2-19 %) are generally lower than those of the sunflower oil pot (9.4-28 %) which is an opposite behaviour to the water heating case. This is possibly due to the higher cooking and thermal energy storage temperatures achieved by the sunflower oil pot which outweighs the larger thermal mass of erythritol during utilisation of the stored heat. It is also important to

note that the heat utilisation efficiencies with the lower thermal mass of sunflower oil as the cooking load are lower than those depicted in Table 4.4 using water as the heating load. Thus, it can be concluded that larger thermal masses are more appropriate for storage cooking processes. In reality, sunflower oil is used in much smaller amounts with larger amounts of food thus the cooking load is expected to be comparable or smaller.

In terms of the average mass loss due to evaporation during the solar cooking periods, the mass loss for both cooking pots is much lower than when using water since sunflower oil evaporates at much higher temperatures (above 250 °C). The mass losses during the solar cooking period are comparable for both storage cooking pots with the erythritol pot showing 1.6–2.7% mass loss, and the sunflower oil pot showing between 2.0 and 5.3% mass loss.

These much lower mass losses during the solar cooking period suggest that sunflower oil can be used to evaluate accurately the cooking performance of these storage pots compared to water which shows very large mass losses, especially at the lower cooking loads. The mass losses are also almost independent of the cooking load with some loads almost showing the same mass losses. The percentage mass losses for the storage periods for the erythritol pot (1.6-3. 2%) are also comparable to those for the sunflower oil pot (1.3-2.0 %) and seem to be almost independent of the cooking load. Thus, sunflower oil can be used to accurately determine the solar and storage efficiencies of solar cooking storage pots due to the lower percentage mass losses which can be neglected within experimental uncertainties.

The results presented in Tables 4.4 and 4.5 are summarized graphically in Figure 4.7. The sunflower pot shows higher storage efficiencies than the erythritol pot for both cooking fluids. However, a predictable drop in the storage efficiency with the increase in the load is seen for both pots when using water as the heating load. When using sunflower oil as the heating load, the erythritol pot shows a slight initial rise of the storage efficiency for a load increment of 0.5–1.5 kg, before dropping and rising again. This could be a result of non-uniform heating, and the prevailing weather conditions of the test days. For the sunflower oil storage pot, a general drop in the storage efficiency is seen when using sunflower oil as the heating load except at the highest load, which could be a result of the high solar radiation and low wind speeds during the highest load test days. It is also evident that higher storage efficiencies are obtained using sunflower oil as the cooking load as compared to water. The

heat utilisation efficiencies are seen to generally increase with an increase in the load, except for the 2.5 kg case of heating oil in the oil storage pot. The erythritol storage pot shows higher heat utilisation efficiencies compared to the sunflower oil pot when heating water, and the heat utilisation efficiencies for heating water are greater than those of heating sunflower oil in both storage pots. However, when using sunflower oil as the heating load, the sunflower oil pot shows higher heat utilisation efficiencies suggesting that lower thermal mass loads are not effective in transferring the stored heat to the heating load when using the erythritol storage pot.

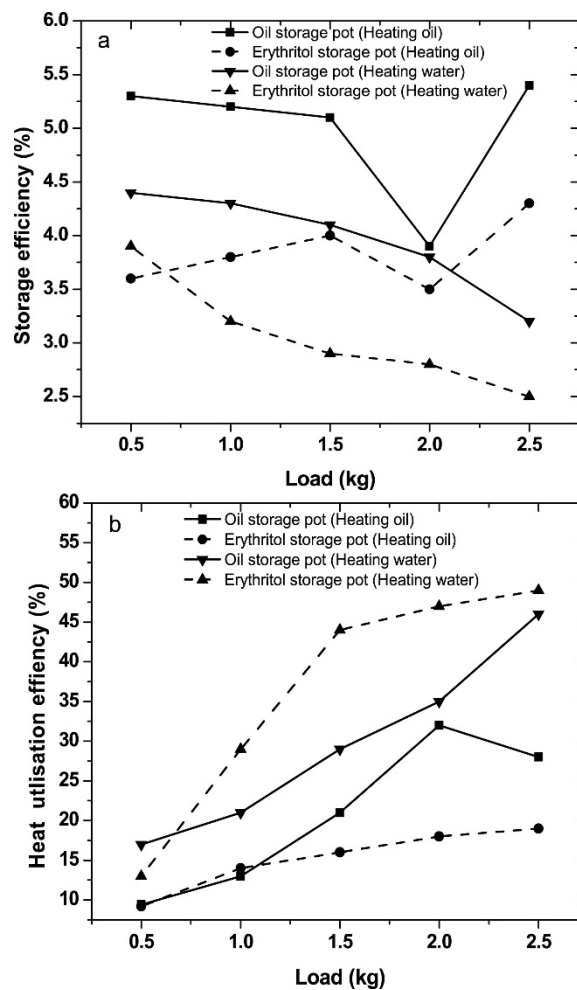


Figure 4.7: Effect of the load on the (a) storage efficiency and, (b) heat utilisation efficiency.

4.5 Conclusion

A comparative experimental study on the effect of different cooking loads for two solar cooking pots incorporated with different thermal energy storage (TES) materials was presented. The pots had cavities in their walls for placing TES materials and are designed to be used with parabolic solar cookers. One pot was filled with erythritol as the TES material in

the cavity, while the cavity of the other pot was filled with sunflower oil as the TES material. During the solar cooking period, the storage pots were heated up with solar energy, and cooking occurred as well as storage of thermal energy in the cavities of the pots. During the storage cooking period, the pots were placed in wonderbag slow cookers for off-sunshine cooking using the stored heat in the cavities. Five different loads were utilized in the cooking experiments (0.5, 1.0, 1.5, 2.0, 2.5 kg) using water and sunflower oil as the heating fluids, and the effects of the load on the storage and heat utilisation efficiencies were investigated. The main conclusions from this study were:

- The average storage efficiencies reduced marginally when using water as the cooking load during the solar cooking period. The sunflower oil pot showed slightly higher average storage efficiencies compared to the erythritol pot for both types of cooking loads. The storage efficiencies when using sunflower oil were slightly greater than when using water as the cooking fluid, and they seemed to be independent of the load.
- Average heat utilisation efficiencies when using water as the heating load during the storage cooking periods increased with an increase in the load for both storage cooking pots. The erythritol pot showed mostly higher heat utilisation efficiencies (13–49 %) compared to the sunflower oil pot (17–46 %) when using water. This was a direct result of the larger thermal mass of erythritol for energy storage. On the other hand, when using sunflower oil as the cooking fluid, the sunflower oil pot showed higher heat utilisation efficiencies (9.4–28 %) compared to the erythritol pot (9.2%–19 %). The heat utilisation efficiencies obtained using water were also greater than those obtained using sunflower oil suggesting that larger thermal masses result in better storage cooking capabilities compared to the lower thermal masses.
- The percentage mass losses due to evaporation were very significant during the solar cooking period using water as the heating load. Due to this mass loss during the water heating period, water should not be used for evaluating the cooking performance during solar cooking periods since this will result in errors in the calculations since the mass is assumed constant in calculations. The percentage mass loss due to evaporation was much lower when using sunflower oil as the heating fluid compared to water during the solar heating periods. Low percentage mass losses were also

observed with sunflower oil as the cooking fluid during the heat utilisation periods. The erythritol pot showed comparable percentage mass losses to the sunflower oil pot. The low percentage mass losses during the solar and storage cooking periods make sunflower oil a suitable fluid to evaluate both the solar and storage cooking performance of the storage cooking pots.

Thermal models are currently being developed for performance optimization for parametric studies of these solar cooking pots of which there is limited literature. The thermal models will be validated with some of the results presented in this paper, and different storage materials will be investigated with the models.

Credit author contribution statement

Ashmore Mawire: Drafted original manuscript, formal analysis, interpreting the results and conceptualization. Katlego Lentswe: Investigation, formal analysis, methodology, reviewing and editing. Prince Owusu: Investigation, reviewing and editing.

Declaration of competing interest

There is no conflict of interest to declare.

Acknowledgement

The authors would like to acknowledge, the University of Nottingham for funding to carry out this research under the internal Global Challenges Research Fund (GCRF) scheme, GCRF Interdisciplinary Research Project Award 2019, SALEC: Safe and Affordable Low Energy Cooking Solutions for Namibia and South Africa (RIS 2483754/RIS 2147131).

References

- [1] Cuce, E., & Cuce, P. M. (2013). A comprehensive review on solar cookers. *Applied Energy*, 102, 1399-1421.
- [2] Nkhonjera, L., Bello-Ochende, T., John, G., & King'onde, C. K. (2017). A review of thermal energy storage designs, heat storage materials and cooking performance of solar cookers with heat storage. *Renewable and Sustainable Energy Reviews*, 75, 157-167.
- [3] Herez, A., Ramadan, M., & Khaled, M. (2018). Review on solar cooker systems: Economic and environmental study for different Lebanese scenarios. *Renewable and Sustainable Energy Reviews*, 81, 421-432.
- [4] Aramesh, M., Ghalebani, M., Kasaeian, A., Zamani, H., Lorenzini, G., Mahian, O., & Wongwises, S. (2019). A review of recent advances in solar cooking technology. *Renewable Energy*, 140, 419-435.

- [5] Omara, A. A., Abuelnuor, A. A., Mohammed, H. A., Habibi, D., & Younis, O. (2020). Improving solar cooker performance using phase change materials: A comprehensive review. *Solar Energy*, 207, 539-563.
- [6] Arunachala, U. C., & Kundapur, A. (2020). Cost-effective solar cookers: A global review. *Solar Energy*, 207, 903-916.
- [7] Lentswe, K., Mawire, A., Owusu, P., & Shobo, A. (2021). A review of parabolic solar cookers with thermal energy storage. *Heliyon*, 7, e08226.
- [8] Senthil, R. (2021). Enhancement of productivity of parabolic dish solar cooker using integrated phase change material. *Materials Today: Proceedings*, 34, 386-388.
- [9] Ebersviller, S. M., & Jetter, J. J. (2020). Evaluation of performance of household solar cookers. *Solar Energy*, 208, 166-172.
- [10] Ahmed, S. M., Al-Amin, M. R., Ahammed, S., Ahmed, F., Saleque, A. M., & Rahman, M. A. (2020). Design, construction and testing of parabolic solar cooker for rural households and refugee camp. *Solar Energy*, 205, 230-240.
- [11] Gupta, P. K., Misal, A., & Agrawal, S. (2021). Development of low-cost reflective panel solar cooker. *Materials Today: Proceedings*, 45, 3010-3013.
- [12] Tawfik, M. A., Sagade, A. A., Palma-Behnke, R., Hanan, M., & Abd Allah, W. E. (2021). Solar cooker with tracking-type bottom reflector: An experimental thermal performance evaluation of a new design. *Solar Energy*, 220, 295-315.
- [13] Devan, P. K., Bibin, C., Gowtham, S., Hariharan, G., & Hariharan, R. (2020). A comprehensive review on solar cooker with sun tracking system. *Materials Today: Proceedings*, 33, 771-777.
- [14] Mekonnen, B. A., Liyew, K. W., & Tigabu, M. T. (2020). Solar cooking in Ethiopia: Experimental testing and performance evaluation of SK14 solar cooker. *Case Studies in Thermal Engineering*, 22, 100766.
- [15] Hosseinzadeh, M., Sadeghirad, R., Zamani, H., Kianifar, A., Mirzababaei, S. M., & Faezian, A. (2021). Experimental study of a nanofluid-based indirect solar cooker: energy and exergy analyses. *Solar Energy Materials and Solar Cells*, 221, 110879.
- [16] Sagade, A. A., Mawire, A., Belgasim, B., Tawfik, M. A., & Sagade, N. A. (2021). Experimental performance evaluation of a parabolic dish solar geyser using a generalized approach for decentralized applications. *Sustainable Energy Technologies and Assessments*, 47, 101454.
- [17] Sagade, A. A., Samdarshi, S. K., Sagade, N. A., & Panja, P. S. (2021). Enabling open sun cooling method-based estimation of effective concentration factor/ratio for concentrating type solar cookers. *Solar Energy*, 227, 568-576.
- [18] Kanyowa, T., Nyakujara, G. V., Ndala, E., & Das, S. (2021). Performance analysis of Scheffler dish type solar thermal cooking system cooking 6000 meals per day. *Solar Energy*, 218, 563-570.
- [19] Apaolaza-Pagoaga, X., Carrillo-Andrés, A., & Ruivo, C. R. (2021). New approach for analysing the effect of minor and major solar cooker design changes: Influence of height trivet on the power of a funnel cooker. *Renewable Energy*, 179, 2071-2085.
- [20] Prasanna, U. R., & Umanand, L. (2011). Optimization and design of energy transport system for solar cooking application. *Applied Energy*, 88, 242-251.

- [21] Mussard, M., & Nydal, O. J. (2013). Comparison of oil and aluminum-based heat storage charged with a small-scale solar parabolic trough. *Applied Thermal Engineering*, 58, 146-154.
- [22] Kumaresan, G., Sridhar, R., & Velraj, R. (2012). Performance studies of a solar parabolic trough collector with a thermal energy storage system. *Energy*, 47, 395-402.
- [23] Mbodji, N., & Hajji, A. (2017). Modeling, testing, and parametric analysis of a parabolic solar cooking system with heat storage for indoor cooking. *Energy, Sustainability and Society*, 7, 1-16.
- [24] Babu Sasi Kumar, S., & Chinna Pandian, M. (2019, July). Experimental analysis of a solar cooker with a parabolic trough enhanced with PCM based thermal storage. In *IOP Conference Series: Materials Science and Engineering*, 574, 012019.
- [25] El Moussaoui, N., Talbi, S., Atmane, I., Kassmi, K., Schwarzer, K., Chayeb, H., & Bachiri, N. (2020). Feasibility of a new design of a Parabolic Trough Solar Thermal Cooker (PSTC). *Solar Energy*, 201, 866-871.
- [26] Lecuona, A., Nogueira, J. I., Ventas, R., & Legrand, M. (2013). Solar cooker of the portable parabolic type incorporating heat storage based on PCM. *Applied Energy*, 111, 1136-1146.
- [27] Chaudhary, A., Kumar, A., & Yadav, A. (2013). Experimental investigation of a solar cooker based on parabolic dish collector with phase change thermal storage unit in Indian climatic conditions. *Journal of Renewable and Sustainable Energy*, 5, 023107.
- [28] Santhi Rekha, S. M., & Sukchai, S. (2018). Design of phase change material based domestic solar cooking system for both indoor and outdoor cooking applications. *Journal of Solar Energy Engineering*, 140, 041010.
- [29] Bhawe, A. G., & Thakare, K. A. (2018). Development of a solar thermal storage cum cooking device using salt hydrate. *Solar Energy*, 171, 784-789.
- [30] Yadav, V., Kumar, Y., Agrawal, H., & Yadav, A. (2017). Thermal performance evaluation of solar cooker with latent and sensible heat storage unit for evening cooking. *Australian Journal of Mechanical Engineering*, 15, 93-102.
- [31] Keith, A., Brown, N. J., & Zhou, J. L. (2019). The feasibility of a collapsible parabolic solar cooker incorporating phase change materials. *Renewable Energy Focus*, 30, 58-70.
- [32] Choudhari, K. S., & Shende, M. D. (2015). Solar cooker using PCM material. *Journal Basic Applied Engineering Research*, 2, 1449-1453.
- [33] Bhawe, A. G., & Kale, C. K. (2020). Development of a thermal storage type solar cooker for high temperature cooking using solar salt. *Solar Energy Materials and Solar Cells*, 208, 110394.
- [34] Mawire, A., Lentswe, K., Owusu, P., Shobo, A., Darkwa, J., Calautit, J., & Worall, M. (2020). Performance comparison of two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking. *Solar Energy*, 208, 1166-1180.
- [35] Mawire, A., Lentswe, K., & Owusu, P. (2022). Performance of two solar cooking storage pots using parabolic dish solar concentrators during solar and storage cooking periods with different heating loads. *Results in Engineering*, 13, 100336.
- [36] A.M.K.S. Islam, S. Salehin, Performance Test of Wonder Bag: A Pathway to Reduce Cooking Energy Consumption and CO₂ Emission, GIZ Technical Report, 2014, pp. 1–

44.https://energypedia.info/images/a/af/Report_Performance_Test_of_retained_heat_cooker_%28WonderBag%29_GIZ.pdf. (Accessed 20 June 2020).

Chapter 5: A thermal model of a solar cooker with thermal energy storage using computational fluid dynamics

Overview and abstract

In this chapter, a thermal model of a solar cooker with a thermal energy storage (TES) cooking unit is developed. This chapter consists of work that has been published in ISES Solar World Congress 2023 proceedings ([ISES SWC 2021 Conference Proceedings](#)).

In this paper, a thermal model of a solar cooking pot of a parabolic solar cooker is developed and experimentally validated. The solar cooker is a parabolic dish concentrating cooker. To allow cooking during hours with limited or no sunlight, thermal energy storage material is integrated in the cavities of the cooker. Sunflower oil is used both as thermal storage material and cooking fluid. As this oil is a fluid, computational fluid dynamics (CFD) was used to model the fluid flow and heat transfer within the solar cooker. The model was validated with experiments, and comparison shows that the RMS error between experiments and simulations was around 2 %. The fluctuating solar flux in the experiments was the main reason for this deviation. With the validated model, the physics of the charging of the TES and its interaction with the cooking pot is studied. During the beginning of the process, heat is transferred to the TES by conduction through the bottom and sidewalls. When the TES is heated up, the dominant heat transfer mechanism becomes natural convection, which transports the heat from the TES towards the cooking pot. This natural convection induces a fairly uniform temperature profile in both the TES and the cooking pot. With an incoming solar power of 4750 W m^2 , a steady state temperature of 409.8 K in the TES, and 405.8 K in the cooking pot can be reached within 4 hours. The maximum temperatures are very close to those observed in the experiments (410.9 K for the TES and 406.8 K for the cooking pot), and these temperatures are sufficiently high to cook or bake various food items.

5.1 Introduction

The use of solar cookers eliminates the usage of traditional fuels such as coal or wood and reduces greenhouse gas emissions. The most efficient type of solar cooker in terms of the shortest cooking time and the highest cooking temperature is the parabolic dish solar cooker. Cheap and efficient designs of parabolic dish solar cookers for developing countries have been investigated recently [1, 2]. However, a major drawback of these solar cookers is that they

cannot be used when the sunlight is limited or unavailable, for instance at night or during cloudy periods. To cater for this drawback, thermal energy storage (TES) systems can be integrated with solar cookers so that off-sunshine cooking can be possible [3, 4]. The two main options for TES for solar cookers are indirectly storing the thermal energy in a storage tank using a heat transfer fluid (HTF) or storing the thermal energy directly in the cooking pot. The latter seems to be more economically viable since the use of fluid circulating pumps and pipes is eliminated. Plenty of experimental studies have been performed to optimize the design of these solar cookers, to choose the most appropriate materials for the TES and to study the cooking performance [4, 5, 6].



Figure 5.1: Photograph of the parabolic dish solar cooker with TES system implemented in the cooking pot. Left: parabolic solar collector, right: cooking pot with TES system

Nevertheless, some authors have suggested the use of a numerical model for performance enhancement and optimization. In particular, experimentally validated computational fluid dynamics (CFD) tends to provide detailed insight of the fluid flow and heat transfer mechanisms. Studies on CFD models for cooking processes are rather limited [3, 7, 8, 9], thus it is essential to develop models that can be used to enhance and optimize the performance of solar cooking storage pots that can be used for off-sunshine cooking hours. Therefore, the aim of the paper is to develop such a CFD model for a solar cooking storage pot for performance enhancement and optimization. The novel aspect of the study is the use of vegetable oil as TES, promoting a greener environment and a cheap sustainable cooking solution for developing countries. Few studies have appeared in recent literature on solar cooking pots using vegetable oils, and the results presented will provide invaluable information on the design and heat transfer mechanisms of these cooking pots. After model

validation with experiments, a detailed study on the heat transfer characteristics and performance parameters is done, including the transient charging process of the TES and the steady state temperatures in both the TES and cooking pot.

5.2 Numerical model

The solar cooker used in this work is based on the parabolic dish solar cooker used in the study by Mawire et al. [4]. A photograph of this setup is shown in Figure 5.1. Solar radiation is concentrated by a parabolic dish with a diameter of 1.2m and focussed on the bottom of a cooking pot. In this study, only the cooking pot with TES system is modelled and the parabolic collector is substituted by a solar heat flux input at the bottom of the pot. A schematic view of the pot geometry is shown in Figure 5.2. The cooker is axisymmetric with the x-axis as the symmetry line and the radius is $R_c = 0.16$ m and the height $H_c = 0.11$ m. The cooker consists of two compartments: one for the thermal energy storage (TES) system on the bottom with a height $H = 3.2$ cm and one for the cooking fluid in the middle (called the cooking pot) with a radius $R = 0.125$ m. The walls of the cooker (represented by the thick black lines) are made of stainless steel and have a thickness of 3 mm. For both compartments, sunflower oil is used as the heat transfer fluid. The volume of oil in the TES system is 3.75 liters and for cooking, a mass of 0.5 kg oil is used. As both the TES and cooking pot consist of a mixture of oil and air, Computational Fluid Dynamics (CFD) is used to model the heat transfer and associated natural convection within both volumes. The equations governing the fluid flow are given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \quad (5.1)$$

for the continuity equation and

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = -\nabla p + \nabla \cdot (\mu (\nabla \mathbf{V} + (\nabla \mathbf{V})^T)) - \frac{2}{3} \mu (\nabla \cdot \mathbf{V}) \mathbf{I} + \rho \mathbf{g}, \quad (5.2)$$

for the momentum equation, where ρ (kg m^{-3}) is the density of the fluid, $\mathbf{V}$ (m/s) is the velocity vector, μ ($\text{kg m}^{-1} \text{s}^{-1}$) the dynamic viscosity, p (Pa) the pressure, $\mathbf{I}$ the unity tensor and $\mathbf{g}$ (m s^{-2}) the gravitational acceleration. In each compartment, a mixture of oil and air is present. To capture the free surface between them, the volume of fluid method is used. The material properties of the sunflower oil, like density, heat capacity, viscosity and thermal conductivity are temperature dependent and taken from the studies of Mawire et al. [4], Fasina and Colley [10], Cancaim [11] and Hoffmann et al. [12].

The boundary conditions are estimated from the work of Mawire et al. [4]. At the bottom of the cooker, a constant heat flux of 4950 W m^{-2} is applied, which corresponds to the average solar flux measured in the experiments.

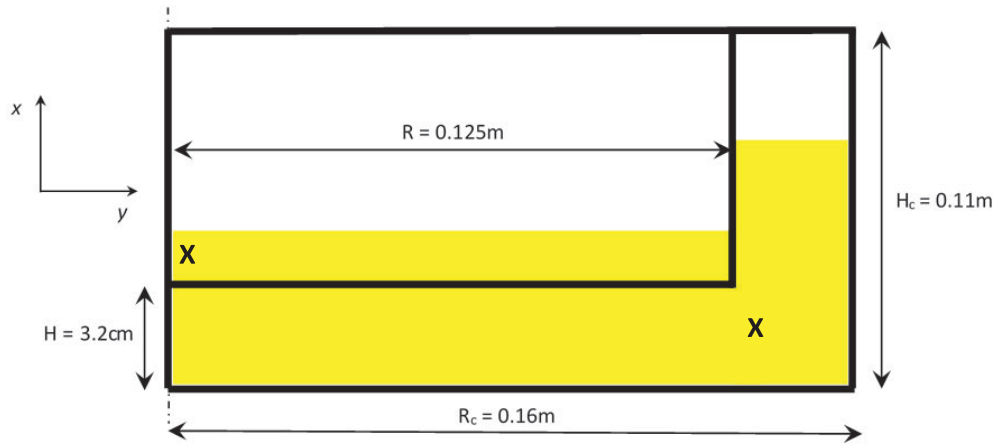


Figure 5.2: Schematic view of the geometry of the solar cooker with a TES system. The X's denote the locations of the temperature measurements for validation

The heat losses through the top and side walls are modelled as a combination of convective and radiation heat fluxes. The corresponding parameters are determined from the experiments, which give an average heat transfer coefficient $h = 26.5 \text{ W m}^{-2} \text{ K}^{-1}$. As the pot was painted black, the emissivity is chosen to be 1.

All governing equations for the gas and liquid phase were solved simultaneously using the pressure-based finite-volume solver ANSYS Fluent. For convective and diffusion terms, a second-order upwind discretization scheme was used. The PRESTO! interpolation scheme was adopted to obtain the pressure at the cell faces. The temporal derivative is discretized using a second order implicit scheme. A grid study using three different mesh sizes, coarse = 48.024 cells, medium = 216.512 cells, and fine = 768.384 cells, shows that the results of the medium mesh are within 0.3 % of the fine mesh and therefore the medium mesh is chosen in this study. To study the influence of the temporal discretization, 3 different timesteps (1, 0.5 and 0.25 s) were adopted and the results of 0.5 s were within 0.5 % of the smallest time step and hence this timestep was chosen in the simulations.

5.3 Experimental validation

The numerical simulations are validated by thermocouple measurements at two locations in the cooker (denoted by the X's in Figure 5.2) in the study of Mawire et al. [4]. Temperature measurements were taken every 30 seconds and the temperature evolution is shown in

Figure 5.3. Initially, the oil heats up very fast reaching a temperature of around 366 K in the TES and 363 K in the pot in the first hour. Afterwards, the temperature increase is slower, and the varying experimental conditions have more influence on the temperature profile. Nevertheless, the CFD simulation is within measurement accuracy of the experiments for all timesteps. The RMS error between experiments and simulations was around 2 % and is mainly attributed to the fluctuating solar flux in the experiments. In the simulations, an average flux was implemented as a boundary condition, which means that transient flux variations, for instance like the temperature decrease found in Figure 5.3 near the end, are not incorporated in the simulations. Hence, the CFD model is considered to be adequate in predicting the transient heat transfer in the cooking pot.

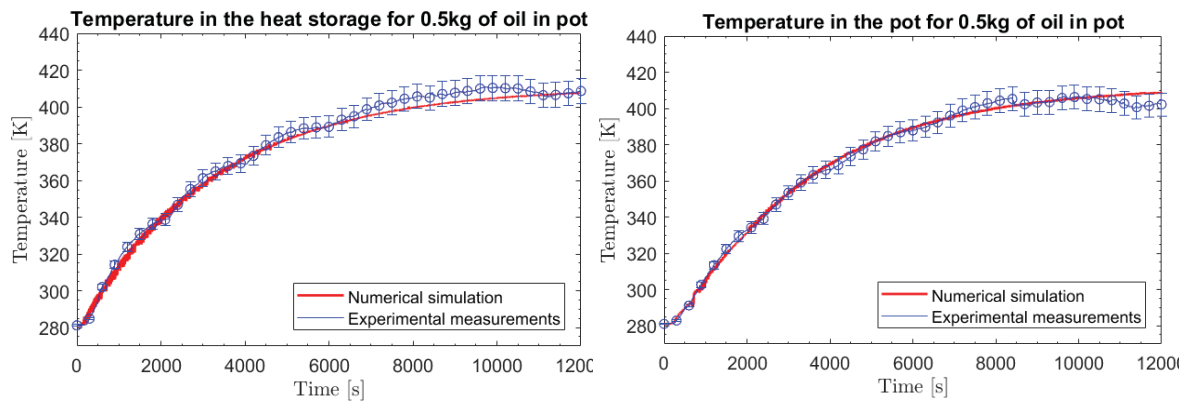


Figure 5.3: Validation of the numerical simulations with the experiments of Mawire et al. [4].

5.4 Heat transfer mechanisms

5.4.1 Transient heating

With the validated CFD model, the different heat transfer mechanisms can be studied in the heating process of the solar cooking pot. Figure 5.4 shows the temperature distribution in the cooker at different time intervals. At the beginning, the bottom of the pot is heated by the solar radiation flux, and this heat is transferred to the oil of the TES by conduction. The density and viscosity of the oil near the bottom decrease which creates buoyancy forces and less viscous resistance, and hence hot oil uses convection to move upwards. This induces Rayleigh-Bénard convection cells (Figure 5.4 a). These cells are the main heat transfer mechanism from the bottom of the cooker to the oil. Their regime is governed by the Rayleigh number, which is given by

$$Ra_L = \frac{g\beta}{\nu\alpha} (T_b - T_u) H^3, \quad (5.3)$$

where β ($6.9858 \times 10^{-4} \text{ K}^{-1}$) is the thermal expansion coefficient [11], ν ($2.4854 \times 10^{-5} \text{ m}^2 \text{ s}^{-2}$) the kinematic viscosity, α ($8.5283 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$) the thermal diffusivity, T_b (330 K) the temperature of the bottom and T_u (281 K) the temperature of the top. The properties of the oil are taken at an initial temperature of 281 K. At the start, the Rayleigh number is equal to 5.1913×10^6 . The Grasshoff number,

$$\text{Ra}_L = \frac{g\beta}{\nu^2} (T_b - T_u) H^3, \quad (5.4)$$

is equal to 1.7814×10^4 , which means that the natural convection is in the turbulent regime. As the oil heats up further, Figure 5.4b, these Rayleigh-Bénard convection cells also appear in the oil in the cooking pot. As the temperature at the bottom of the cooking pot is lower, these convection cells are weaker than the ones in the TES. Due to convection, the oil in both the TES and cooking pot heat up quite uniformly as shown in Figures 5.4(c and d).

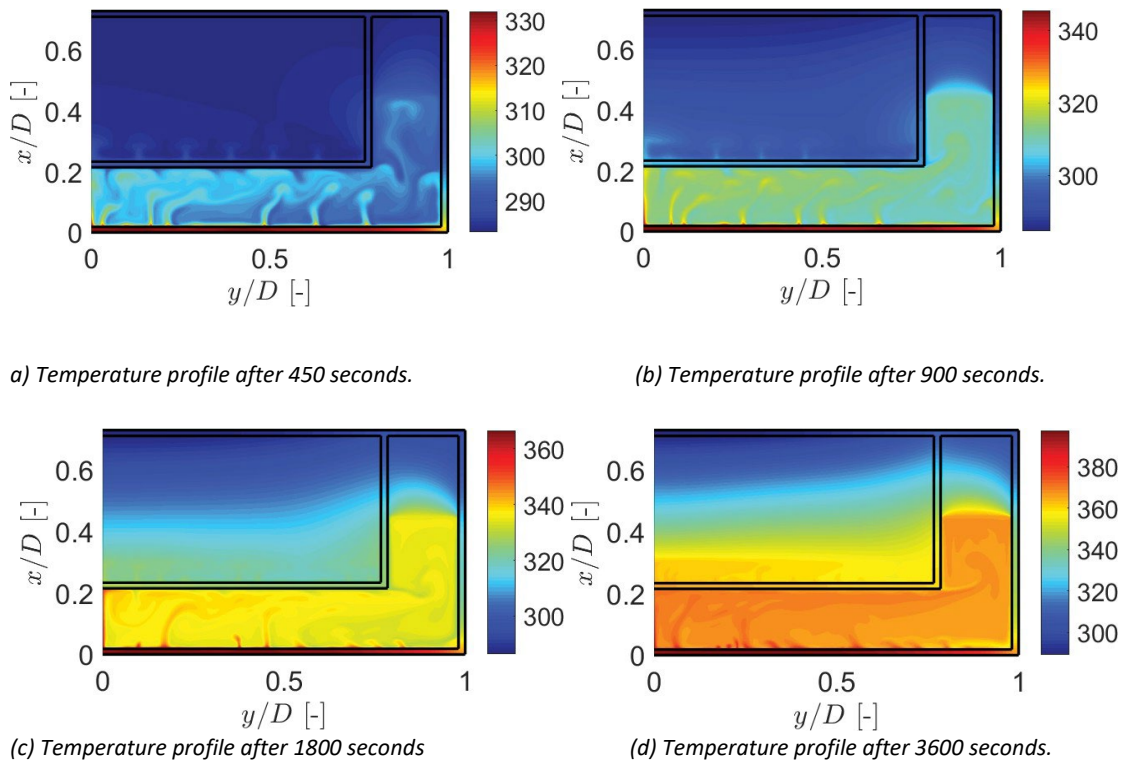


Figure 5.4: Temperature (K) profiles in the cooking pot at different time instants

5.4.2 Steady state

The steady state temperature profile is shown in Figure 5.5, and it is reached after about 4 hours. The average temperature at the bottom of the TES is 427.2 K and at the bottom of the cooking pot, it is 406.5 K. The average oil temperature in the TES is 409.8 K and the temperature distribution is very uniform due to the natural convection. Inside the cooking

pot, the average temperature is 405.8 K, and it is also very uniform. These temperatures are very close to the ones observed in the experiments (410.9 K for the TES and 406.8 K for the cooking pot) and are sufficiently high to cook or bake various food items.

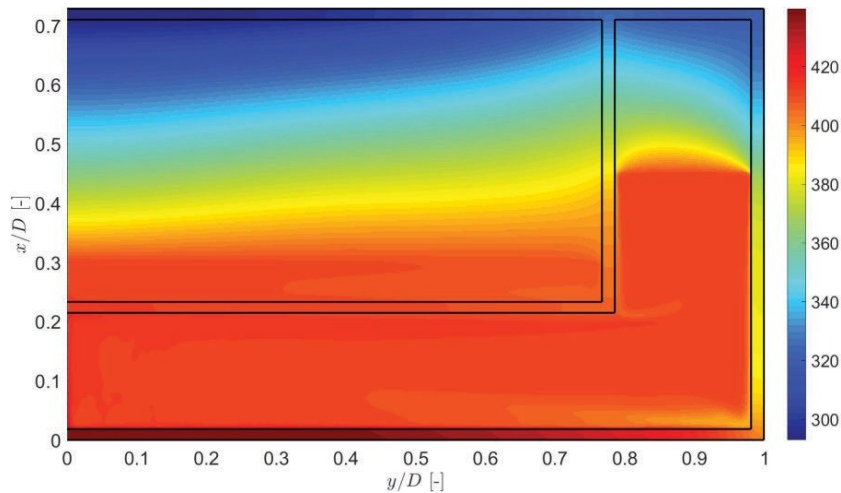


Figure 5.5: Steady state temperature profile

5.5 Conclusion

In this paper, a thermal model of a solar cooking pot has been developed and validated using computational fluid dynamics (CFD). Comparison with experiments shows that the resemblance between the two is within measurement accuracy, and differences are attributed to solar flux variations in the experiments. With the numerical model, the physics in the heating of the cooker is studied. At the beginning, the main heat transfer mechanism is natural convection in the TES system, which creates a fairly uniform temperature profile. After 4 hours, a steady state temperature of 405.8 K in the cooking pot is reached, which is sufficiently high to cook all sorts of food and vegetables. With the newly developed model in this study, solar cooking pots with integrated TES systems can be further optimized towards heat transfer, maximum temperature and warming up time.

Credit author contribution statement

Petros Tegenaw: Methodology, conceptualization, investigation, drafted original manuscript, formal analysis, software development. Katlego Lentswe: Conceptualization, investigation, reviewing and editing, formal analysis and software development. Ashmore Mawire: Reviewing, editing and supervision. Prince Owusu: Reviewing and editing. Maarten Vanierschot: Reviewing, editing and supervision.

Acknowledgements

The Interfaculty Council for Development Cooperation (IRO) of KU Leuven through the scholarship of Petros Tegenaw and VLIRUOS through grant number ZA2020SIN306A101 are gratefully acknowledged for funding this research.

References

- [1] Ahmed, S. M., Al-Amin, M. R., Ahammed, S., Ahmed, F., Saleque, A. M., & Rahman, M. A. (2020). Design, construction and testing of parabolic solar cooker for rural households and refugee camp. *Solar Energy*, 205, 230-240.
- [2] Mohod, A. G., Khandetod, Y. P., & Sengar, S. (2010). Eco-friendly utilization of parabolic concentrating solar cooker for extraction of cashew nut shell oil and household cooking. *International Journal of Sustainable Energy*, 29, 125-132.
- [3] Mbodji, N., & Hajji, A. (2017). Modeling, testing, and parametric analysis of a parabolic solar cooking system with heat storage for indoor cooking. *Energy, Sustainability and Society*, 7, 1-16.
- [4] Mawire, A., Lentswe, K., Owusu, P., Shobo, A., Darkwa, J., Calautit, J., & Worall, M. (2020). Performance comparison of two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking. *Solar Energy*, 208, 1166-1180.
- [5] Vigneswaran, V. S., Kumaresan, G., Sudhakar, P., & Santosh, R. (2017, May). Performance evaluation of solar box cooker assisted with latent heat energy storage system for cooking application. In *IOP Conference Series: Earth and Environmental Science*, 67, 012017.
- [6] Wollele, M. B., & Hassen, A. A. (2019). Design and experimental investigation of solar cooker with thermal energy storage. *AIMS Energy*, 7, 957-970.
- [7] Joshi, J. B., Pandit, A. B., Patel, S. B., Singhal, R. S., Bhide, G. K., Mariwala, K. V., ... & Shinde, Y. H. (2012). Development of efficient designs of cooking systems. II. Computational fluid dynamics and optimization. *Industrial and Engineering Chemistry Research*, 51, 1897-1922.
- [8] Kumaresan, G., Raju, G., Iniyan, S., & Velraj, R. (2015). CFD analysis of flow and geometric parameter for a double walled solar cooking unit. *Applied Mathematical Modelling*, 39, 137-146.
- [9] Abreha, B. G., Mahanta, P., & Trivedi, G. (2019, April). Numerical modeling and simulation of thermal energy storage for solar cooking using Comsol multiphysics software. In *AIP Conference Proceedings*, 2091.
- [10] Fasina, O. O., & Colley, Z. (2008). Viscosity and specific heat of vegetable oils as a function of temperature: 35 C to 180 C. *International Journal of Food Properties*, 11, 738-746.
- [11] Cancaim, C.A., (2012). Prediction of the Thermal Expansion Coefficient of the Sunflower Oil through the Application of Linear Regression Analysis. *Revista Brasileira de Tecnologia Agroindustrial* 6, 852-863.
- [12] Hoffmann, J. F., Vaitilingom, G., Henry, J. F., Chirtoc, M., Olivès, R., Goetz, V., & Py, X. (2018). Temperature dependence of thermophysical and rheological properties of

seven vegetable oils in view of their use as heat transfer fluids in concentrated solar plants. *Solar Energy Materials and Solar Cells*, 178, 129-138.

Chapter 6: An experimental study of a combined solar cooking and thermal energy storage system for domestic applications

Overview and abstract

In this chapter, a combined solar cooker with a sunflower oil storage tank is presented. This chapter consists of work that has been published in SAIP 2021 conference proceedings ([SAIP 2021 Conference Proceedings](#))

The solar cooker consists of a 1.8 m parabolic dish that has an oil circulating copper spiral coil receiver embedded at the bottom of a metallic cooking plate. During sunny periods, cooking and charging of the storage tank take place. 1 L of water is heated up in a cooking pot that is placed on the cooking plate when solar radiation is focused on it, while oil circulating through a spiral coil receiver charges the storage tank. The receiver is connected to a 30 L sunflower oil storage tank that is used to store heat during charging. A DC pump is used to circulate the oil during charging and discharging. Sunflower oil is the heat transfer fluid during the cooking /charging experiments. Storage tank temperatures above 100 °C are achieved in the storage tank. During the discharging cycle, the dish is defocused from the sun, and the pump is reversed to extract heat from the storage tank. 1.0 L of water is heated up with the stored heat, however, heat transfer is poor with the heated water only achieving temperatures just above 40 °C. Preliminary experiments are presented, and the charging process is seen to be more efficient than the discharging process with the charging pump reversed. The average charging and discharging efficiencies are found to be 18 % and 14 %, respectively. The system can be used to cook food as well as provide heat for indirect cooking using insulated bag slow cookers. However, cooking food directly on the cooking plate using the reverse discharging process is not efficient, and heat transfer should be enhanced to make the process more efficient and viable.

6.1 Introduction

Disadvantaged communities and rural areas depend on polluting energy sources such as coal, wood, cow dung and agricultural waste for cooking. Utilizing these harmful energy sources daily increases the chances of health risks, negative environmental impacts, and disrupting the nutritional value of food [1]. To prevent these negative impacts, solar cookers that are affordable and user friendly must be introduced and promoted to disadvantaged

communities that have abundant access to solar energy. Solar cookers are suitable devices that can cook food by converting solar energy to heat energy. They can also be used for pasteurization and sterilisation of food. Researchers, scientists, and engineers have done extensive work on improving solar cooking systems in recent years [2-13]. Solar cooking is becoming a potential cooking option for disadvantaged communities and rural areas that cannot afford and access traditional cooking methods such as electricity or gas [14-16].

The advantages of solar cookers are that they have no running costs, they produce nutritious food, they emit no greenhouse gases, and most of them can be homemade (e.g., box solar cookers). There are three common types of solar cookers which are: (1) concentrating solar cookers, (2) box solar cookers, and (3) panel solar cookers. An appealing solar cooker must be user friendly, locally available at an affordable price, and must be able to reach high cooking temperatures in a short period of time. Concentrating solar cookers are appealing because they cook faster, reach higher cooking temperatures, and can cook multiple individual meals more rapidly than other types of solar cookers [17]. The disadvantage of solar cookers is that they cannot be operated during off-shine periods (e.g., cloudy periods). In order to address this shortcoming, solar cookers must be integrated with thermal energy storage (TES) materials. An ideal thermal energy storage material must be readily available, easy to access and cheap. Sunflower oil is widely used in South Africa for a variety of cooking methods such as frying fast foods like chips. It is locally available in commercial stores, and it is manufactured in South Africa. Although it is mostly utilized for cooking purposes, it can also be used as thermal energy storage (TES) material [18-21].

Limited research has been done on the combination of a concentrating solar cooker and a TES system for the dual purpose of cooking and storing energy [2, 7, 22, 23]. In an attempt to understand the thermal performance of a concentrating solar cooker combined with a TES system, an experimental evaluation of a parabolic dish solar cooker combined with a sunflower oil storage system is presented in this paper. The novelty of the study is that the concentrating solar cooker coupled with a TES system can cook and store energy simultaneously, which is a different design from the other cookers with storage whereby thermal energy has to be stored first before cooking. The stored heat can be used to cook food and other domestic applications during off-shine periods. Combined solar cookers with

storage are an important innovation to mitigate greenhouse gas emissions generated by the use of fossil fuels used for cooking in developing countries.

6.2 Experimental setup and procedure

Figure 6.1 shows a laboratory experimental setup of a solar parabolic dish cooker combined with a TES system. An insulated 30-L cylindrical stainless steel storage tank (1) was filled with sunflower oil. K-type thermocouples with accuracy of ± 2.2 °C were fitted at five different axial positions from the top to the bottom of the storage tank. A DC pump (2) connected to the outlet of the storage tank was used to circulate sunflower oil from the bottom of the storage tank to the receiver and back to the top of the storage tank. The flow rate of sunflower oil was measured with a pulse-type positive displacement flow meter (3) with an accuracy of ± 1 %. The inlet and outlet pipes of the receiver (4) were coupled with thermocouples to measure the inlet and outlet receiver temperatures. The receiver which was a copper spiral coil was placed at the focal region of the solar parabolic dish cooker (5) to allow the heat transfer fluid to be heated thus charging the storage tank. A black cooking pot (6) filled with different test loads (water and sunflower oil of different masses) was placed on top of the receiver during experimental periods.

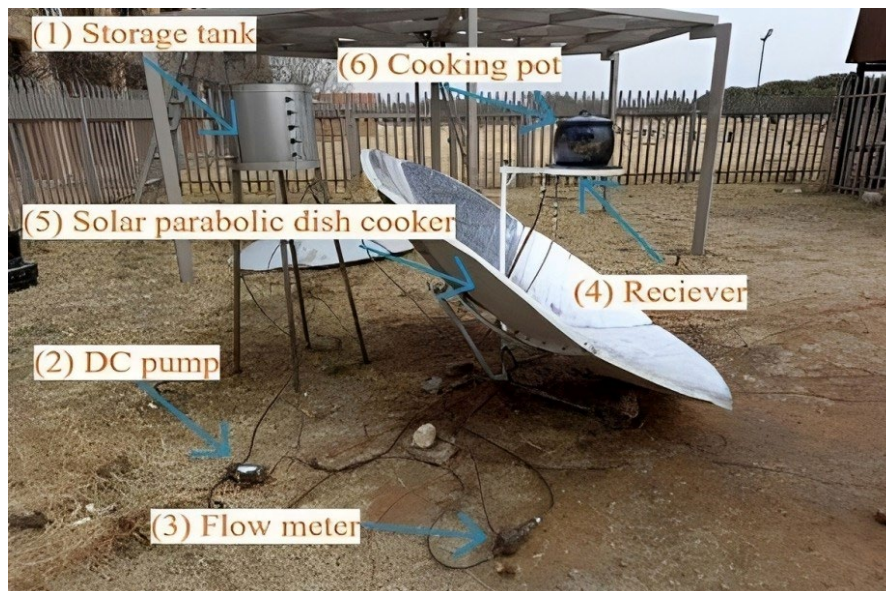
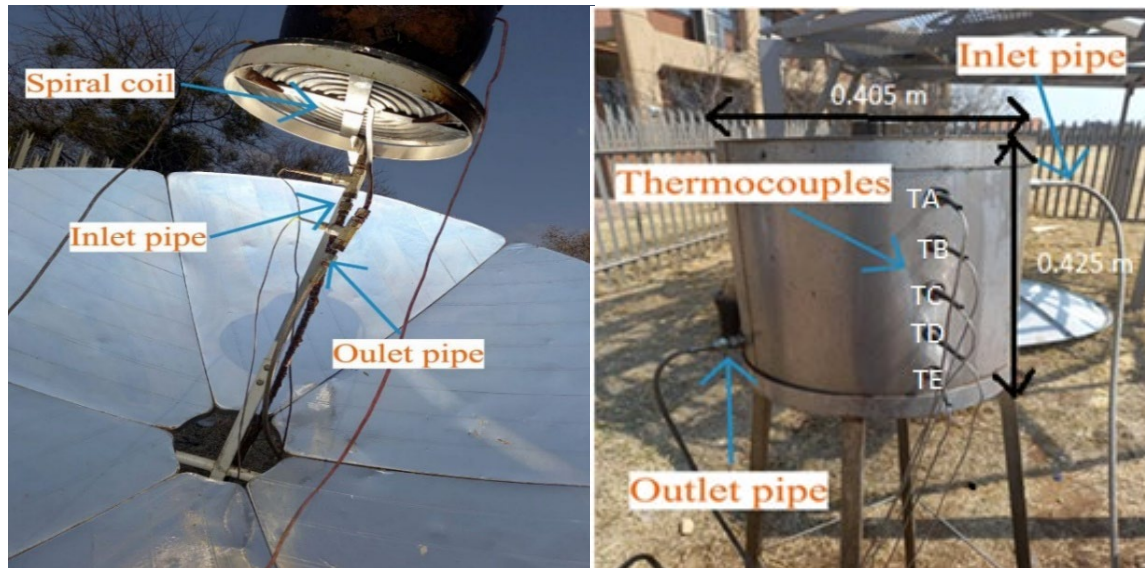


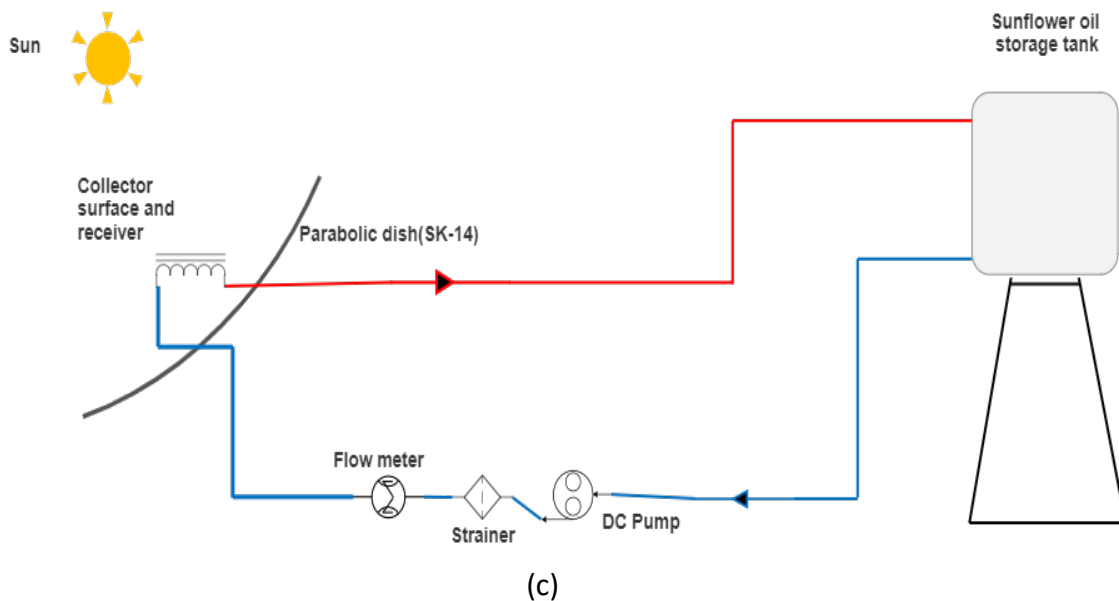
Figure 6.1: Experimental setup of a solar parabolic dish cooker combined with a TES system. (1) Storage tank, (2) DC pump, (3) Flow meter, (4) Receiver, (5) Solar parabolic dish cooker and (6) Cooking pot.

Figure 6.2 shows magnified photographs of the receiver, the storage tank and schematic diagram of the experimental setup. The receiver was composed of a black painted flat stainless-steel plate, and a copper spiral coil which was connected with the inlet and outlet



(a)

(b)



(c)

Figure 6.2: (a) Magnified photographs of the receiver, the (b) storage tank and, (c) schematic diagram of the experimental setup.

pipes to the storage tank. The diameter of the cooking plate was 0.310 m. The receiver was placed at the focal region of the solar parabolic dish cooker, and solar radiation was reflected to it as shown in Figure 6.2 (a). During experiments, Sunflower oil flowed from the bottom of

the storage to the inlet pipe of the receiver which was integrated with a thermocouple. Heat was absorbed from the spiral coil by Sunflower oil, and it exited through the outlet pipe to the top of the storage tank thus charging the storage tank. The storage tank was a cylindrical stainless steel tank fitted with 5 thermocouples (TA-TE) to measure the axial thermal distribution (Figure 6.2(b and c)). The storage tank had a diameter of 0.405 m, and a height of 0.425 m. Thermocouples were placed at axial distances of 0.083 m (TA), 0.150 m (TB), 0.220 m (TC), 0.285 m (TD), and 0.355 m (TE), respectively from the top of the storage tank. The outlet pipe of the tank was connected to a DC pump, and the inlet pipe was connected to the receiver. The insulation of the storage tank was glass wool fitted between the inner vessel and the outer vessel of the storage tank. When conducting experiments, 30 L of Sunflower oil was filled to a level just above the top thermocouple (TA).

6.3 Thermal analysis

The receiver power from the circulating oil in receiver coil to the storage tank is calculated as:

$$Pr = \rho_{av} c_{av} \dot{V} (T_{Rout} - T_{Rin}), \quad (6.1)$$

where ρ_{av} is the average density, C_{av} is the average specific capacity, $\dot{V}$ is the flowrate of the oil during the circulating period, T_{Rout} is the outlet of the receiver and T_{Rin} is the inlet of the receiver. The average density is calculated as:

$$\rho_{av} = 932.37 - 0.66T \quad (6.2)$$

, and the average specific capacity is:

$$c_{av} = 2115 + 3.13T. \quad (6.3)$$

The charging efficiency is calculated by the ratio of the receiver power to the solar collecting power, and it is expressed as:

$$\eta_{ch} = \frac{\rho_{av} c_{av} \dot{V} (T_{Rout} - T_{Rin})}{A_{ap} G}, \quad (6.4)$$

where the aperture area of the parabolic dish is A_{ap} , and G is the direct solar radiation that falls on the parabolic dish collector. The discharging efficiency can be calculated from the ratio of total energy discharged to the total energy stored from the initial (t_i) to the final time (t_f), and this is expressed as:

$$\eta_{dis} = \frac{\sum_{t_i}^{t_f} \rho_{av} c_{av} \dot{V} (T_{Rout} - T_{Rin}) dt_{(dis)}}{\sum_{t_i}^{t_f} \rho_{av} c_{av} \dot{V} (T_{Rout} - T_{Rin}) dt_{(ch)}}. \quad (6.5)$$

6.4 Results and discussion

Figure 6.3 shows the solar radiation, temperature profiles of the receiver, and storage tank temperatures on 17 May 2021 using 1.0 L of water as the load at a flow rate of 2 ml/s. The solar radiation (Figure 6.3(a)) during the solar cooking period (11:00-14:00 h) is seen to be around 840 W/m² for the duration of the experiment except for brief cloudy periods around 13:00 h, 13:15 h and 13:45 h., respectively. The inlet and outlet (T_{Rout} , T_{Rin}) temperatures (Figure 6.3(b)) of the receiver fluctuate up and down during the solar cooking period due to manual tracking of the receiver. T_{Rout} achieves a maximum temperature close to 160 °C, and T_{Rin} achieves a maximum temperature close to 70 °C during the solar cooking period. The temperature of the water in the pot reaches a maximum stagnation temperature of around 75 °C from about 12:30 h-14:00 h during the solar cooking period thus supporting the idea of dual solar cooking and storage of thermal energy. The surface temperature at the cooking plate shows lower temperatures than the receiver outlet temperature since heat is being extracted by the fluid to charge the storage tank. Figure 6.3 (c) shows that the top of the storage tank (TA) achieves a maximum temperature above 120 °C during the solar cooking period with the bottom (TE) achieving a maximum temperature close to 80 °C. A clear stratified distribution of the thermal profiles in the storage tank is seen during charging.

During storage cooking, stored heat in the tank (Figure 6.3(c)) is used to heat up 1 L of water by reversing the direction of the pump and defocusing the solar receiver from the sun. During the 3 h discharging period, the maximum temperature achieved by water in a pot is around 41 °C at 16:00 h which is not sufficient to cook food but enough to warm food. This is because

of the long flow pipes which induced heat losses during discharging since the same charging loop was used for discharging.

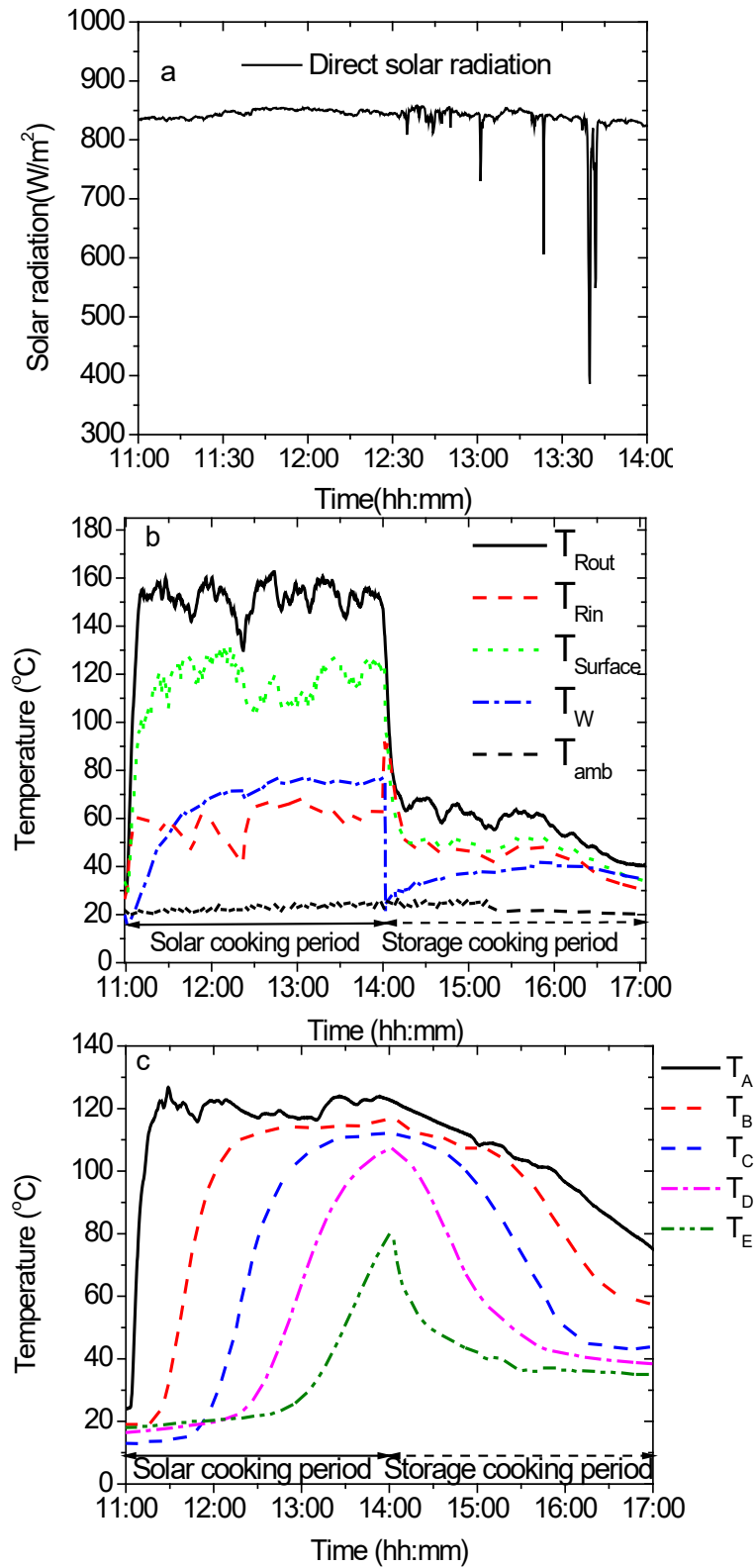


Figure 6.3: (a) Direct solar radiation, (b) temperature profiles of the receiver, and (c) temperature profiles of the storage tank using 1 kg of water as the test load performed on 17 May 2021 using a flow-rate of 2 ml/s.

Introducing shorter discharging loop pipes will definitely improve the heat transfer rate during discharging. Another improvement will be an optimized receiver to extract and discharge heat efficiently. However, the stored heat can be used indirectly to cook food using slow insulated wonderbag cookers, as recently reported in [3]. The storage tank temperature (Figure 6.3(c)) drops from around 120 °C at the top of the storage tank (TA) to around 70 °C during the 3 h discharging period. On the other hand, the bottom storage tank temperature drops from around 80 °C to 35 °C at the end of the discharging period. As already mentioned, this discharging process can be optimized to improve the thermal performance.

Table 6.1 shows a summary of receiver energy efficiencies on different days (17 and 18 May 2021) using a water heating load of 1 kg. During the charging cycle, the average charging efficiencies were approximately 18 % and 17 %, which represents an average receiver power of around 367 W at a collector power of around 2100 W. This lower receiver power is expected since some of the solar energy heats up water used for cooking. This is evidence that the receiver can harness energy that can cook light meals such rice, noodles and chicken. During the discharging cycle, the average discharging efficiency was found to be 14 % and 13 %, respectively, indicating poor heat transfer from the storage tank during discharging, possibly due to the long connecting pipes. This shows that during the discharging cycle, the stored heat was not suitable for cooking purposes, but the stored heat can be used indirectly in storage cooking pots as reported in [3]. Although the performance during discharging is unsatisfactory, heat transfer mechanisms can be employed to make it more economically viable such it can be scaled up to cook food for at least 10 people. In addition to this, future work intends to replace Sunflower oil with water so that the system can cook as well as provide hot water for a variety of domestic applications such as bathing, cooking and washing dishes.

Table 6.1. A comparison of receiver charging and discharging efficiencies on different days using 1.0 kg of water

Date	Average charging efficiency (%)	Average discharging efficiency (%)
17 May 2021	18	14
18 May 2021	17	13

6.5 Conclusion

A combined solar cooker with a Sunflower oil storage tank was investigated experimentally. The solar cooker consisted of a 1.8 m parabolic dish that had an oil circulating copper spiral coil receiver embedded to a metallic cooking plate to charge a 30 L Sunflower oil storage tank. During charging, 1.0 L of water was heated up to around 75 °C in a cooking pot with storage tank temperatures above 100 °C being achieved. During discharging, the heat transfer was poor with the heated water only achieving temperatures just above 40 °C. Preliminary experiments showed that the charging process was more efficient than the discharging process with the charging pump reversed. The system can be used to cook food for a minimum of 3 people in the solar cooking period as well as provide heat for indirect cooking using insulated bag slow cookers. However, cooking food directly on the cooking plate using the reverse discharging process was not efficient, and heat transfer should be enhanced to make the process more efficient and viable.

Credit author contribution statement

Katlego Lentswe: Investigation, conceptualization, drafted original manuscript, reviewing and editing, formal analysis, interpreting the results. Ashmore Mawire: Methodology, reviewing, editing and supervision. Prince Owusu: Investigation, reviewing and editing. Adedamola Shobo: Reviewing, editing and supervision.

Acknowledgement

The authors would like to thank the National Research Funding (NRF) of South Africa for funds to carry out the research under the Incentive Funding for Rated Researchers (IFRR) scheme, Grant Number:127192. Reference: RA181002364433. We acknowledge that opinions, findings and conclusions or recommendations expressed in any publication generated by the NRF supported research are our own, and that the NRF accepts no liability whatsoever in this regard.

References

- [1] Iessa, L., De Vries, Y. A., Swinkels, C. E., Smits, M., & Butijn, C. A. A. (2017). What's cooking? Unverified assumptions, overlooking of local needs and pro-solution biases in the solar cooking literature. *Energy Research & Social Science*, 28, 98-108.
- [2] Omara, A. A., Abuelnuor, A. A., Mohammed, H. A., Habibi, D., & Younis, O. (2020). Improving solar cooker performance using phase change materials: A comprehensive review. *Solar Energy*, 207, 539-563.

- [3] Mawire, A., Lentswe, K., Owusu, P., Shobo, A., Darkwa, J., Calautit, J., & Worall, M. (2020). Performance comparison of two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking. *Solar Energy*, 208, 1166-1180.
- [4] Panwar, N. L., Kaushik, S. C., & Kothari, S. (2012). State of the art of solar cooking: An overview. *Renewable and Sustainable Energy Reviews*, 16, 3776-3785.
- [5] Cuce, E. (2018). Improving thermal power of a cylindrical solar cooker via novel micro/nano porous absorbers: a thermodynamic analysis with experimental validation. *Solar Energy*, 176, 211-219.
- [6] Aramesh, M., Ghalebani, M., Kasaeian, A., Zamani, H., Lorenzini, G., Mahian, O., & Wongwises, S. (2019). A review of recent advances in solar cooking technology. *Renewable Energy*, 140, 419-435.
- [7] Mussard, M., Gueno, A., & Nydal, O. J. (2013). Experimental study of solar cooking using heat storage in comparison with direct heating. *Solar Energy*, 98, 375-383.
- [8] Indora, S., & Kandpal, T. C. (2019). A framework for analyzing impact of potential financial/fiscal incentives for promoting institutional solar cooking in India. *Renewable Energy*, 143, 1531-1543.
- [9] Shukla, S. K., & Khandal, R. K. (2016). Design investigations on solar cooking devices for rural India. *Distributed Generation & Alternative Energy Journal*, 31, 29-65.
- [10] Ayub, H. R., Ambusso, W. J., Manene, F. M., & Nyaanga, D. M. (2021). A review of cooking systems and energy efficiencies. *American Journal of Energy Engineering*, 9, 1-7.
- [11] Arunachala, U. C., & Kundapur, A. (2020). Cost-effective solar cookers: A global review. *Solar Energy*, 207, 903-916.
- [12] Saxena, A., Lath, S., & Tirth, V. (2013). Solar cooking by using PCM as a thermal heat storage. *MIT International Journal of Mechanical Engineering*, 3, 91-95.
- [13] Zalengera, C., Blanchard, R. E., Eames, P. C., Juma, A. M., Chitawo, M. L., & Gondwe, K. T. (2014). Overview of the Malawi energy situation and A PESTLE analysis for sustainable development of renewable energy. *Renewable and Sustainable Energy Reviews*, 38, 335-347.
- [14] Baptista, T. L., Curnow, K., Hiranaga, B. J., Magnus, B. D., & Perry, D. (2003). Solar Household Energy, Incorporated: a market-based strategy for introducing passive solar ovens in Kenya. *Ann Arbor: Michigan Business School*.
- [15] Martínez, N. N., Mäusezahl, D., & Hartinger, S. M. (2020). A cultural perspective on cooking patterns, energy transfer programmes and determinants of liquefied petroleum gas use in the Andean Peru. *Energy for Sustainable Development*, 57, 160-167.
- [16] Kumar, A. (2018). Justice and politics in energy access for education, livelihoods and health: How socio-cultural processes mediate the winners and losers. *Energy Research and Social Science*, 40, 3-13.
- [17] Lahkar, P. J., & Samdarshi, S. K. (2010). A review of the thermal performance parameters of box type solar cookers and identification of their correlations. *Renewable and Sustainable Energy Reviews*, 14, 1615-1621.
- [18] Mawire, A. (2016). Performance of Sunflower Oil as a sensible heat storage medium for domestic applications. *Journal of Energy Storage*, 5, 1-9.
- [19] Sousa, L. A., Zotin, J. L., & Da Silva, V. T. (2012). Hydrotreatment of sunflower oil using supported molybdenum carbide. *Applied Catalysis A: General*, 449, 105-111.

- [20] Echarte, M. M., Puntel, L. A., & Aguirrezabal, L. A. (2013). Assessment of the critical period for the effect of intercepted solar radiation on sunflower oil fatty acid composition. *Field Crops Research*, 149, 213-222.
- [21] Jiao, J., Gai, Q. Y., Fu, Y. J., Zu, Y. G., Luo, M., Wang, W., & Zhao, C. J. (2013). Microwave-assisted ionic liquids pretreatment followed by hydro-distillation for the efficient extraction of essential oil from *Dryopteris fragrans* and evaluation of its antioxidant efficacy in sunflower oil storage. *Journal of Food Engineering*, 117, 477-485.
- [22] Li, Q., Tehrani, S. S. M., & Taylor, R. A. (2017). Techno-economic analysis of a concentrating solar collector with built-in shell and tube latent heat thermal energy storage. *Energy*, 121, 220-237.
- [23] Yadav, V., Kumar, Y., Agrawal, H., & Yadav, A. (2017). Thermal performance evaluation of solar cooker with latent and sensible heat storage unit for evening cooking. *Australian Journal of Mechanical Engineering*, 15, 93-102.

Chapter 7: Charging energetic and exergetic evaluation of a combined solar cooking and thermal energy storage system.

Overview and abstract

This chapter consists of work that has been published in the 11th International Conference on Renewable Energy Research and Applications 2023 ([ICRERA 2023](#)).

Experimental charging energy and exergy results of the thermal performance of a solar cooker combined with a thermal energy storage system are presented. The combined solar cooking and storage system comprises of a parabolic dish which has a diameter of 1.8 m, and it focuses solar radiation onto a receiver consisting of an oil circulating coil and a cooking plate. Sunflower oil is heated while circulating in the coil to charge the storage system as well as simultaneously heating up water in a black stainless-steel pot that is placed on the cooking plate of the receiver. Charging experiments are carried out with four different flowrates (2, 3, 4 and 5 ml/s). The average charging energy rate and the charging efficiency increases with the flowrate, except for the highest flowrate (5 ml/s), due to lower solar radiation conditions during the experimental test. This indicates that environmental conditions affect the performance of the reported system. The average charging exergy rate and exergy efficiency increase with the flowrate, except for the 5 ml/s case.

7.1 Introduction

Solar cooking offers an alternative to polluting fossil fuels for cooking purposes [1]. Different types of solar cookers with and without storage have developed in recent years to mitigate greenhouse gas emissions [2-8]. Thermal energy storage (TES) is particularly useful during low or no sunshine periods like cloudy periods and at night since the stored heat can be used to cook food [9-12]. Most of the reported solar cookers have direct or indirect storage units which are used for off-sunshine cooking after the heat has been stored during sunshine periods. Research on dual/combined systems which can cook and store heat simultaneously for other domestic purposes such as the provision of hot water is rather limited [13-14]. Dual/combined systems are economically more viable since these systems solve two problems at the same time such as simultaneously cooking as well as storing heat that is used for other domestic purposes such as the provision of hot water for bathing, drinking, and cooking.

Limited work on dual-purpose domestic solar thermal systems has been done in recent years which justifies further investigation on the domestic dual-purpose solar thermal system. To fully understand a thermal system from the perspective of the quantity and quality of the energy, energetic thermal performance needs to be complemented with exergetic thermal performance which accounts for irreversibility such as heat loss [14]. To access the viability of a dual-purpose solar thermal system during charging, an experimental investigation of a combined cooking and TES system which can simultaneously cook, and store thermal energy is presented in this paper. A 1.8 m parabolic dish solar cooker with an oil circulating receiver combined with a Sunflower oil storage system is evaluated during charging with four different charging flowrates (2, 3, 4 and 5 ml/s) using 0.5 kg of water as the cooking load. Average energetic and exergetic performance measures during charging are also evaluated with the four different flowrates. The novelty of the study is that the concentrating solar cooker coupled with a TES system can cook and store energy simultaneously which is a different design from other cookers with storage whereby thermal energy must be stored first before cooking. The stored heat can be used to cook food or for other domestic purposes such as space heating and water heating. It is important to state that the same system has been used also to store hot water. This paper only focuses on a sunflower oil as the heat storage system, since Sunflower oil achieves higher temperatures compared to water which can be used for cooking. Combined solar cookers with storage have the potential of being an important innovation to mitigate greenhouse gas emissions generated using fossil fuels used for cooking in developing countries.

7.2 Experimental method and setup

A photograph of the experimental setup is shown in Figure 7.1. A 30-L cylindrical storage tank (1) constructed from stainless steel was insulated with rock wool that had a thickness of 0.005 m and a diameter of approximately 0.03 m. Sunflower oil, the heat transfer fluid and storage medium was filled inside the storage tank. The heat transfer fluid was circulated with a DC pump (2) which was connected from the outlet of the storage tank into the flowmeter (3). The flowmeter (3) was connected to the inlet pipe of the receiver (4). After absorbing solar thermal energy from the receiver, hot sunflower oil charged the storage tank at the top to complete the charging cycle.

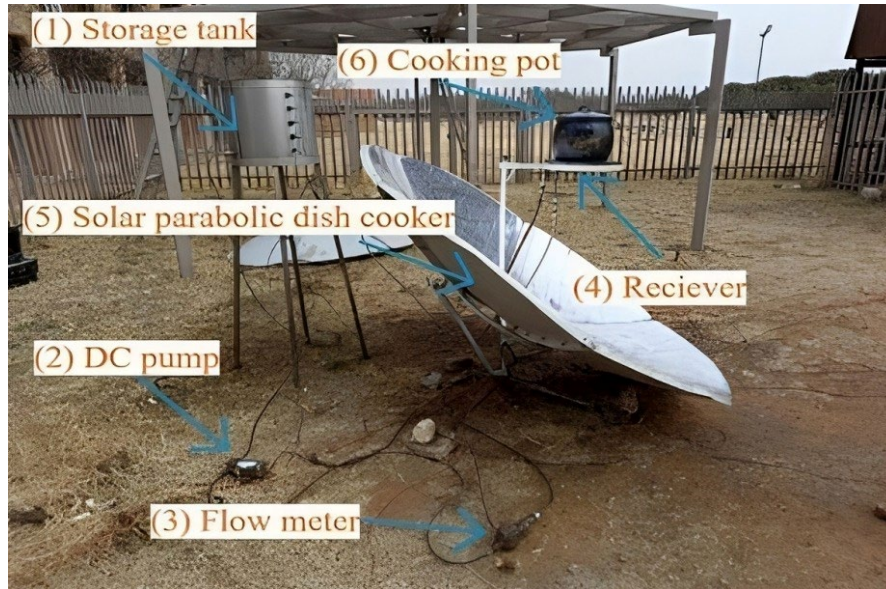


Figure 7.1: A photograph of the experimental setup.

The positive displacement flow meter (3) with an accuracy $\pm 1\%$ was used to measure the flowrate of the heat transfer fluid. Two K-type thermocouples are connected to the inlet pipe and outlet pipes of the receiver to measure their temperatures. The receiver was composed of a circular flat plate surface embedded with spiral copper pipe underneath. Heat from the parabolic dish (5) was transferred to the receiver. The receiver circulated sunflower oil to charge the storage system. The direct solar radiation was measured with a Kipp & Zonen CHP1 pyrheliometer that was placed on a Kipp & Zonen SOLYS 2 Solar tracker. The absorbed heat from the concentrator was used to simultaneously heat sunflower oil circulating through the coil as well as heat the load in a black cooking pot (6) that was placed on top of the receiver. The receiver was designed to operate at the focal region of the parabolic dish. A cooking pot (black) was placed on top of the receiver. Figure 7.2 shows the receiver that was composed of a top flat circular stainless-steel plate which had a thickness and diameter of 0.0807 and 0.013m, respectively. The bottom of the receiver consisted of a copper spiral coil attached to the circular plate to circulate the heat transfer fluid. The receiver was painted black with a high-temperature paint to increase the absorption of solar energy. A photograph of the experimental storage tank is shown in Figure 7.3. The height and diameter of the storage tank were 0.425 m and 0.405 m, respectively. The axial thermal distribution was measured with K-type thermocouples placed along the height of the tank. The axial thermocouples were at

axial distances of 0.080 (TA), 0.150 (TB), 0.220 (TC), 0.290 (TD) and 0.360 m (TE) from the top of the storage.



Figure 7.2: A photograph showing the main components of the receiver.

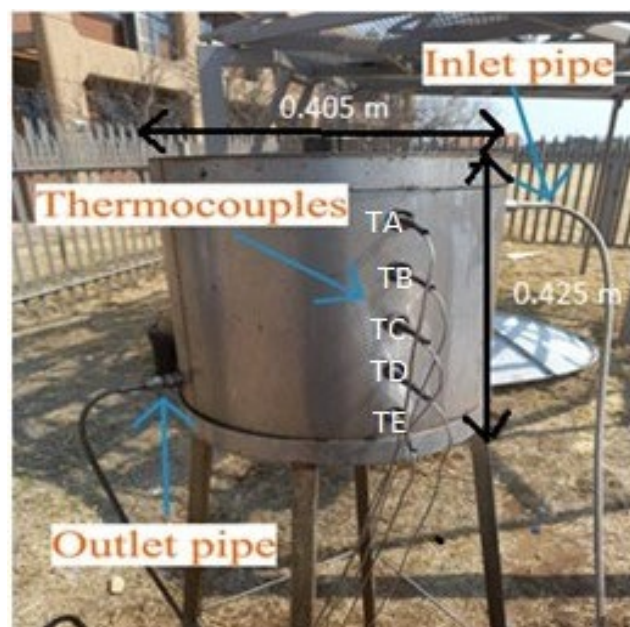


Figure 7.3: The photograph of the storage tank showing dimensions.

Figure 7.4 shows a schematic diagram of the experimental setup. Cold heat transfer fluid flows from the bottom of the storage tank into the inlet of the receiver absorbing solar thermal energy. It then exits as hot fluid from the outlet of the receiver into the top

section of the storage tank. A pot placed at the top of the receiver with a heating load is also heated up during the charging cycle. To investigate the effect of the flowrate on energy and exergy performance, a test load of 0.5 kg was used with 4 different flowrates of 2, 3, 4, and 5 ml/s, respectively.

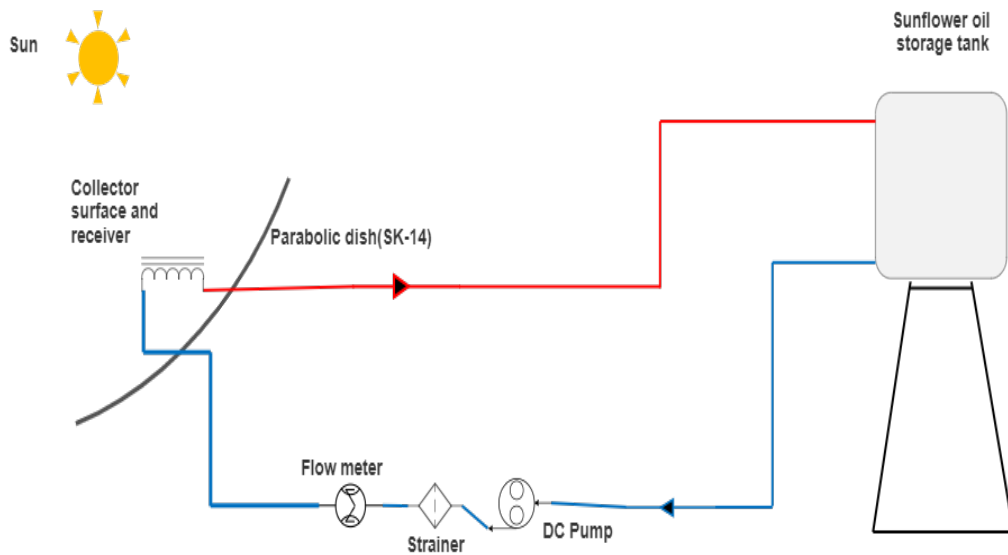


Figure 7.4: A schematic diagram of the experimental setup.

7.3 Thermal analysis

The receiver energy rate being delivered to the circulating heat transfer fluid of the receiver after absorbing solar energy is expressed as:

$$P_R = \rho_{av} c_{av} \dot{V}_{av} (T_{Rout} - T_{Rin}), \quad (7.1)$$

and it depends on ρ_{av} , the average density of the oil and the average specific heat capacity (c_{av}) of the oil. $\dot{V}_{av}$ is the moving average flowrate of circulating Sunflower oil, T_{Rout} is the outlet temperature of the receiver, and T_{Rin} is the inlet temperature of the receiver. The average density of the oil and average density of the oil can be expressed as:

$$\rho_{av} = 932.37 - 0.66T, \quad (7.2)$$

and

$$c_{av} = 2115 + 3.13T. \quad (7.3)$$

The incident solar power on the receiver using the parabolic dish cooker can be expressed as:

$$P_s = \eta_o A_p G_T \quad (7.4)$$

where η_o is the optical efficiency of the parabolic dish, A_p is the aperture area and G_T is direct solar radiation. The average charging energy efficiency of the receiver is defined as the ratio of the receiver energy rate (P_R) divided by the incident solar power (P_s), and it is expressed as follows:

$$\eta_{Ech} = \frac{\rho_{av} c_{av} \dot{V}_{av} (T_{Rout} - T_{Rin})}{\eta_o A_p G_T} \quad (7.5)$$

The quality of energy or the charging exergy rate is calculated with reference to the surrounding temperature, and it is expressed as follows:

$$E_{ChXR} = P_R - \rho_{av} c_{av} \dot{V}_{av} T_{amb} \ln \left(\frac{T_{Rout}}{T_{Rin}} \right), \quad (7.6)$$

where the T_{amb} is the ambient temperature or the surrounding temperature. The quality of energy that is delivered from the sun to the parabolic dish cooker is the solar exergy rate, and it is expressed as:

$$E_{XS} = \eta_o G_T A_p \left[1 + \frac{1}{3} \left(\frac{T_{amb}}{T_s} \right)^4 - \frac{4T_{amb}}{3T_s} \right], \quad (7.7)$$

where T_s is the surface temperature of the sun which is around 5778 KK. The average charging exergy efficiency of the receiver is calculated by dividing the exergy rate over the solar exergy rate, and it is expressed as follows:

$$\eta_{Exch} = \frac{P_R - \rho_{av} c_{av} \dot{V}_{av} T_{amb} \ln \left(\frac{T_{Rout}}{T_{Rin}} \right)}{G_T A_p \left[1 + \frac{1}{3} \left(\frac{T_{amb}}{T_s} \right)^4 - \frac{4T_{amb}}{3T_s} \right]} \quad (7.8)$$

7.4 Results and discussion

The results of solar cooking experiments with 0.5 kg of waterutilizing a charging flowrate of 2 ml/s are shown in Figure 7.5 when the solar cooking period was 3 h (11h00-14h00). Figure 7.5(A) shows a graph of the direct solar radiation and wind speed. The solar radiation is seen to be approximately 850 W/m² for most of the duration of charging. Up and down fluctuations in the wind speed are seen for the duration of the experiment with a maximum wind speed of around 1.7 m/s obtained at 13h30. The temperature profiles of the receiver during charging are shown in Figure 7.5 (B).

T_{Rin} and T_{Rout} are the receiver inlet and temperatures during charging and T_{Surface} is the surface temperature of the cooking plate where the cooking pot is heated. During the solar cooking period, up and down fluctuations of both T_{Rout} and T_{Surface} are seen due to

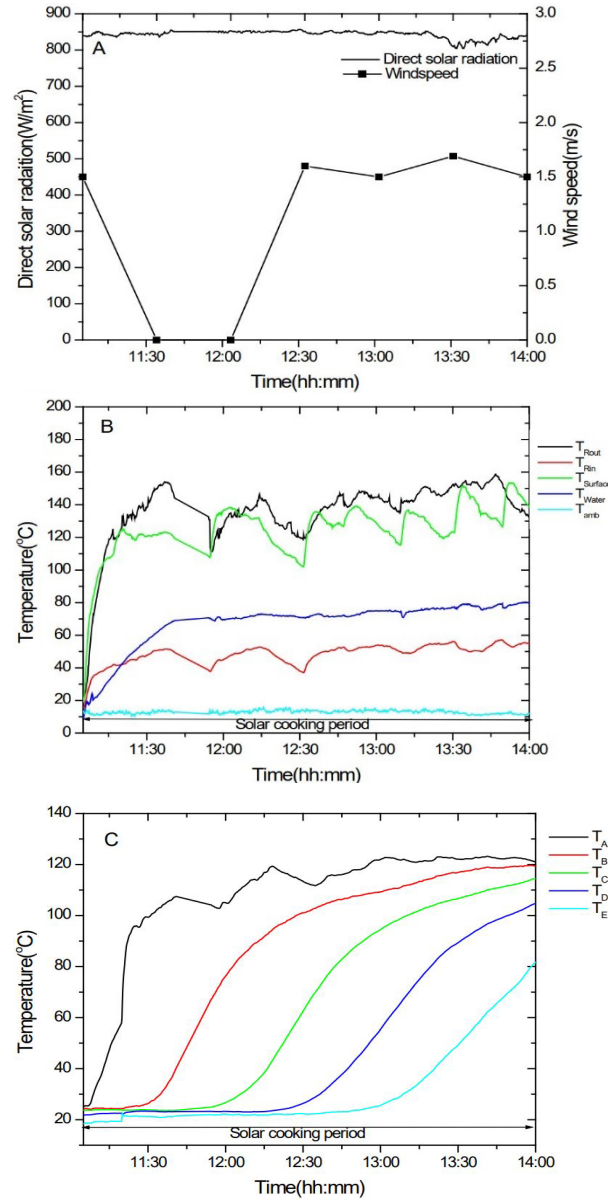


Figure 7.5: Water heating experimental results using a mass of 0.5 kg and a charging flowrate of 2 ml/s. (A) Direct solar radiation and wind speed, (B) the temperature profiles of the solar and (C) the temperature profiles of a storage tank. The experiments were performed on 10 July 2021.

manual tracking of the dish. Manual tracking was used to lower the cost of the system since an automatic tracker would have been expensive and complicated to manufacture due to the articulated flexible piping that was used in the flow loop. Generally, T_{Rout} was higher than T_{Surface} due to the heat from the surface being transferred to the cooking load. The maximum temperature achieved out of the receiver was about 160 °C at the end of charging. The

maximum temperature achieved by water was around 80 °C during the solar cooking period. The receiver inlet temperature fluctuates up and down to a maximum temperature of around 55 °C. Figure 7.5(C) shows the temperature profiles of the storage tank during charging. The temperature at the top of the tank (TA), showed fluctuations during charging as it was connected to the receiver outlet which fluctuated due to manual tracking of the dish. TA achieved a maximum temperature of around 125 °C, at the end of charging, while TE at the bottom of the tank was around 80 °C at the end of charging.

Figure 7.6 shows the results of an experimental charging test with a flowrate of 4 ml/s and a water heating load of 0.5 kg. The average direct solar radiation was around 840 W/m², and the highest wind speed was around 1.5 m/s as depicted in Figure 7.6(A). The receiver temperature profiles are shown in Figure 7.6(B). The same trend is observed with the lower flowrate in Figure 7.5(B). A faster rise in the load temperatures is observed for the higher flowrate of 4ml/s compared to 2 ml/s in Figure 7.5(B) due to increased heat transfer. A maximum nearly constant water temperature of 97 °C is achieved at the end of charging (for around 45 mins) which is suitable for cooking most foods (meat, rice, potatoes etc.) compared to 80 °C for the lower flowrate (only at the end of charging). Figure 7.6(C) shows charging storage tank temperature profiles using 4 ml/s. The higher flowrate reduces thermal stratification in the storage tank compared to the lower flowrate of 2 ml/s as observed by the reduction of the axial temperature difference between adjacent storage levels. The maximum temperature attained at the top of storage (TA) was 138 °C using 4 ml/s. The temperatures in the storage system rise faster with the higher charging flowrate and layering of the thermal profiles at a constant temperature just below 100 °C is observed from around 11h30 to 13h00. This thermal behaviour commences from the top and progresses to the bottom of the tank like a phase change process. This phenomenon can be explained by an increase in the thermal conductivity radially at the higher flowrate reducing axial heat transfer. This phenomenon cannot be explained by phase change because Sunflower oil only stores sensible heat. The same phenomenon has been observed by Mawire et al. [15] and Mawire [16] when evaluating a sunflower oil storage tank with a similar flowrate of 4.2 ml/s. Another occurrence of thermal layering to a lesser extent is seen at higher constant temperatures above 100 °C for the storage tank after 13h00. The lower flowrate does not show this behaviour.

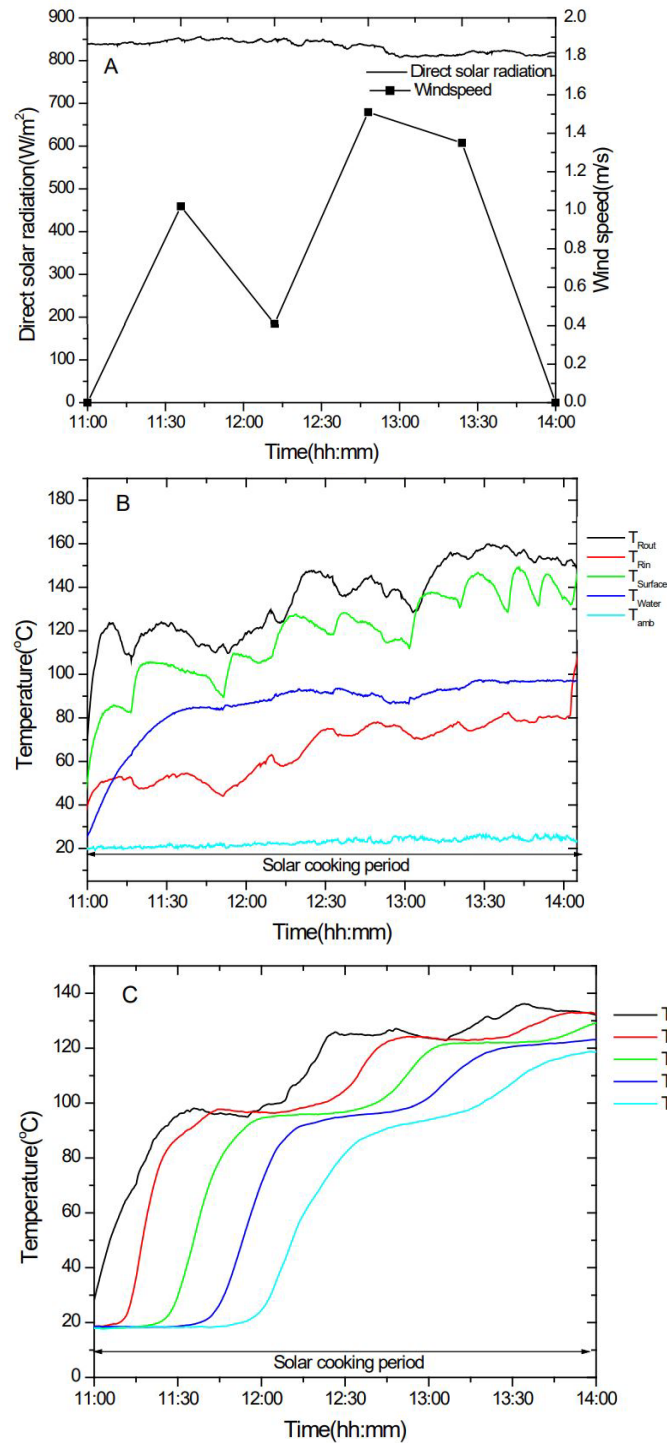


Figure 7.6: Water heating experimental results using a mass of 0.5 kg and a charging flowrate of 4 ml/s. (A) Direct solar radiation and wind speed. (B) the temperature profiles of the solar and (C) the temperature profiles of a storage tank. The experiments were performed on 3 July 2021.

Figure 7.7(A) presents the average direct solar radiation and average wind speed at different flowrates. For the water heating test, the average direct solar radiation varied between 850 - 760 W/m². The test with the highest flowrate for water (5 ml/s) had the lowest average solar

radiation conditions. The average wind speed varied between 0.4-1.9 m/s. There was no general trend in the variation of the wind speed.

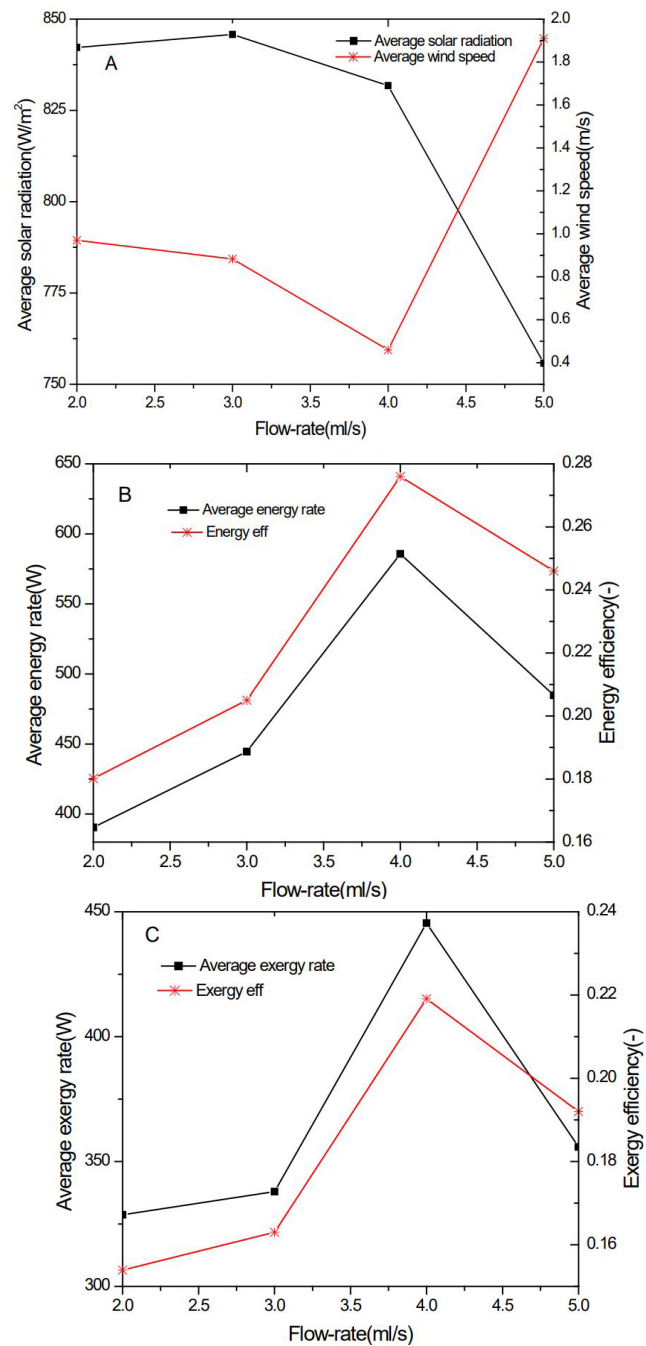


Figure 7.7: Experimental results of the effect of flow rate showing; (A) the average solar radiation and average wind speed, (B) the average energy rate, and energy efficiency and (C) the exergy rate and exergy during the charging cycles.

Figure 7.7(B) shows the average energy rates and energy efficiency variations with respect to the flowrate. The average energy rate was just below 400 W, and the energy rate efficiency was approximately 0.18 when the flowrate was set to 2 ml/s. The average energy rates increase with the flowrate due to the increased heat transfer with higher flowrates. However,

for the 5 ml/s test, the average energy rate drops to 480 W from around 590 W using 4 ml/s possibly due to the lower average direct solar radiation conditions and higher average wind speed conditions during this test. The energy efficiencies are seen to vary similarly to the energy rate values. There is a general increase in the energy efficiency flowrate except for the highest flowrate (5 ml/s) case where the energy efficiency drops from around 0.28 to 0.25 for the increment from 4-5 ml/s. This is attributed to the lower direct average solar radiation conditions for the 5 ml/s case. The average exergy rates vary similarly to the average energy rates with a general increase in the exergy rates with increasing flowrates. For the increase from 4-5 ml/s, the average exergy rate also drops from around 450 W to 360 W due to the lower direct average solar radiation conditions with the 5 ml/s test. Average exergy rates are lower than average energy rates as expected because exergy rates take into consideration irreversibility such as heat loss. The exergy efficiency also increases with the flowrate except for the 5 ml/s case.

7.5 Conclusion

Experimental charging energy and exergy results of the thermal performance of a solar cooker combined with a thermal energy storage system have been presented. The combined solar cooking and storage system consisted of a 1.8 m parabolic dish that focused solar radiation onto a receiver consisting of an oil circulating coil and a cooking plate. Sunflower oil circulating in the coil was heated to charge the storage system while water was simultaneously heated in a black stainless-steel pot that was placed on the cooking plate of the receiver. Four different charging flowrates (2, 3, 4 and 5 ml/s) were used in the experimental tests. The average charging energy rate and the charging efficiency generally increased with an increase in the flowrate except for the highest flowrate (5 ml/s) due to lower average direct solar radiation conditions during the experimental test. This indicated that environmental conditions affected the performance of the combined solar cooking and thermal energy storage system. The average charging exergy rate and the exergy efficiency also increased with the flowrate except for the highest flowrate of 5 ml/s. Future work will investigate different heating loads at the same flowrate. Discharging experiments after charging will also be done to use the stored energy to cook. The experimental system will also be tested with water as the storage medium for the application of providing hot water as well as cooking.

Credit author contribution statement

Katlego Lentswe: Conceptualization, investigation, drafted original manuscript, reviewing and editing, formal analysis and interpreting the results. Ashmore Mawire: Conceptualization, methodology, supervision, reviewing and editing.

Acknowledgement

The authors would like to acknowledge the Instruments Making Department of the North-West University for fabricating the experimental setup, in particular the head of the Department, Mr. Thys Taljaard.

References

- [1] Aramesh, M., Ghalebani, M., Kasaeian, A., Zamani, H., Lorenzini, G., Mahian, O., & Wongwises, S. (2019). A review of recent advances in solar cooking technology. *Renewable Energy*, 140, 419-435.
- [2] Muthusivagami, R. M., Velraj, R., & Sethumadhavan, R. (2010). Solar cookers with and without thermal storage—a review. *Renewable and Sustainable Energy Reviews*, 14, 691-701.
- [3] Rao, A. N., & Subramanyam, S. (2005). Solar cookers—part-II—cooking vessel with central annular cavity. *Solar Energy*, 78, 19-22.
- [4] Coccia, G., Di Nicola, G., Pierantozzi, M., Tomassetti, S., & Aquilanti, A. (2017). Design, manufacturing, and test of a high concentration ratio solar box cooker with multiple reflectors. *Solar Energy*, 155, 781-792.
- [5] Ahmed, S. M., Al-Amin, M. R., Ahammed, S., Ahmed, F., Saleque, A. M., & Rahman, M. A. (2020). Design, construction and testing of parabolic solar cooker for rural households and refugee camp. *Solar Energy*, 205, 230-240.
- [6] Nkhonjera, L., Bello-Ochende, T., John, G., & King'ondeu, C. K. (2017). A review of thermal energy storage designs, heat storage materials and cooking performance of solar cookers with heat storage. *Renewable and Sustainable Energy Reviews*, 75, 157-167.
- [7] Omara, A. A., Abuelnuor, A. A., Mohammed, H. A., Habibi, D., & Younis, O. (2020). Improving solar cooker performance using phase change materials: A comprehensive review. *Solar Energy*, 207, 539-563.
- [8] Sagade, A. A., Samdarshi, S. K., Sagade, N. A., & Panja, P. S. (2021). Enabling open sun cooling method-based estimation of effective concentration factor/ratio for concentrating type solar cookers. *Solar Energy*, 227, 568-576.
- [9] Mawire, A., Lentswe, K., Owusu, P., Shobo, A., Darkwa, J., Calautit, J., & Worall, M. (2020). Performance comparison of two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking. *Solar Energy*, 208, 1166-1180.
- [10] Mussard, M., & Nydal, O. J. (2013). Charging of a heat storage coupled with a low-cost small-scale solar parabolic trough for cooking purposes. *Solar Energy*, 95, 144-154.
- [11] Abu-Hamdeh, N. H., & Alnefaie, K. A. (2019). Assessment of thermal performance of PCM in latent heat storage system for different applications. *Solar Energy*, 177, 317-323.
- [12] Bhawe, A. G., & Kale, C. K. (2020). Development of a thermal storage type solar cooker

for high temperature cooking using solar salt. *Solar Energy Materials and Solar Cells*, 208, 110394.

- [13] Badran, A. A., Yousef, I. A., Joudeh, N. K., Al Hamad, R., Halawa, H., & Hassouneh, H. K. (2010). Portable solar cooker and water heater. *Energy Conversion and Management*, 51, 1605-1609.
- [14] Sagade, A. A., Mawire, A., Belgasim, B., Tawfik, M. A., & Sagade, N. A. (2021). Experimental performance evaluation of a parabolic dish solar geyser using a generalized approach for decentralized applications. *Sustainable Energy Technologies and Assessments*, 47, 101454.
- [15] Mawire, A., Phori, A., & Taole, S. (2014). Performance comparison of thermal energy storage oils for solar cookers during charging. *Applied Thermal Engineering*, 73, 1323-1331.
- [16] Mawire, A. (2016). Performance of Sunflower Oil as a sensible heat storage medium for domestic applications. *Journal of Energy Storage*, 5, 1-9.

Chapter 8: Experimental energetic and exergetic performance of a combined solar cooking and thermal energy storage system

Abstract and overview

In this chapter, a detailed experimental evaluation using energy and exergy analyses of a combined solar cooking and thermal energy storage system during both charging and discharging cycles is presented. This chapter consists of work that has been published in the *Energies* journal ([Energies 15 \(2022\)](#)).

Most solar cookers usually perform a single task of solely cooking food during sunshine hours. Solar cookers coupled with thermal energy storage (TES) material for off-sunshine cooking are usually expensive and require complex engineering designs, and cannot be used for dual purposes, for example, solar water heating and cooking. In this paper, a solar cooker which can perform dual tasks of cooking as well as storing thermal energy to be used during off-sunshine periods is presented. The experimental setup is composed of a parabolic dish, a solar receiver coupled with a flat-plate and an oil circulating copper coil for charging and discharging a storage tank. The objective of the experiment is to evaluate the energy and exergy thermal performance parameters of the dual-purpose system during charging and discharging cycles. The effect of the flowrate and the mass of the load are investigated while using sunflower oil as both the heat transfer fluid and the storage material. Charging and discharging experiments are conducted using four different flowrates (2, 3, 4, 5 ml/s), and with different masses (0.5, 1, 1.5, 2.0 kg) with water and sunflower oil as the test loads. The charging results show that the average energy and exergy rates as well as their corresponding efficiencies increase with an increase in the charging flowrate. On the other hand, the increase in the mass load tends to decrease the average energy and exergy rates, and their corresponding efficiencies. Water generally shows higher charging and discharging energy and exergy efficiencies compared to sunflower oil with an increase in the flowrate. However, for discharging with different loads, sunflower oil shows higher energy and exergy rate values. For discharging results, the correlations between the energy and exergy thermal performance parameters with respect to the flowrate and the heating load are not well

defined possibly due to different initial storage tank temperatures at the onset of discharging and the inefficient discharging process which needs to be optimized in future.

8.1 Introduction

Cooking is a process that is performed daily in all households, and most disadvantaged communities utilize polluting cooking energy resources such as paraffin, wood, cow dung, and coal. These non-clean energy sources emit harmful gases that are lethal to the environment and human beings [1-3]. To reduce harmful gases, an alternative method to cook is to utilize solar cooking. Cooking using the sun is completed by capturing energy from the sun using a solar cooker, and there are several types of solar cookers depending on the temperature range and cooking style [4]. The most common types are (1) solar box cookers, (2) solar panel cookers, and (3) concentrating solar cookers. Each type of solar cooker is designed to accommodate certain types of cooking methods such as frying, boiling, and roasting. One of the major disadvantages of solar cookers is that they cannot operate during non-sunshine periods. A possible solution for this disadvantage is to combine solar cookers with thermal energy storage (TES) systems to utilize the stored heat during non-sunshine hours. The most common TES materials that have been studied over the years are sensible heat storage materials [5-11] and phase change materials (PCMs) [12-16]. Researchers have studied the integration of solar cookers with the TES systems, and evaluated their performances, particularly solar concentrating cookers because of the higher temperatures they achieve which implies a shorter cooking period and the possibility of a wide variety of cooking processes such as frying, baking, and boiling [17].

Thermal energy storage (TES) is the ability of a material to store thermal energy [18]. TES systems combined with solar cookers can be advantageous during non-sunshine periods. In recent years, researchers have extensively investigated solar cookers integrated with TES systems [19-32]. Saxena and Karakilcik evaluated a solar cooker with low- cost storage material [19]. The experimental setup had the objective of evaluating the thermal performance of a solar box cooker with additional reflective mirrors, and low- cost thermal energy storage. Different ratios of a mixture of sand and granular carbon were utilized as the thermal heat storage, and this was placed inside the solar box cooker. Experiments were conducted to determine the optimum ratio of sand and granular carbon. The results obtained showed that the thermal efficiency was 37 %,

and it was concluded that the experimental setup was viable to cook during off-sunshine periods. An experiment on a box-type solar cooker with a sensible heat TES medium was performed by Cuce [20]. A comparison of the thermodynamic behavior of two solar box cookers with and without a sensible heat TES medium was presented. Bayburt stone was used as the TES medium. The energy efficiency of the Bayburt stone cooker was found to be in the range of 21.7-35.3 %, while the energy efficiency of the conventional cooker was lower ranging between 16.9-27.6 %. Vigneswaran et al. [21] presented an evaluation of a solar box cooker assisted with a latent heat energy storage system. The experimental setup was composed of a solar box cooker, a variable number of reflectors, and PCM. The performance of the experimental setup was evaluated by varying the number of reflectors with a latent heat storage medium. Results showed that incorporating the latent heat storage medium in a solar box cooker with an optimum number of four mirrors enabled cooking during off-sunshine periods. Saxena et al. [22] evaluated the performance of a solar box cooker integrated with sensible storage material on the surface of the absorbing plate. Sand and granular carbon were used as sensible heat materials. Cooking experiments were conducted using different food products to establish the performance of sensible heat material during non-sunshine periods. The results obtained showed that there was an improvement in the solar cooking performance when both sensible heat materials were mixed compared to the non-storage case. Milikias et al. [23] evaluated an improved box solar cooker with sensible heat TES. The experimental setup aimed to evaluate the box cookers with and without TES using black stone and concrete as the sensible heat storage materials. Cooking experiments were performed to evaluate the thermal behavior of the two solar box cookers. Experimental results of the evaluation showed that the improved box-type solar cooker took two hours to boil water, whereas the conventional box took three hours.

The selection of PCM for a solar box cooker integrated with a TES unit using a multi-criteria decision-making technique was performed by Anilkumar et al. [24]. The study aimed to select an optimum PCM for a solar box cooker. Multi-criteria decision-making (MCDM) models were utilized to determine efficient PCMs. Erythritol was found to be the recommended PCM with a mass that was less than 6.06 kg. Saxena et al. [25] designed and investigated the thermal performance of a box cooker with flexible solar collector tubes. The objective of the experiment

was to develop a solar box cooker that has a faster response and is uninterrupted during the cooking process. Three TES materials (grain carbon power, paraffin wax, and a mixture of carbon powder and paraffin wax) were inserted in cylindrical copper tubes to determine the thermal parameters of the improved solar box cooker. The results obtained showed that the overall thermal efficiency of the modified solar box cooker was 53.81 % more than that of a conventional solar box cooker. The performance assessment of a box-type solar cooker using *Jatropha* oil as a heat storage material was done by Nébié et al. [26]. Experiments were carried out to evaluate the cooking power and the efficiency of the solar box cooker during off-sunshine periods. The results showed that by integrating *Jatropha* oil with a solar box cooker, the maximum temperature achieved as 157.7 °C. Experimental validation of a high-temperature solar box cooker with a solar-salt-based thermal storage unit was performed by Coccia et al. [27]. The objective of the experiment was to characterize the solar box cooker integrated with a PCM solar-salt-mixture TES unit. The results showed that the PCM improved the load thermal stabilization during off-sunshine periods. Palanikumar et al. [28] investigated a solar box-type cooker with nanocomposite PCMs using flexible thermography. The experiment aimed to compare a solar box cooker with PCM, one with nanoparticles and PCM, and one without nanoparticles PCM. The results showed that the solar box cooker with nanoparticles and PCM was 11% more efficient than the solar box cooker configuration without PCM.

In addition to solar box cookers with TES, recent work has also been done on solar concentrating cookers with TES. A solar parabolic dish cooker with a porous medium was experimentally evaluated by Lokeswaran and Eswaramoorthy [29]. The experiment aimed to build an affordable and energy-efficient parabolic dish cooker. The experimental test was conducted with and without the porous medium. The scrap material receiver was combined with a cooking vessel, and stagnation and water boiling tests were conducted to determine the thermal performance, heat factor, and cooking power. Results showed that the optical efficiency factor with and without porous medium increased to maximum values of 61 % and 57 %, respectively. The stagnation temperature for the utensil with a porous medium receiver was about 8 °C more than the stagnation temperature of the utensil with the plain receiver. Wollele and Hassen [30] presented an experimental evaluation of two solar cookers with storage. In the experiments, two

TES cooking pots were heated at the focal regions of the two parabolic dish cookers. The heat storage materials in the pots were rocks and engine oil. Charging and discharging experiments using water as the test load were performed to determine the maximum temperatures that could be achieved. The maximum temperature achieved was 355 K after 40 min, and this was evidence that the TES pot could cook rice.

An analysis of the thermal performance of solid and liquid energy storage materials in a parabolic dish solar cooker was done by Senthil and Cheralathan [31]. The objective of the experiment was to enhance the thermal performance of a solar cooking pot using different sensible heat storage media. The sensible heat storage media considered were sand, stone pebbles, iron grits, steel balls, coconut oil, sunflower oil, and olive oil. Charging and discharging experiments were performed using the different sensible storage media to determine which storage material was the most efficient. Sunflower oil showed the best thermal performance compared to the other storage media. The performance comparison of two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking was reported by Mawire et al. [32]. The experimental setup was composed of a parabolic dish cooker which was used to reflect the sun rays to the storage pots, and two storage pots that contained sunflower oil and erythritol PCM as the storage materials. Cooking experiments were carried out using different food during sunny periods and off-sunshine to evaluate the performance of the storage pots. During non-sunshine periods, the storage pots were inserted into wonderbag slow-insulated cookers. The results showed that the sunflower oil storage cooking pot cooked faster and had higher temperatures compared to the erythritol PCM storage cooking pot during solar cooking periods. However, during off-sunshine periods, erythritol performed better than sunflower oil.

As presented in the literature review, there has been a limited amount of recent research that has been focused on dual-purpose/combined solar cookers with TES for cooking simultaneously while storing thermal energy for other domestic purposes such as cooking and water heating. This research gap that has been identified needs to be investigated. In this work, a solar cooking system combined with storage was designed and developed for domestic applications in rural communities to perform dual tasks of simultaneously cooking and storing solar thermal energy for usage later. The novelty lies in the fact that solar cooking is possible as well as storing energy

for usage later for other domestic purposes. The system is envisaged to be more cost-effective and versatile than the current solar cooking systems which only are used for the single purpose of cooking food. This paper aims to evaluate the thermal performance of the combined solar cooking and TES system based on thermal performance evaluators from energetic and exergetic perspectives. The stored energy during the solar cooking periods is used for off-sunshine cooking in this paper, although other applications can be investigated such as solar water heating and solar food drying. The results will be useful for the further development of dual-purpose/combined solar cooking systems with thermal energy storage. Very few of these systems have been developed.

8.2 Experimental setup and procedure

A photograph of an experimental setup of a solar parabolic dish cooker combined with a TES tank is shown in Figure 8.1.

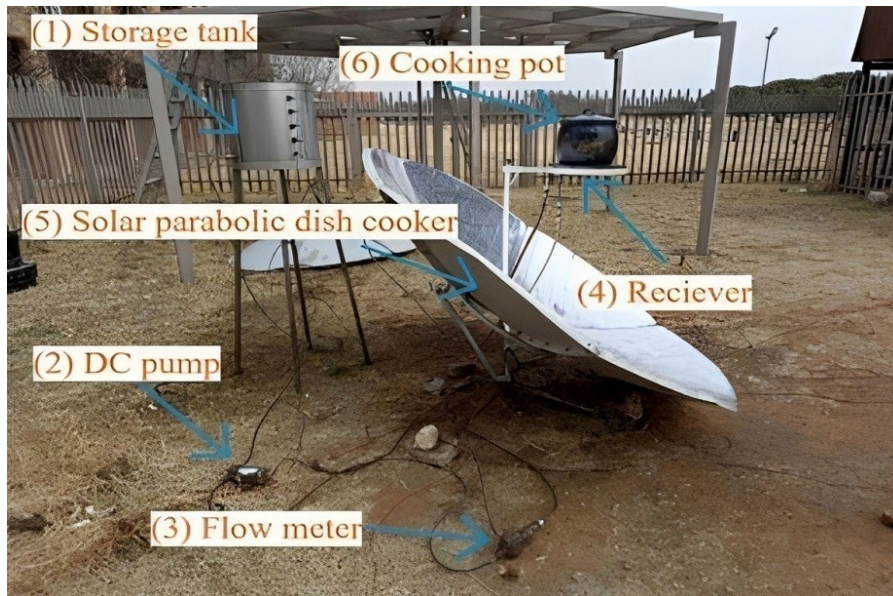


Figure 8.1: An outdoor experimental setup of an SK-14 parabolic dish cooker combined with a TES system. The experimental components that were utilized are (1) a storage tank, (2) DC pump, (3) flow meter, (4) receiver, (5) solar parabolic dish cooker, and (6) a cooking pot.

A 30 L stainless steel storage tank (1) with a diameter of around 0.03 m was filled with sunflower oil. It was insulated with 0.005 m of rock wool, and it was a cylindrical structure. Sunflower oil was also used as the heat transfer fluid (HTF). Five K-type were attached along the height of the storage to measure the axial temperature distribution (TA-TE) as shown in Figure 8.2b.

Circulation of the heat transfer fluid was induced by a DC pump (2) which was connected to the storage tank via a positive displacement flowmeter (3) with an accuracy of $\pm 1\%$. The HTF was heated in a receiver (4) which was connected to the top of the storage tank to charge it after absorbing concentrated solar thermal energy from the parabolic dish solar cooker (5). A copper spiral coil embedded underneath a black-painted circular plate constituted the receiver as shown in Figure 8.2(a). The receiver placed at the focal point of the parabolic dish absorbed concentrated solar thermal radiation from the parabolic dish. A Kipp & Zonen CMP1 pyrliometer measured the direct solar radiation while placed on a Kipp & Zonen SOLYS 2 Solar tracker. Simultaneous heating of the load in a black cooking pot (6), and heating of circulating sunflower oil in the coil was made possible by absorbing the concentrated solar radiation. Different test loads of both sunflower oil and water were poured into the pot and used in the experiments.

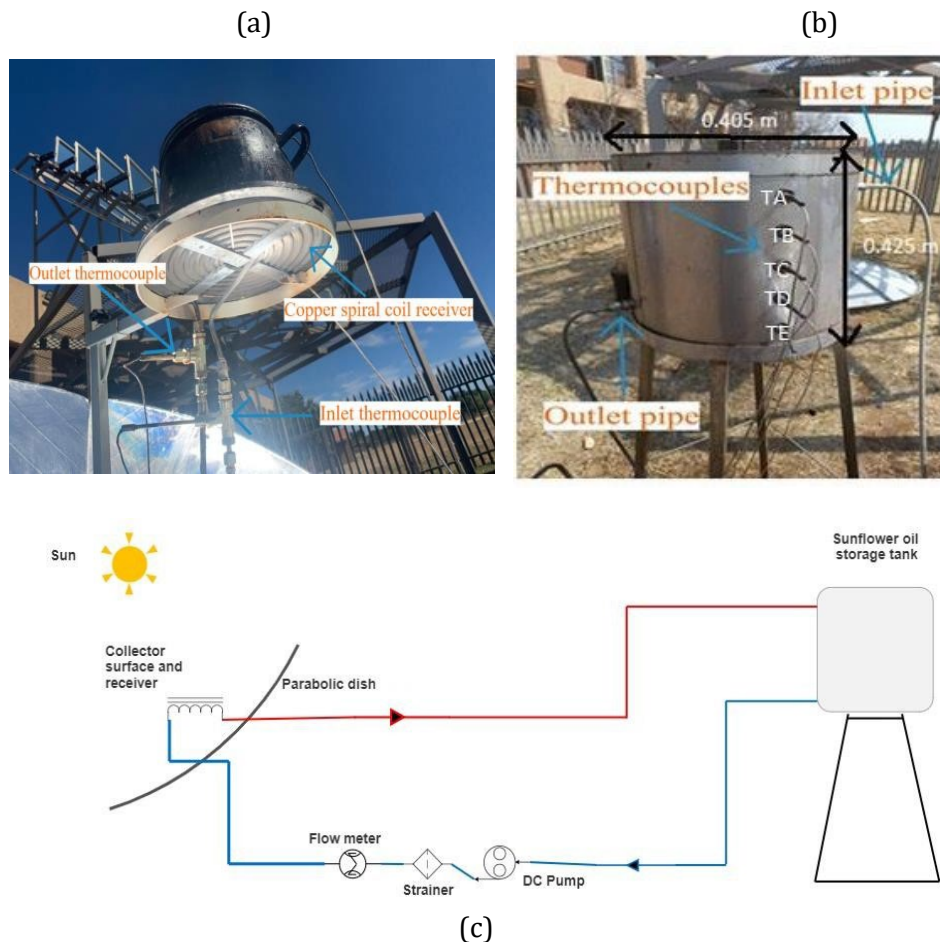


Figure 8.2: Photographs of the (a) receiver, (b) storage tank, and (c) a schematic flow diagram of the experimental setup.

During the discharging period, the solar parabolic dish cooker was defocused, and the DC pump was configured to extract the heated fluid from the top of the storage tank. The hot oil extracted from the top storage tank flowed into the outlet pipe of the receiver to deliver heat to the spiral coil that is attached to a circular cooking plate. A black cooking pot filled with the test load was placed on top of the black plate absorber to heat the load. Sunflower oil flowed from the outlet pipe of the copper spiral coil to the inlet pipe of the storage tank to charge the storage tank. Photographs of the receiver (a), the storage tank with its dimensions (b), and a schematic diagram of the experimental setup (c) are shown in Figure 8.2. The receiver at the focal region of the parabolic dish heated circulating sunflower oil to charge the storage tank as well as the load contained in black cooking pot placed on it are shown in Figure 8.2(a). The top of the receiver was a flat circular stainless-steel plate with a diameter of 0.013 m and a thickness of 0.008 m. A copper spiral coil was attached at the bottom of the plate for circulating the HTF to charge the storage tank. The whole receiver was painted black with a specialized high-temperature resistance paint to increase its absorbance of solar radiation.

The dimensions of the storage tank and thermocouples to measure the temperatures at 5 axial levels (TA-TE, TA = 0.080 m, TB = 0.150 m, TC = 0.220 m, TD = 0.290 m and TE = 0.360 m from the top of the storage) are shown in Figure 8.2(b). The storage tank has a height of 0.425 m and a diameter of 0.405 m. A schematic diagram of the experimental setup is shown in Figure 8.2(c). The DC pump circulated cold sunflower oil at the bottom of the storage system to the inlet of the receiver. Circulating sunflower oil absorbed concentrated solar radiation to come out hot at the outlet of the receiver thus charging up the storage system. A pot placed at the top of the receiver with a heating load was also simultaneously heated up during charging. The flowmeter measured the flow rate during the charging cycle, and a strainer blocked solid residues from entering the flowmeter. During discharging, the pump was reversed to extract heat from the storage system, while the receiver was defocused. The stored thermal energy was used to heat the cooking pot with the test load. Test loads of 0.5, 1.0, 1.5, and 2.0 kg were used in the black cooking pot during charging and discharging cycles to investigate the effect of the mass on the energy and exergy performance at a flow rate of 2 mL/s. Water and sunflower oil were used as the loads for each test mass. A constant test load of 0.5 kg was used while using 4 different flow rates (2.0, 3.0, 4.0,

and 5.0 mL/s) to evaluate the effect of the flow rate on the energetic and exergetic performance. Each test was conducted separately with water and sunflower oil as the heating loads.

8.3 Thermal performance parameters

8.3.1 Energy analysis

The energy-based thermal performance parameters during the charging and discharging cycles are presented in this section. The receiver power or energy rate of the circulating fluid is given as [33]:

$$P_R = \rho_{av} c_{av} \dot{V}_{av} (T_{Rout} - T_{Rin}), \quad (8.1)$$

where ρ_{av} is the average density of sunflower oil circulating through the receiver, c_{av} is the average specific heat capacity, $\dot{V}_{av}$ is the average flow rate of sunflower oil, T_{Rout} is the outlet temperature of sunflower oil exiting the receiver, and T_{Rin} is the inlet temperature of sunflower oil entering the receiver. The average density and specific heat capacity of sunflower oil are temperature dependent, and vary with temperature (T) as [34,35]:

$$\rho_{av} = 932.37 - 0.66T, \quad (8.2)$$

and

$$c_{av} = 2115 + 3.13T. \quad (8.3)$$

The parabolic dish solar power (P_s) concentrated at the receiver is expressed as [33]:

$$P_s = \eta_o A_p G_T, \quad (8.4)$$

where η_o is the optical efficiency of the dish, A_p is the aperture area of the parabolic dish and G_T is the amount of direct solar radiation from the sun. The average charging energy efficiency (η_{Ech}) is defined as the ratio of receiver energy rate (P_R) to the solar energy power (P_s), and it is expressed as [33]:

$$\eta_{Ech} = \frac{P_R}{P_s} = \frac{\rho_{av} c_{av} \dot{V}_{av} (T_{Rout} - T_{Rin})}{\eta_o A_p G_T}. \quad (8.5)$$

The discharging energy efficiency of the storage tank can be defined as the ratio of the total energy discharged from the storage tank to the total energy stored during charging, and it is expressed as [34]:

$$\eta_{Ech} = \frac{\sum_{ti}^{tf} \rho_{av} c_{av} \dot{V}_{av} (T_{Rout} - T_{Rin}) dt_{(dis)}}{\sum_{ti}^{tf} \rho_{av} c_{av} \dot{V}_{av} (T_{Rout} - T_{Rin}) dt_{(ch)}}. \quad (8.6)$$

where ti and tf are the initial and final times during charging (ch) and discharging (dis) cycles.

8.3.2 Exergy analysis

The charging exergy rate (E_{ChXR}) with reference to the ambient temperature is expressed as [33]:

$$E_{ChXR} = P_R - \rho_{av} c_{av} \dot{V}_{av} T_{amb} \ln \left(\frac{T_{Rout}}{T_{Rin}} \right), \quad (8.7)$$

where the T_{amb} is the ambient temperature. The quality of energy delivered to the parabolic dish and the receiver is the solar exergy rate expressed by the Petela expression multiplied by the solar power [33,36,37] giving:

$$E_{XS} = \eta_o G_T A_P \left[1 + \frac{1}{3} \left(\frac{T_{amb}}{T_S} \right)^4 - \frac{4T_{amb}}{3T_S} \right], \quad (8.8)$$

where T_S the surface temperature on the sun is around 5778 K. η_{Exch} the exergy efficiency during charging is determined by dividing the charging exergy rate and the solar exergy rate giving the expression [33,37]:

$$\eta_{Exch} = \frac{P_R - \rho_{av} c_{av} \dot{V}_{av} T_{amb} \ln \left(\frac{T_{Rout}}{T_{Rin}} \right)}{\eta_o G_T A_P \left[1 + \frac{1}{3} \left(\frac{T_{amb}}{T_S} \right)^4 - \frac{4T_{amb}}{3T_S} \right]}. \quad (8.9)$$

The discharging exergy efficiency (η_{Exdis}) is calculated as the ratio of the total discharging exergy (dis) to the total charging exergy (ch), and it is expressed as [34]:

$$\eta_{Exch} = \frac{\sum_{ti}^{tf} P_R - \rho_{av} c_{av} \dot{V}_{av} T_{amb} \ln\left(\frac{T_{Rout}}{T_{Rin}}\right) dt_{(dis)}}{\sum_{ti}^{tf} P_R - \rho_{av} c_{av} \dot{V}_{av} T_{amb} \ln\left(\frac{T_{Rout}}{T_{Rin}}\right) dt_{(ch)}}. \quad (8.10)$$

8.3.3 Experimental uncertainty

The uncertainty analysis method [34] based on the propagation of errors was used to estimate the uncertainties in the derived thermal performance parameters such as the energy and exergy rates during charging and discharging. For example, the uncertainty in the receiver energy rate is given as [34]:

$$\delta P_R = \sqrt{\left(\frac{\delta P_R}{\partial \rho_{av}}\right)^2 (\partial \rho_{av})^2 + \left(\frac{\delta P_R}{\partial c_{av}}\right)^2 (\partial c_{av})^2 + \left(\frac{\delta P_R}{\partial \dot{V}_{av}}\right)^2 (\partial \dot{V}_{av})^2 + \left(\frac{\delta P_R}{\partial T_{Rout}}\right)^2 (\partial T_{Rout})^2 + \left(\frac{\delta P_R}{\partial T_{Rin}}\right)^2 (\partial T_{Rin})^2}, \quad (8.11)$$

where $\delta \rho_{av} = \pm 0.069 \text{ g/cm}^3$, $\delta c_{av} = \pm 0.069 \text{ J/gK}$, $\delta \dot{V}_{av} = \pm 0.1 \text{ ml/s}$, δT_{Rin} and δT_{Rout} are $\pm 2^\circ\text{C}$. Other uncertainties in other derived quantities were determined similarly, and the uncertainties varied between $\pm 1\text{-}5\%$ of the average values which was deemed not too high and acceptable within the limits of the experimental measurement equipment.

8.4 Results

Solar and storage cooking experimental results using 0.5 kg of water and oil utilizing a flow rate of 2 mL/s are shown in Figure 8.3. The solar and storage cooking periods were both 3h, 11h00–14h00, and 14h00–17h00, respectively. Solar radiation was only considered for the solar cooking period, and during the storage cooking period, the parabolic dish cooker was defocused because it did not affect heat retention. The plots of Figure 8.3(A1) present wind speed and solar radiation profiles using water as the load charging with a flow rate of 2 mL/s. For most of the duration of charging, the solar radiation is around 850 W/m^2 , while the wind speed shows a maximum value close to 1.7 m/s at 13h30. The wind is seen to fluctuate up and down during the charging process. Figure 8.3(A2) shows the solar radiation and wind speed behavior during the solar cooking period when oil was used as a test load. The solar radiation was approximately 770 W/m^2 from 11h00 to 13h00, and it decreased to around 740 W/m^2 from 13h00–14h00. For the oil test, the solar radiation was lower as compared to the water test. The wind speed for the oil test also fluctuated up and down as seen with the water test load. However, the wind speed values were

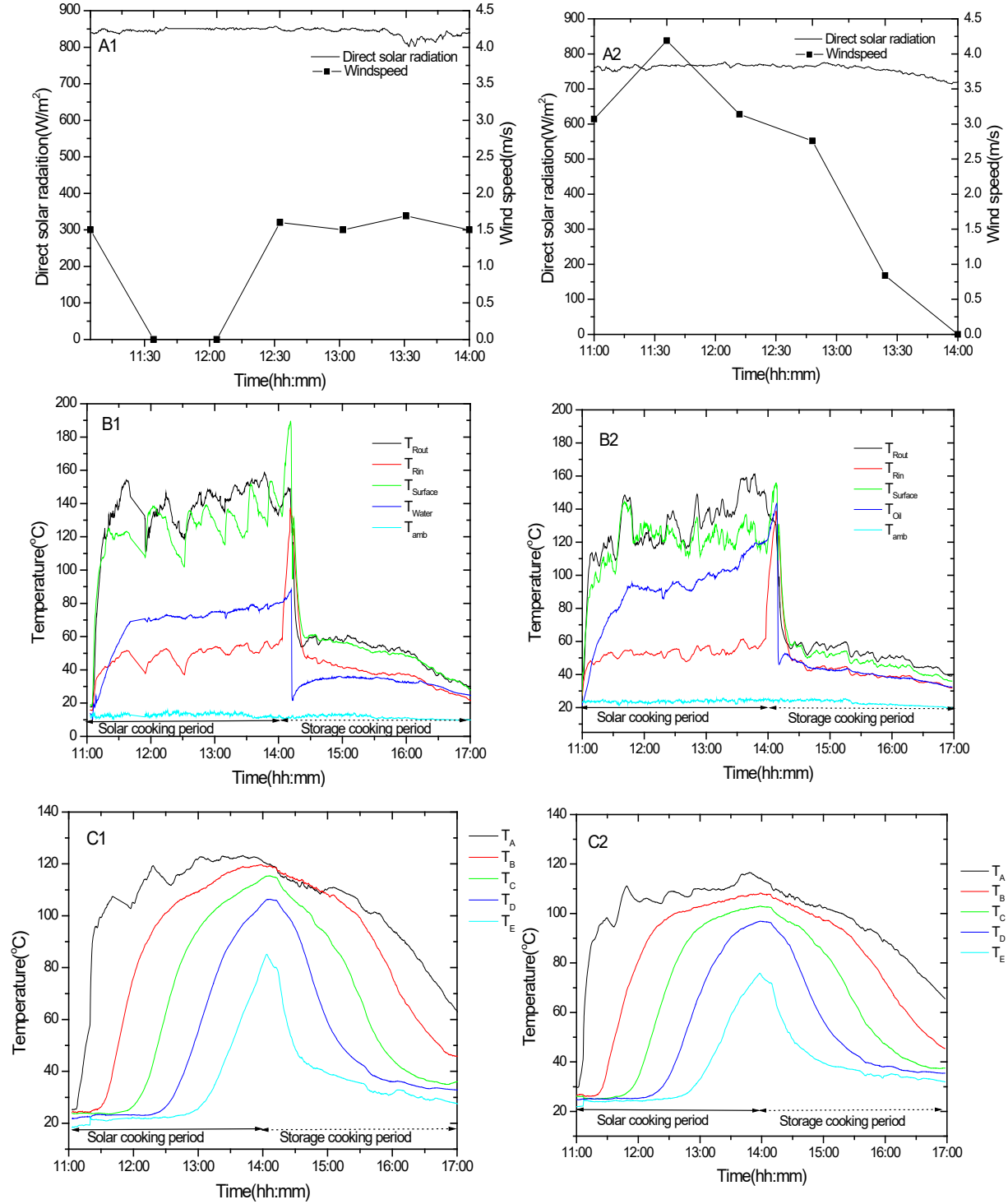


Figure 8.3: Experimental results of two test loads (water and sunflower oil) for a load of 0.5 kg utilizing a flow rate of 2.0 mL/s. (A) Direct solar radiation and wind speed (A1—water, A2—sunflower oil), (B) the temperature profiles of the solar receiver (B1—water, B2—sunflower oil), and (C) the temperature profiles of a storage tank (C1—water, C2—sunflower oil). Experimental dates were 10 July 2021 and 13 July 2021 for water and oil tests, respectively.

greater compared to the water test, with a maximum value of approximately 4.2 m/s being achieved at 11h30.

Figure 8.3(B1, B2) presents the receiver temperature profiles for both test loads (water and sunflower oil) during charging and discharging. The inlet and outlet receiver temperatures are given as T_{Rin} and T_{Rout} , respectively, while the cooking temperature at the surface of the plate is T_{Surface} . Both the surface and receiver temperatures during the charging process (solar cooking) for both loads fluctuate up and down due to manual tracking of the dish. The use of manual tracking lowered the cost of the system since automatic tracking was deemed rather expensive and complicated because of the articulated flexible piping used in the flow loop. Surface plate temperatures were in general lower than the receiver outlet temperatures due to the transfer of heat from the cooking plate to the heated load. For water as a test load, the outlet receiver temperature was around 160 °C, whereas the surface temperature was around 190 °C at the end of charging. This was due to not defocusing the receiver immediately before commencing the discharging process. Water achieved a maximum temperature close to 90 °C at the end of the solar cooking process. The receiver inlet temperature fluctuated up and down to a maximum of around 55 °C except when discharging was about to start where it rose sharply because of not defocusing the receiver. Using oil as the test load, the same fluctuation of the receiver and surface temperatures are seen due to the manual tracking of the parabolic dish solar cooker. However, the maximum receiver inlet and outlet temperatures achieved were comparable to the water test regardless of higher ambient wind speed and lower solar radiation conditions. The higher wind speed conditions for the oil test only marginally reduce the receiver temperatures. Possibly due to the low thermal mass of oil as the cooking load, higher temperatures were seen with oil as compared to water as the load. The oil cooking pot achieved a maximum temperature of around 120 °C. The effect of not immediately defocusing the receiver before discharging is also seen during the heating of oil where the temperatures rose sharply at the end of the charging cycle. For the discharging cycle, both heating loads show a drop in the receiver temperatures as the stored energy is used to heat the loads. For water, the temperature rises to a maximum of around 35 °C, whereas the oil drops from about 50 °C to just above 30 °C at the end of the discharging period. This shows ineffective heat transfer during the discharging period probably

because of the long connecting pipes that were used in the experimental setup, since the same charging and discharging flow loop was used to cut down on costs. These long pipes resulted in poor heat transfer due to large exergy losses induced by heat losses to the environment. A more effective way to use the stored heat is directly transferring the stored energy to a storage cooking pot placed in an insulated slow cooker as recently reported by Mawire et al. [32]. Another possibility is to use shorter pipes for the discharging loop and enhance heat transfer at the plate so that acceptable cooking temperatures can be attained. Storage tank temperature profiles for the whole charging and discharging cycles are shown in Figure 8.3(C1, C2). The two thermal profiles for both heating loads are almost comparable and show similar thermal behavior. Fluctuations such as the receiver outlet temperature are seen with the top storage temperature (TA) during charging since the top of the storage tank was connected to the outlet of the receiver. Manual tracking seemed to affect the top of the storage tank. Water as a test load achieved a maximum temperature of around 125 °C at the top of the storage tank while sunflower oil achieved a maximum of around 118 °C. This is possibly due to the higher charging solar radiation conditions for the water load. Additionally, slightly higher temperatures are seen in the storage tank for the water load because of the higher solar radiation. The discharging cycle shows higher temperature drops in the storage tank with water compared to oil. This suggests that stored energy is utilized more effectively when using water as the discharging load compared to oil. This is supported by plots B1 and B2 of Figure 8.3 which show a temperature rise for water as a load compared to a continual temperature drop with oil as the heating load. Stratification is visible at the beginning of the charging and discharging period for both heating loads. The degree of thermal stratification reduces as charging and discharging progress. Figure 8.4(A1, A2) shows direct solar radiation and wind speed profiles for experiments performed on 3 July 2021 and 4 July 2021 using a flow rate of 4.0 mL/s using 0.5 kg of water and oil as the heating loads, respectively. The average solar radiation for both tests was comparable. The average solar radiation conditions for the water and oil loads of around 840 W/m² and 830 W/m², respectively, were comparable. The wind speeds were significantly different during the experimental tests. For oil as the load, 5.8 m/s was the highest wind speed compared to 2.0 m/s for water as the test load. Lower wind speed conditions were seen with water as the heating load directly implying

lower heat losses for the water test. These ambient wind conditions cannot be controlled since they change daily as already presented in Figure 8.3(A1, A2).

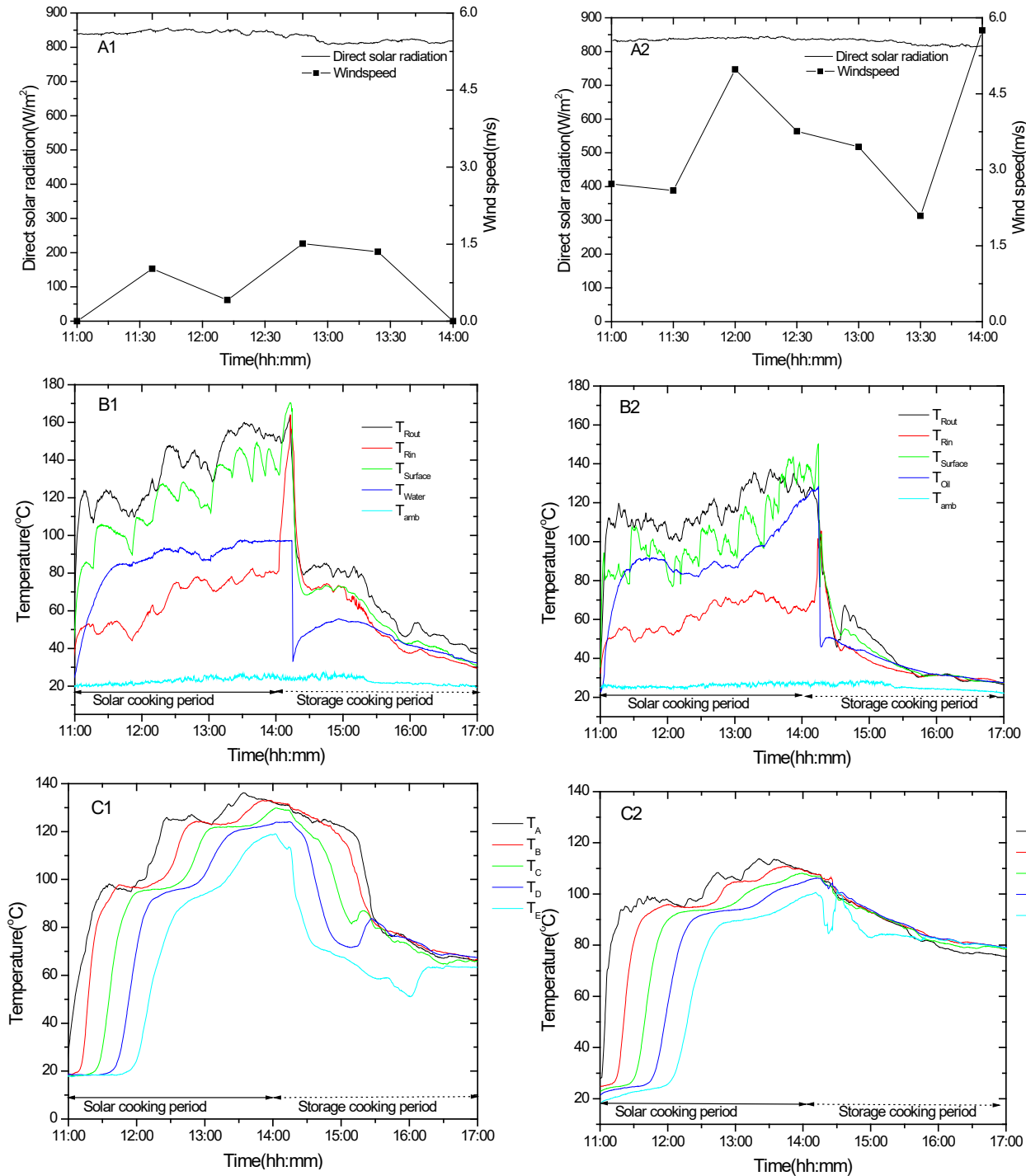


Figure 8.4: Experimental results of two test loads (water and sunflower oil) for a load of 0.5 kg utilizing a flow rate of 4.0 mL/s. (A) Direct solar radiation and wind speed (A1-water, A2-sunflower oil), (B) the temperature profiles of the solar receiver (B1-water, B2-sunflower oil), and (C) the temperature profiles of a storage tank (C1-water, C2-sunflower oil). Experimental dates were 3 July 2021 and 4 July 2021 for water and oil tests, respectively.

Figure 8.4(B1, B2) shows receiver temperature profiles which show the same trend as with the lower flow rate in Figure 8.3(B1, B2). Higher receiver temperatures are observed with water load as the heating load (Figure 8.3(B1)) due to lower heat losses because of the lower ambient wind speed conditions since the average solar radiation is comparable. The maximum receiver outlet temperature attained for the water test is 165 °C compared to around 140 °C; however, the temperature differences between the outlet and inlet temperatures are comparable, implying similar charging power conditions. The higher flow rate of 4 mL/s induces a faster rise in the load temperature compared to the lower flow rate of 2 mL/s due to the increased heat transfer rates. The maximum temperature of around 97 °C is achieved for water with the higher flow rate, for around 45 min, which is suitable for cooking most foods such as meat, rice, and potatoes. It is higher than 90 °C for the lower flow rate (2 mL/s) attained at the end of the charging process. As with the lower flow rate, the temperature of sunflower oil rose faster compared to the water load due to the lower thermal mass of oil, and sunflower oil attained a higher temperature of about 130 °C when charging ended. During the discharging cycle, the temperature of water rose faster compared with the lower flow rate, achieving a maximum cooking temperature of around 57 °C compared to 35 °C for the lower flow rate. A similar oil load temperature profile was observed during discharging for the higher flow rate; however, the temperature drops were from around 50 °C to 27 °C with the higher flow rate due to the increased heat transfer rate. As with the lower flow rate, the water temperature rose steadily before dropping, unlike the oil temperature, which showed a continual drop for the duration of discharging cycle except for a very insignificant rise at the start of discharge. Figure 8.4(C1, C2) presents storage tank thermal profiles for the whole charging and discharging periods utilizing a higher flow rate of 4 mL/s for the two test fluids. Thermal stratification in the storage tank is reduced for both test loads. The reduction in the adjacent axial temperature differences provides evidence of the reduced thermal stratification. The maximum temperatures achieved for the top of the storage tank were 138 °C and 115 °C, respectively, for the water and sunflower oil heating loads during the charging cycles. The prevailing higher ambient wind conditions for the oil heating test have the effect of reducing the outlet temperature from the charging coil. Storage tank temperatures rise faster with the higher charging flow rate. There is layering in thermal profiles at a constant temperature

just below 100 °C that is observed from around 11h30 to 13h00. The layering commences from the top of the tank and progresses to the bottom, like a phase change process in a cylindrical geometry heated from the top to the bottom as the one reported in this paper. This behavior can possibly be explained by the decrease in thermal conductivity with higher temperatures for the higher flow rate particularly as 100 °C is approached at the top of the storage tank. This decrease in thermal conductivity at higher temperatures outweighs the heat transfer increase due to the higher flow rate. Phase change cannot explain the layering observed since sunflower oil is a sensible heat storage material. Mawire et al. [35] and Mawire [38] observed a similar phenomenon when evaluating the charging process of a sunflower oil storage tank with a high charging flow rate of 4.2 mL/s under controlled laboratory conditions with very little or no wind in the tests. Thermal layering is also observed to a lesser extent above 100 °C for both storage tanks after 13h00. This layering behavior is not seen with the lower flow rate. During the discharging process, thermal stratification in the storage tank is lost more rapidly compared to the lower flow rate due to the increased heat transfer rate. The water load with higher charging temperatures achieved in the storage tank showed better initial thermal stratification between 14h00-15h30 compared to the sunflower oil load as a direct result of the larger initial temperature difference along with the height of the storage tank at the onset of discharging. This larger temperature difference results in higher water temperatures being achieved than the oil temperatures in the pot during discharging. However, after 15h30, the stratification in the storage tank is severely reduced for both cooking loads, unlike with the lower flow rate where stratification is maintained for the duration of the discharging process.

Figure 8.5 shows test results using 1 kg of water and oil at a flow rate of 2 mL/s performed on 17 July 2021 and 20 July 2021, respectively. Generally, the solar radiation for the duration of the experiment was almost constant as with the other tests (Figures 8.3 and 8.4). The average solar radiation was seen to be roughly around 850 W/m² and 750 W/m², respectively, for the sunflower oil and water loads. The wind speeds were generally comparable for the water (0–2.0 m/s) and sunflower oil test loads (0–2.5 m/s). Figure 8.5(B1, B2) shows the temperature profiles of the receiver which show similar trends to the previous tests. Generally, for both tests, the rise of the load temperatures was lower than in the other experimental tests. This was due to the

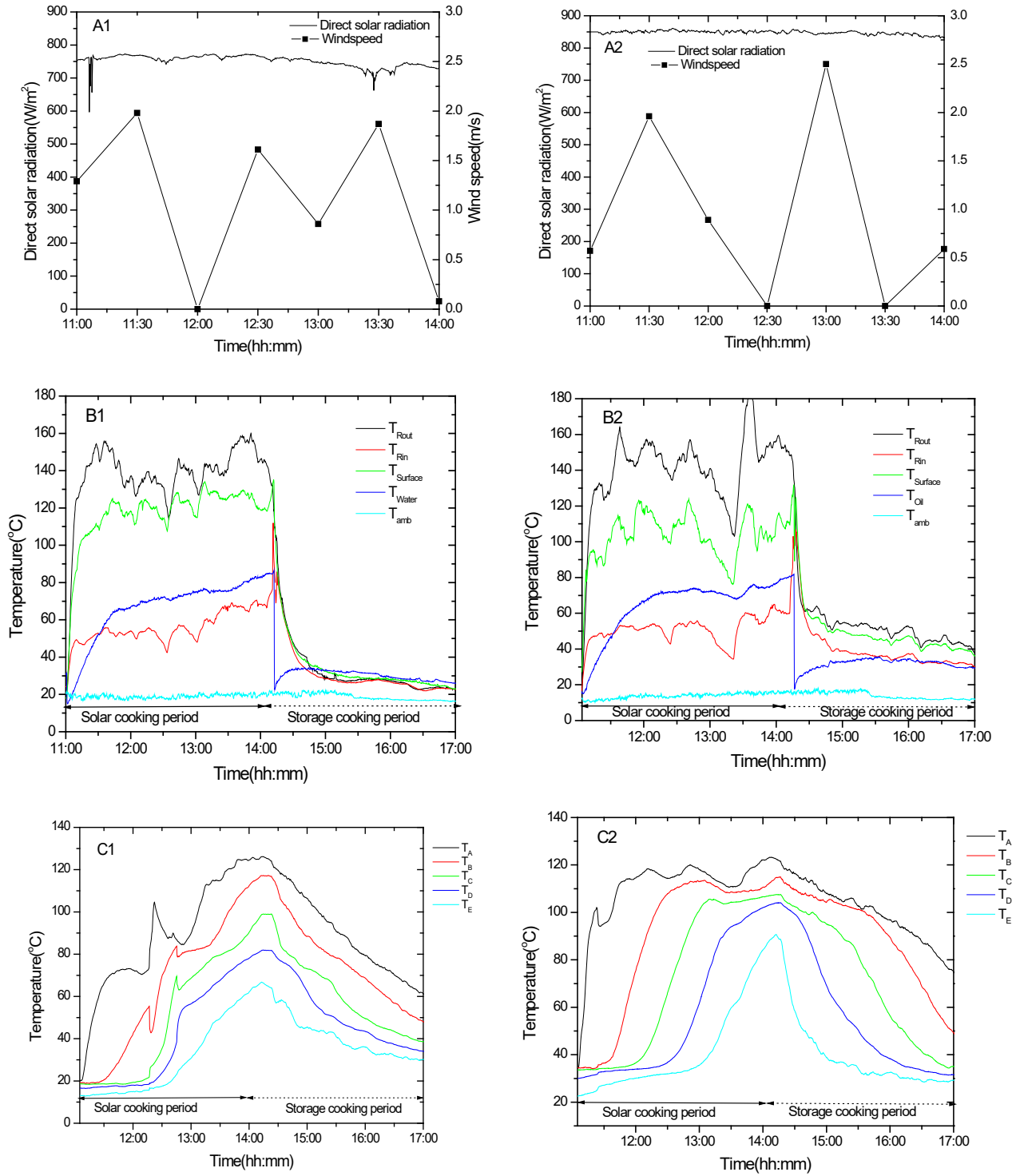


Figure 8.5: Experimental results of two test loads (water and sunflower oil) for a load of 1.0 kg utilizing a flow rate of 2.0 mL/s. (A) Direct solar radiation and wind speed (A1—water, A2—sunflower oil), (B) the temperature profiles of the solar receiver (B1—water, B2—sunflower oil), and (C) the temperature profiles of a storage tank (C1—water, C2—sunflower oil). Experimental dates were 17 July 2021 and 20 July 2021 for water and oil tests, respectively.

larger thermal mass of the test load (1 kg). The highest temperature achieved at the end of the solar cooking period was $\sim 82^{\circ}\text{C}$ for water and $\sim 80^{\circ}\text{C}$ for sunflower oil. When comparing the two tests with 1 kg, a faster rise was seen with water, possibly due to slightly lower initial ambient temperatures for the oil heating test. This shows that the initial ambient temperature conditions have an influence on the temperature even with higher incident solar radiation for the sunflower oil test. The ambient conditions of the temperature and the wind speed cannot be controlled; thus, identical ideal test conditions for experimental tests are very difficult to achieve. The temperatures achieved in the loads are suitable for the slow cooking of some foods. During the discharging process, the effect of the larger thermal mass is very evident with the water as the test load as it only attains a maximum temperature of around 30°C whereas sunflower oil achieves a maximum temperature of around 36°C . These temperatures are lower than the other experimental tests. Storage tank temperature profiles utilizing 1 kg water and sunflower oil at a flow rate of 2 mL/s are shown in plots (C1 and C2) of Figure 8.5. For both experimental setups, the maximum temperatures achieved in the storage tank were both just above 120°C . The rise of all axial levels for water was slower than for sunflower oil due to the larger thermal mass of the water test load. The peaking and fall of the upper-level storage temperatures (TA and TB) between 12h15-12h30 for water as the test load can be attributed to the rise and fall of the inlet temperature during that same period. Manual tracking can be attributed to this behavior as well as convective heat losses. Compared to other temperature profiles (Figures 8.3 and 8.4) of the storage tank which were almost identical for water and sunflower oil, the storage tank profiles for water as the load showed the largest temperature difference between the top and the bottom of the storage tank at the end of charging (60°C). This explains why the stored energy for the water test load is not able to induce a high temperature rise in the discharging process due to the lower bottom-level storage temperatures. The highest storage tank temperatures were seen with the highest flow rate (4 mL/s—Figure 8.4) because of increased heat transfer.

8.5 Discussion of the Results

8.5.1 Charging Energetic and Exergetic Performance with Different Flow Rates and Heating Loads

Table 8.1 shows the effect of the flow rate on the average energetic and exergetic thermal performance parameters with the associated standard deviations during charging. The water and sunflower oil loads were kept constant at 0.5 kg, while the flow rate varied from 2-5 mL/s in steps of 1 mL/s. The average solar radiation varied between 756–846 W/m² for the water tests. The lowest average solar radiation for the water heating tests was seen with the highest charging flow rate (5 mL/s). On the other hand, for the sunflower oil tests, the average solar radiation varied between 757-848 W/m² in the experimental tests, which are comparable to the water heating tests. Higher average external wind speeds (1.19-3.62 m/s) are seen with sunflower oil heating tests compared to the water tests (0.66-2.49 m/s). Generally, the increase in the oil and water loads increases both the average energy and exergy rates for both test loads. However, the water showed higher values of energy and exergy rates compared to sunflower oil, possibly due to the lower temperatures achieved with water as a test load which reduces heat losses. For the water heating load using 5.0 mL/s, the thermal performance parameters are lower compared to 4.0 mL/s due to lower average solar radiation conditions. The average energy and exergy efficiencies for water and sunflower generally increase with the flow rate except for the 5 mL/s case with the least average solar radiation. The energy and exergy efficiency values are generally greater for water as a test load compared to sunflower oil. The change in the windspeed shows no correlation with energy and exergy efficiencies values since the efficiencies increase even with drastic changes in the average wind speed. As an example, the sunflower oil tests for a change in the flow rate from 3.0–4.0 mL/s, the average windspeed changes by a factor of 3 (1.19–3.62 m/s) but an expected corresponding decrease in the average energy and exergy efficiencies is not seen. Instead, the average energy and exergy efficiencies increase from 0.16–0.22 and 0.15–0.17, respectively.

Table 8.2 shows the effect of the load on the energetic and exergetic thermal parameters while charging with a constant flow rate of 2.0 mL/s for water and sunflower oil loads. The load was varied from 0.5-2.0 kg in steps of 0.5 kg. The average solar radiation is between 795-846 W/m² for the water tests which is comparable to the sunflower oil tests of 757-833 W/m². Generally

higher (1.11-2.67 m/s) but comparable wind speeds were seen in the sunflower oil heating tests in comparison to the water heat tests (1.08-1.17 m/s)

Table 8.1: Effect of the flowrate on the energetic and exergetic parameters for water and sunflower oil loads during charging cycles with a load of 0.5 kg.

Flowrate (ml/s) Water	Sunflower Oil*	Average solar radiation (W/m ²)	Average wind speed (m/s)	Average energy rate(W)	Average energy rate(W)	Average exergy rate(W)	Average efficiency (-)	Average energy efficiency (-)	Average exergy efficiency (-)
2.0		842±10 757±15*	1.11±0.76 2.67±1.70*	390±20	391±30*	328±20; 266 ±22*	0.18±0.02; 0.17±0.03*		0.15±0.04 0.14±0.02*
3.0		846±10 848±11*	1.05±0.51 1.19±1.10*	444±55 450 ±60*		338±17; 332 ±15*	0.21±0.04; ±0.03*	0.16	0.16±0.03 0.16±0.05*
4.0		832±14 831±10*	0.66±0.63 3.62±1.33*	586±43 482 ±23*		445±25. 336 ±19*	0.28±0.03; ±0.04*	0.22	0.22±0.05 0.17 ±0.03*
5.0		756±7 760 ±6*	2.49 ±0.72 3.12 ±0.52*	484±40 518 ±23*		355±18; 373 ±21*	0.25±0.05; ±0.02*	0.19	0.19±0.02 0.19±0.04*

Sunflower Oil values are represented by *.

Table 8.2: Effect of the mass on the energetic and exergetic parameters for water and sunflower oil loads during charging cycles with 2.0 ml/s.

Mass Load (kg) Water	Sunflower Oil*	Average solar radiation (W/m ²)	Average wind speed (m/s)	Average energy rate(W)	Average energy rate (W)	Average exergy rate (W)	Average efficiency (-)	Average Energy efficiency (-)	Average Exergy efficiency (-)
0.5		842±10 756 ±15*	1.11±0.76 2.67±1.70*	390±10 391 ±18*		329±25 266±18*	0.19±0.06 0.18±0.02*		0.15±0.04 0.14 ±0.03*
1.0		846±17 803 ±10*	1.10±0.81 1.11±0.76*	387±25 367 ±30*		314±15 186±8*	0.18±0.03 0.17±0.04*		0.16±0.03 0.09±0.03*
1.5		840±10 833±15*	1.08±0.64 1.84±0.95*	374±33 317±25*		310±23 175±13*	0.18±0.02 0.16±0.03*		0.16±0.04 0.08±0.02*
2.0		795±9 828 ±7*	1.17 ±0.68 2.46±0.73*	334±28 244 ±22*		309±25 104±19*	0.16±0.02 0.16±0.02*		0.16±0.02 0.05±0.01*

The average energy and exergy rates for water as a test load decrease marginally with the increase in the load whereas a larger decrease with the load is seen with sunflower oil. Higher energy and exergy rate values of water are due to the larger specific heat capacity of water compared to sunflower oil as well as the lower temperatures attained using water which resulted in lower heat losses. The decrease in the average energy and exergy rates with respect to the mass is due to the lower receiver temperatures obtained with the larger heating load. The average energy efficiency values for both water and sunflower oil decrease very marginally with load, and it seems the average energy efficiency is independent of the load. The average energy

efficiencies are comparable for both loads. The average exergy efficiency for water is independent of the load since it shows very little variation with an increase in the load. On the other hand, the exergy efficiency of sunflower oil as the test load decreases with an increase in the load (0.14–0.05). The exergy efficiency values for sunflower decrease with the load and are lower than those for water due to the lower receiver temperatures attained for water which has a direct influence on the heat losses. Generally, water as a test load is seen to be more effective in terms of energy and exergy delivered while charging the storage tank. The flow rate has a more significant effect on the energetic and exergetic performance of the combined system than the heating load.

8.5.2 Discharging Energetic and Exergetic Performance with Different Flow Rates and Heating Loads

Table 8.3 shows the effect of the flow rate on the discharging energetic and exergetic performance. The average initial storage tank temperatures of water as the load (94–125 °C) were slightly higher but comparable to those of sunflower oil (97–104 °C *). The differences in the initial storage tank temperatures are unavoidable due to different ambient conditions such as the different ambient temperatures and different wind speeds. There is no general trend in variation of the average energy and exergy rates with respect to the flow rate for both water and sunflower oil heating loads due to the varying initial storage tank temperatures which cannot be controlled under real-life conditions. However, higher average energy and exergy rates (49–95 W; 23–55 W) are seen with water compared to sunflower oil (34–68 W*; 15–34 W*) possibly due to the large heating thermal mass of water. The energy and exergy efficiencies also show no variation trend with the flow rate. The energy and exergy efficiencies for water (0.06–0.14; 0.05–0.12) are slightly higher than those of sunflower oil (0.06–0.12*; 0.04–0.08) suggesting water as a slightly better heating load during discharging.

Table 8.4 shows the effect of the mass of the discharging thermal performance parameters using a constant discharging flow rate of 2 mL/s. The average initial storage tank temperatures for water (97–114 °C) are slightly greater than those of sunflower oil (95–100 °C*). The average wind speed conditions for the water tests (1.10–1.17 m/s) are lower than for the sunflower oil tests (1.11–2.67 m/s*). As with the effect of the flow rate tests, there is no general trend of the

variation of the average energy and exergy rates with the load. In some cases, sunflower oil shows higher average energy and exergy rate values compared to water so no general conclusive evidence can be drawn up on which fluid performs better than the other with different mass loads. The variation of the discharging energy and exergy efficiencies also show no correlation with the heating load for both fluids, and no generalized conclusion can be drawn up. For the larger loads (1.5–2.0 kg), the energy and exergy efficiency values for sunflower oil are greater than those of water, suggesting the better performance of sunflower oil with the larger loads when using similar discharging flow rates.

It is suggested that future experiments should be carried out in an environmentally controlled location or laboratory where the initial and final temperatures can be controlled to understand more fully the discharging characteristics. However, in real-life situations, the environmental variations cannot be controlled, and the most important issue is whether the system performs its specified tasks regardless of varying environmental conditions.

Table 8.3: Effect of the flowrate on the energetic and exergetic of water and sunflower oil loads during discharging cycles with a load of 0.5 kg.

Flowrate (ml/s) Water Oil*	Sunflower	Average initial storage temperature (°C)	Average speed (m/s)	wind	Average energy (W)	rate	Average exergy (W)	rate	Energy efficiency (-)	Exergy efficiency (-)
2.0		106±6 97±6*	0.91±0.89 2.93±1.00*		59±4 51±2*		41±2 26±1*		0.14 0.12*	0.12 0.08*
3.0		109±8 99±7*	0.77±0.60 0.67±0.98*		57±3 58 ±2*		35±3 34±2*		0.11 0.09*	0.09 0.08*
4.0		125±7 104±4*	0.24±0.45 1.61±1.44*		95±1 34 ±2*		55±2 15±2*		0.13 0.06*	0.10 0.04*
5.0		94 ±4 100±3*	1.61 ±1.08 2.59±0.78*		49±2 68±2*		23±2 31±2*		0.06 0.11*	0.05 0.07*

Table 8. 4: Effect of the mass on the energetic and exergetic parameters for water and sunflower oil loads during discharging cycles with 2 ml/s.

Mass Load (kg)	initial	Average	wind	Average	Average	Energy	efficiency	Exergy	efficiency
Water		storage		speed (m/s)	energy	(-)		(-)	
Oil*	Sunflower	temperature (°C)			rate(W)				
0.5		107±6 97±6*		1.11±0.76 2.67±1.70*	59±4 51±2*	41±2 26±2*	0.14 0.12*	0.12 0.08*	
1.0		110±10 95±7*		1.10±0.81 1.11±0.76*	42±3 90±6*	21±1 34 ±2*	0.14 0.11*	0.10 0.08*	
1.5		97±5 95±9*		1.08±0.64 1.84±0.95*	41±3 46±2*	26±0.5 15±0.2*	0.09 0.13*	0.07 0.10*	
2.0		114±7 100±7*		1.17 ±0.68 2.46±0.73*	28±0.5 43±3*	23±0.5 31±2*	0.01 0.09*	0.01 0.06*	

8.5.3 Comparison of results with other researchers and cost

Table 8.5 presents a comparison of the current presented work and previous work by other authors. It is important to state that our reported system is different from other reported systems since our system has a cooking plate as well as an oil circulating coil to heat the storage tank. The other systems only circulated fluids to heat the storage tanks. The reported system shows generally better or comparable energy rate, exergy rate and efficiencies compared to other reported systems, in spite of performing the dual purpose of cooking as well as storing solar thermal energy. The proposed system seems to be a practical system for implementation in decentralized communities because of the higher or comparable energy and exergy rates to other systems reported in Table 8.5.

Table 8.5: A comparison of the present work with previous work done by other researchers.

Author	Year	Heat transfer fluid	Test load	Optimum flowrate (ml/s)	Energy rate (W)	Energy efficiency (-)	Exergy rate (W)	Exergy efficiency (-)
Mawire et al. [32]	2020	Sunflower oil	Water	6.0	1000	0.325	200	0.112
Asmelash et al. [35]	2014	Soya bean oil	Water	-	200	0.06	-	-
Farooqui [36]	2013	Thermal fluids (vegetable oil and sunflower oil)	Water	-	203	0.300	-	-
Noman et al. [37]	2019	Water	None	3.2	-	0.065	-	0.072
Sharma et al. [38]	2005	Water	Water	8.1	-	-	-	-
Lentswe et al. [Present work]	2022	Sunflower oil	Water Sunflower oil*	4	586 482*	0.28 0.22*	445 336*	0.22 0.17*

The estimated cost of the combined solar cooking and TES system is summarized in Table 8.6.

The system costs around R 6300 (USD343). This is higher than a single purpose parabolic dish

solar cooker which costs around R2500 (USD136*) [42], however, the dual-purpose functions make it more versatile. When comparing the price to the cheapest commercial 100 L domestic solar water heating systems [43-44] which cost R9899 (USD 539*-evacuated tube) and R10560 (USD575-flat plate), respectively, the reported system is considerably cheaper and more versatile since it is dual-purpose. Even with the up-scaling of the storage tank of the combined system from 30 L to 100 L, the total cost of the combined system (R8000 (USD435)) is still less than that of commercial 100 L domestic solar water heating systems.

Table 8.6: Estimated total cost of the combined solar cooking and TES system.

Component No	Component Description	Cost R(USD*)
1	Parabolic Dish	2500(136*)
2	Storage Tank	800(44*)
3	Receiver	500(27*)
4	Pipes	500(27*)
5	Pump	2000(109*)
Total		6300(343*)

8.6 Conclusion

A dual-purpose solar cooker for cooking and storing thermal energy simultaneously that can be used during off-sunshine periods was presented. The experimental setup was composed of a parabolic dish, a solar receiver coupled with a flat-plate and an oil-circulating copper coil for charging a storage tank. Energy and exergy thermal performance parameters of the dual-purpose system during charging and discharging cycles were presented. The effect of the flowrate and the mass of the load were investigated using sunflower oil both as the heat transfer fluid and the storage material. Charging and discharging experiments are conducted using four different flowrates (2, 3, 4, 5 ml/s), and with different masses (0.5, 1, 1.5, 2.0 kg) with water and sunflower oil as the test loads. In summary, the following conclusions were drawn up from the study:

- Charging results showed that the average energy and exergy rates as well as their corresponding efficiencies increased with an increase in the charging flowrate. Water showed higher average charging energy and exergy efficiencies compared to sunflower oil.
- The increase in the mass load decreased marginally the average charging energy and exergy rates for water, and their corresponding efficiencies. For sunflower oil, the average

charging energy and exergy rates and efficiencies showed a more pronounced decrease with an increase in the mass, and sunflower oil showed lower values compared to water.

- c. For the discharging results, the correlations between the energy and exergy thermal performance parameters with respect to the flowrate and the heating load were not well defined for both heating loads possibly due to different initial storage tank temperatures at the onset of discharging, and the inefficient discharging process which needs to be optimized in future. However, the discharging average energy and exergy rates and their corresponding efficiencies were higher for water than sunflower oil when using different discharging flowrates.
- d. The proposed dual-purpose system is cheaper than less versatile single-purpose commercial domestic solar hot water heating systems hence it is viable to commercialize it for decentralized rural communities.

Future work will investigate the proposed system under laboratory-controlled conditions using artificial sunlight to eliminate the variable and uncontrolled ambient conditions during charging and discharging. This might, however, be very expensive for moderately equipped laboratories in the developing world, thus collaborating with researchers in the developed world seems to be the best option. In the future, we intend also to test the system with water for a dual-purpose solar cooking and water heating system. The proposed system, regardless of its low efficiency during discharging, seems to add to the body of knowledge of new proposed dual-purpose systems which can cook as well as store thermal energy for later usage. These systems are more economically viable and can be used in the developing world as sustainable solar energy solutions for domestic purposes in decentralized communities.

Credit author contribution statement

Katlego Lentswe: Investigation, conceptualization, methodology, drafted original manuscript, reviewing and editing, formal analysis and interpreting the results. Ashmore Mawire: Conceptualization, supervision, reviewing and editing. Prince Owusu: Investigation, reviewing and editing.

Acknowledgement

The authors acknowledge the Instruments Making Department of the North-West University for fabricating the experimental setup, in particular the head of the Department, Mr. Thys Taljaard. The first author (Katlego Lentswe) wishes to acknowledge SOLTRAIN (Southern African Solar Thermal Training and Demonstration Initiative) for a bursary to carry out the research reported in this paper.

References

- [1] Bhutto, A. W., Bazmi, A. A., & Zahedi, G. (2011). Greener energy: Issues and challenges for Pakistan—Biomass energy prospective. *Renewable and Sustainable Energy Reviews*, 15, 3207-3219.
- [2] Akinbami, J. F., Ilori, M. O., Oyebisi, T. O., Akinwumi, I. O., & Adeoti, O. (2001). Biogas energy use in Nigeria: current status, future prospects and policy implications. *Renewable and Sustainable Energy Reviews*, 5, 97-112.
- [3] Surendra, K. C., Khanal, S. K., Shrestha, P., & Lamsal, B. (2011). Current status of renewable energy in Nepal: Opportunities and challenges. *Renewable and Sustainable Energy Reviews*, 15, 4107-4117.
- [4] Herez, A., Ramadan, M., & Khaled, M. (2018). Review on solar cooker systems: Economic and environmental study for different Lebanese scenarios. *Renewable and Sustainable Energy Reviews*, 81, 421-432.
- [5] Muthusivagami, R. M., Velraj, R., & Sethumadhavan, R. (2010). Solar cookers with and without thermal storage—a review. *Renewable and Sustainable Energy Reviews*, 14, 691-701.
- [6] Patel, P., & Kumar, R. (2016). Comparative performance evaluation of modified passive solar still using sensible heat storage material and increased frontal height. *Procedia Technology*, 23, 431-438.
- [7] Caraballo, A., Galán-Casado, S., Caballero, Á., & Serena, S. (2021). Molten salts for sensible thermal energy storage: a review and an energy performance analysis. *Energies*, 14, 1197.
- [8] Dincer, I., Dost, S., & Li, X. (1997). Performance analyses of sensible heat storage systems for thermal applications. *International Journal of Energy Research*, 21, 1157-1171.
- [9] Gautam, A., & Saini, R. P. (2020). A review on sensible heat based packed bed solar thermal energy storage system for low temperature applications. *Solar Energy*, 207, 937-956.
- [10] Li, G. (2016). Sensible heat thermal storage energy and exergy performance evaluations. *Renewable and Sustainable Energy Reviews*, 53, 897-923.

- [11] Ayyappan, S., Mayilsamy, K., & Sreenarayanan, V. V. (2016). Performance improvement studies in a solar greenhouse drier using sensible heat storage materials. *Heat and Mass Transfer*, 52, 459-467.
- [12] Salunkhe, P. B., & Shembekar, P. S. (2012). A review on effect of phase change material encapsulation on the thermal performance of a system. *Renewable and Sustainable Energy reviews*, 16, 5603-5616.
- [13] Zhang, D., Tian, S., & Xiao, D. (2007). Experimental study on the phase change behavior of phase change material confined in pores. *Solar Energy*, 81, 653-660.
- [14] Zivkovic, B., & Fujii, I. (2001). An analysis of isothermal phase change of phase change material within rectangular and cylindrical containers. *Solar Energy*, 70, 51-61.
- [15] Laing, D., Bauer, T., Breidenbach, N., Hachmann, B., & Johnson, M. (2013). Development of high temperature phase-change-material storages. *Applied Energy*, 109, 497-504.
- [16] Socaciu, L. G. (2012). Thermal energy storage with phase change material. *Leonardo Electronic Journal of Practices and Technologies*, 20, 75-98.
- [17] Sharma, S. D., Iwata, T., Kitano, H., & Sagara, K. (2005). Thermal performance of a solar cooker based on an evacuated tube solar collector with a PCM storage unit. *Solar Energy*, 78, 416-426.
- [18] Pagkalos, C., Dogkas, G., Koukou, M. K., Konstantaras, J., Lymperis, K., & Vrachopoulos, M. G. (2020). Evaluation of water and paraffin PCM as storage media for use in thermal energy storage applications: A numerical approach. *International Journal of Thermofluids*, 1, 100006.
- [19] Saxena, A., & Karakilcik, M. (2017). Performance evaluation of a solar cooker with low cost heat storage material. *International Journal of Sustainable Green Energy*, 6, 57-63.
- [20] Cuce, P. M. (2018). Box type solar cookers with sensible thermal energy storage medium: A comparative experimental investigation and thermodynamic analysis. *Solar Energy*, 166, 432-440.
- [21] Vigneswaran, V. S., Kumaresan, G., Sudhakar, P., & Santosh, R. (2017, May). Performance evaluation of solar box cooker assisted with latent heat energy storage system for cooking application. In *IOP Conference Series: Earth and Environmental Science*, 67, 012017.
- [22] Saxena, A., Varun, & Srivastava, G. (2012). A technical note on performance testing of a solar box cooker provided with sensible storage material on the surface of absorbing plate. *International Journal of Renewable Energy Technology*, 3, 165-173.
- [23] Milikias, E., Bekele, A., & Venkatachalam, C. (2021). Performance investigation of improved box-type solar cooker with sensible thermal energy storage. *International Journal of Sustainable Engineering*, 14, 507-516.

- [24] Anilkumar, B. C., Maniyeri, R., & Anish, S. (2021). Optimum selection of phase change material for solar box cooker integrated with thermal energy storage unit using multi-criteria decision-making technique. *Journal of Energy Storage*, 40, 102807.
- [25] Saxena, A., Cuce, E., Tiwari, G. N., & Kumar, A. (2020). Design and thermal performance investigation of a box cooker with flexible solar collector tubes: An experimental research. *Energy*, 206, 118144.
- [26] Nébié, J., Zongo, S., C Tubreoumya, G., S Zongo, A., Konkobo, I., Bagré, B., ... & Béré, A. (2022). Performance Assessment of a Box Type Solar Cooker Using Jatropa Oil as a Heat Storage Material. *Energy and Power Engineering*, 14, 124-132.
- [27] Coccia, G., Di Nicola, G., Tomassetti, S., Pierantozzi, M., Chieruzzi, M., & Torre, L. (2018). Experimental validation of a high-temperature solar box cooker with a solar-salt-based thermal storage unit. *Solar Energy*, 170, 1016-1025.
- [28] Palanikumar, G., Shanmugan, S., Chithambaram, V., Gorjian, S., Pruncu, C. I., Essa, F. A., ... & Selvaraju, P. (2021). Thermal investigation of a solar box-type cooker with nanocomposite phase change materials using flexible thermography. *Renewable Energy*, 178, 260-282.
- [29] Lokeswaran, S., & Eswaramoorthy, M. (2012). Experimental studies on solar parabolic dish cooker with porous medium. *Applied Solar Energy*, 48, 169-174.
- [30] Wollele, M. B., & Hassen, A. A. (2019). Design and experimental investigation of solar cooker with thermal energy storage. *AIMS Energy*, 7, 957-970.
- [31] Senthil, R. A. M. A. L. I. N. G. A. M., & Cheralathan, M. (2016). Thermal performance of solid and liquid energy storage materials in a parabolic dish solar cooker. *International Journal Chemical Science*, 14, 1977-1983.
- [32] Mawire, A., Lentswe, K., Owusu, P., Shobo, A., Darkwa, J., Calautit, J., & Worall, M. (2020). Performance comparison of two solar cooking storage pots combined with wonderbag slow cookers for off-sunshine cooking. *Solar Energy*, 208, 1166-1180.
- [33] Basem, A., Moawed, M., Abbood, M. H., & El-Maghlany, W. M. (2022). The energy and exergy analysis of a combined parabolic solar dish–steam power plant. *Renewable Energy Focus*, 41, 55-68.
- [34] Mawire, A., Ekwomadu, C. S., Lefenya, T. M., & Shobo, A. (2020). Performance comparison of two metallic eutectic solder based medium-temperature domestic thermal energy storage systems. *Energy*, 194, 116828.
- [35] Mawire, A., Phori, A., & Taole, S. (2014). Performance comparison of thermal energy storage oils for solar cookers during charging. *Applied Thermal Engineering*, 73, 1323-1331.

- [36] Farooqui, S. Z. (2013). A vacuum tube based improved solar cooker. *Sustainable Energy Technologies and Assessments*, 3, 33-39.
- [37] Asmelash, H., Bayray, M., Kimambo, C. Z. M., Gebray, P., & Sebbit, A. M. (2014). Performance test of parabolic trough solar cooker for indoor cooking. *Momona Ethiopian Journal of Science*, 6, 39-54.
- [38] Noman, M., Wasim, A., Ali, M., Jahanzaib, M., Hussain, S., Ali, H. M. K., & Ali, H. M. (2019). An investigation of a solar cooker with parabolic trough concentrator. *Case Studies in Thermal Engineering*, 14, 100436.
- [39] Sharma, S. D., Iwata, T., Kitano, H., & Sagara, K. (2005). Thermal performance of a solar cooker based on an evacuated tube solar collector with a PCM storage unit. *Solar Energy*, 78, 416-426.
- [40] Petela, R. (2003). Exergy of undiluted thermal radiation. *Solar Energy*, 74, 469-488.
- [41] Mohammadi, A., & Mehrpooya, M. (2016). Exergy analysis and optimization of an integrated micro gas turbine, compressed air energy storage and solar dish collector process. *Journal of Cleaner Production*, 139, 372-383.
- [42] Sunfire Solutions (2022). <https://www.sunfire.co.za/product-category/solar-cooking/>, Website accessed 16 October 2022.
- [43] Leroy Merlin (2022). <https://leroymerlin.co.za/low-pressure-solar-water-heating-system-110l-on-flat-roof-stand-81465918>, Website accessed 16 October 2022.
- [44] New Year Solar (2022). https://newyellowsolar.com/products/pitch-roof?variant=35431718060196¤cy=ZAR&utm_medium=product_sync&utm_source=google&utm_content=sag_organic&utm_campaign=sag_organic&utm_campaign=gs-2020-08-20&utm_source=google&utm_medium=smart_campaign&gclid=Cj0KCQjw166aBhDEARIsAMEyZh5HLALdK_qSy_PYijck3A68Kq0tNASZKuyk3xXc6HXpQdp1ZDSIAPYaApWmEALw_wcB, Website accessed 16 October 2022.

Chapter 9: Conclusions and recommendations

9.1 Conclusions and summary of the research work

A research study on the performance enhancement of parabolic dish cookers combined with thermal energy storage systems for domestic applications was carried out.

Firstly, in Chapter 2, a critical review of parabolic solar cookers with thermal energy storage (TES) systems was presented to identify research gaps to further improve parabolic solar cookers with TES systems for third-world countries and disadvantaged communities. Parabolic trough and dish solar cookers with TES systems were reviewed. TES systems considered in the review were sensible heat thermal energy storage (SHTES) and latent heat thermal energy storage (LHTES) systems. The results obtained in the review showed that there were more studies conducted in recent years with parabolic dish cookers because of their ability to achieve higher temperatures faster. New reflector materials, practical end-user experimental solar cooking prototypes, and techno-economic and socio-economic analyses of solar cookers were some of the research gaps for future studies identified by the review. The review also highlighted that research on parabolic solar cookers with TES should look at other crucial factors, such as the choice of sensible or latent heat storage materials, environmental impact, different foods to be cooked, and social acceptance.

In Chapter 3, an experimental investigation on the performance of two solar cooking storage pots combined with wonderbag slow cookers for off-shine periods was presented. One storage pot was filled with sunflower oil as the sensible heat thermal energy storage (SHTES), and the other pot was filled with erythritol as latent heat thermal energy storage (LHTES). Foods such as potato chips, rice and chicken were placed inside the storage pots for solar cooking and off-shine cooking periods experimental tests. The thermal performance of the storage pots during solar cooking periods was evaluated using 1.2 m parabolic dish cookers. During off-sunshine periods, the thermal performance was evaluated with the two storage pots placed inside insulated wonderbag slow cookers. Due to the lower thermal mass of the sunflower oil, the sunflower oil storage pot showed faster cooking times (1.8-5.0 h) and higher maximum storage temperatures

(124-145 °C) compared to the erythritol PCM pot (3.8-6.6 h, 118-140 °C) during solar coking periods. The heat utilization efficiency of the erythritol pot was greater (4.8-14.3%) than that of the sunflower pot (3.7-6.0%) during the storage cooking period. During the off-sunshine storage cooking period, the erythritol PCM storage pot showed better thermal performance than the oil storage pot, achieving lower temperature drops regardless of its lower initial storage temperatures.

Chapter 4 presented an experimental comparative study of storage cooking pots using different heating loads during sunshine periods and off-shine periods. Five different mass loads (0.5, 1.0, 1.5, 2.0, and 2.5 kg) of sunflower oil and water were used in the experiment as heating fluids to investigate the effect of the load on the heat utilization and storage efficiencies. Sunflower oil and erythritol were the SHTES and the LHTES materials, respectively, used in the cavities of the storage cooking pots. Results obtained showed that the average storage efficiencies of the erythritol pot reduced from 3.9 to 2.5 % with the increase of load (0.5-2.5 kg), whereas for the sunflower pot the corresponding efficiency reduced from 4.4-3.2 %. The erythritol pot showed greater heat utilization efficiencies (13 to 49 %) compared to the sunflower oil pot (17-46 %) when using water as the heating load. When sunflower oil was used as the cooking fluid, the sunflower oil pot showed greater heat utilisation efficiencies (9.4-28 %) compared to the erythritol pot (9.2-19 %). Higher heat utilization efficiencies achieved with water suggested that larger thermal masses resulted in better storage cooking capabilities when compared to smaller thermal masses. During the solar cooking period, the mass losses due to evaporation were much lower for sunflower oil as the heating fluid compared to water.

A thermal model of a solar cooker with thermal energy storage using computational fluid dynamics (CFD) was presented in Chapter 5. Experimental results showed good agreement with simulation results within measurement uncertainties, and the variances were attributed to solar flux fluctuations in the experiments. The mechanism of heating the storage pot was investigated by numerical model. The results revealed that at the commencement of solar heating, the dominant heat transfer mechanism in the TES system was natural convection, which created a uniform temperature profile. After 4 hours, the storage pot reached a steady state temperature of 405.8 K, which was hot enough to cook a variety of foods and vegetables. It was proposed that

the newly developed model of solar cooking pots integrated with TES systems could be used to optimize heat transfer, maximum temperatures and warming up times.

Preliminary experimental results of a combined solar cooking and thermal energy storage system for domestic applications were presented in Chapter 6. Experiments were carried out on a combined solar cooker with a sunflower oil storage tank. The experimental setup comprised of a 1.8 m parabolic dish with an oil circulating copper spiral coil receiver placed underneath a metallic cooking plate to charge a 30 L sunflower oil storage tank. 1.0 L of water was heated to around 75 °C in the cooking pot during the charging cycle, and the storage tank achieved temperatures above 100 °C. The discharging cycle was inefficient, with the heated water achieving temperatures slightly above 40 °C. The average charging efficiencies for the charging cycle were between 18 % and 17 %, corresponding to an average receiver power of about 367 W and a collector power of about 2100 W. On the other hand, average discharging efficiencies were found to be 14 % and 13%, respectively, during the discharging cycles, showing ineffective heat transfer from the storage tank during discharging, possibly because of the lengthy connecting pipes. The results supported the usage of a solar cooker integrated with TES for preparing foods on a sunny day. The stored heat could be used for indirect cooking using an insulated wonderbag cooker since the discharging cycle was not efficient.

Chapter 7 presented the charging energetic and exergetic evaluation of the combined solar cooking and thermal energy storage system presented in Chapter 6. Four different charging flowrates (2, 3, 4, and 5 ml/s) were utilized during experimental charging tests. The experiment was conducted to evaluate the effect of the flowrate during the charging cycle. The results showed that the average energy rate was just below 400 W, and the energy rate efficiency was approximately 0.18 when the flowrate was set to 2 ml/s. Generally, the average charging energy rate and the charging efficiency increased with an increase in the flowrate, except for the highest flowrate (5 ml/s) due to lower average direct solar radiation conditions during the experimental test. This indicated that environmental conditions affected the performance of the combined solar cooking and thermal energy storage system. The average charging exergy rate and the exergy efficiency also increased with the flowrate except for the highest flowrate of 5 ml/s.

In Chapter 8, detailed energetic and exergetic performance evaluations of the dual-purpose solar cooking and TES system presented in Chapters 6 and 7 were further elaborated during charging and discharging cycles. The effect of the flowrate and the mass load were investigated using sunflower oil as both the heat transfer fluid and the storage material. Charging and discharging experiments were conducted using four different flowrates (2, 3, 4, 5 ml/s), and four different masses (0.5, 1, 1.5, 2.0 kg) using water and sunflower oil as the test loads. Charging results showed that the average energy and exergy rates as well as their corresponding efficiencies increased with an increase in the charging flowrate. Using water as the load, slightly higher average charging energy (18 - 28 %) and exergy (15-22 %) efficiencies were obtained compared to when using sunflower oil (16-22 %, 14-19 %) as the flowrate increased. For sunflower oil as the load, the average charging energy (18-16 %) and exergy (14-5 %) efficiencies showed a more pronounced decrease with an increase in the mass compared to water (19-16 %, 16-15 %). For the discharging results, the energy and exergy efficiencies for water were seen to range between 6-14 % and 5-12 %, and these were slightly higher than for sunflower oil (6-12 %, 4-8 %) for the increase in flowrate. Correlations between the energy and exergy efficiencies with respect to the flowrate and the heating load for discharging were not well defined. This was possibly due to different initial discharging storage tank temperatures for water and sunflower oil loads during discharging tests imposed by environmental conditions.

9.2 Recommendations for possible future work

For future research, an investigation on the effect of using different reflective panels for solar cookers should be carried out, to improve the energetic and exergetic performance on the proposed system. The techno-economic and socio-economic aspects must be critically investigated for parabolic dish solar cookers combined with thermal energy storage. These aspects will give an insight on the affordability, adoption, durability, payback period and viability of parabolic dish solar cookers with TES systems for disadvantaged communities.

It is also essential to study numerically with the use a CFD model, the performance of the dual-purpose solar cooker combined with TES for domestic applications. The model will assist in understanding and optimizing the thermal performance behaviour of the receiver, storage tank,

and cooking pot to improve heat transfer mechanisms for developing more efficient experimental prototypes. The thermal model developed in this study is to be used to improve the efficiency and optimize the design of storage cooking pots. It will also be used for parametric studies with different storage materials, different cooking pot shapes, and different pot materials. The heat transfer efficiency can also be optimized by exploring different shapes of fins and adding nanoparticles to LHTES and SHTES materials. Another approach to be explored for improving the thermal performance of the storage cooking pots is to combine LHTES and SHTES materials inside the same storage unit.

Charging and discharging experiments of a dual-purpose system for domestic applications must also be conducted in a laboratory-controlled environment using artificial sunlight. This will result in minimizing the effect of environmental parameters such as wind, variable solar radiation and rain that affect the energetic and exergetic performance of solar thermal systems. Also, the laboratory-controlled environment can reveal the maximum ability of the dual-purpose system to store energy, and exergy and utilization of stored heat. Another recommendation is to use water both as the heat transfer fluid and storage material for the dual purpose of storage as well as cooking. Preliminary experimental tests on the use of water for cooking and domestic purposes such as bathing, washing hands, making hot beverages, and cleaning dishes are currently in progress, and the results will be published soon. The preliminary results have not been presented since the focus of this study was on the cooking application. Additionally, it is possible to combine portable PV panels with storage cooking pots to enable cooking during low or no solar radiation conditions with the use of battery storage.