

**SOLAR COOKERS WITH THERMAL ENERGY STORAGE: A
SUSTAINABLE COOKING SOLUTION FOR DEVELOPING
COUNTRIES**

INAUGURAL LECTURE

PRESENTED BY

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Solar Cookers with Thermal Energy Storage: A Sustainable Cooking Solution for Developing Countries

Abstract

An overview of the three main types of solar cookers with their basic operating principles is presented in this lecture. Basic operating principles of direct focusing, oven and indirect solar cookers are outlined. These three types of cookers are briefly reviewed and discussed when they are used in conjunction with solar thermal energy storage (TES) units to enhance their usefulness during periods when solar radiation is not available. Solar cookers using both sensible heat thermal energy storage (SHTES) and latent heat thermal energy storage (LHTES) are briefly reviewed and discussed. Advantages and disadvantages of the different types of solar cookers with TES are also highlighted. The most viable options for solar cookers with TES for developing countries are the oven type of solar cookers and direct focusing solar cookers since there are relatively cheap to fabricate and maintain. On the other-hand when issues of efficiency and safety are concerned, indirect solar cookers with TES are more viable and these can be implemented for community scale cooking since they are relatively expensive to construct. Solar cookers with TES offer an alternative to polluting fossil fuels and LPG (Liquid Petroleum Gas) in rural areas of developing countries. Research gaps in solar cookers with thermal energy storage are also identified. The best previous work done by the author is also presented, including recent and future work to be done on solar cookers with thermal energy storage by the solar thermal research group at the Mafikeng campus

Keywords: Solar cookers; Thermal Energy Storage (TES); Sensible Heat Thermal Energy Storage (SHTES); Latent Heat Thermal Energy Storage (LHTES).

1. Introduction

1.1. Solar cookers

Fossil fuel energy resources are the main sources of energy for domestic cooking applications in the developing world. These fossil fuels used for cooking purposes are environmentally unfriendly, and include biomass and petroleum based fuels such as paraffin. Deforestation has a negative impact of the environment as trees are been depleted to provide firewood for cooking in the rural areas of developing countries. Added to this, the smoke generated from cooking with firewood is a main cause of premature deaths in developing countries due to lung related diseases. The cost of petroleum fuels is also rising, and these fuels also emit fumes which are hazardous to the environment. Electricity for cooking food is not always available to the majority of the poverty stricken communities in developing countries, especially in the rural areas. In a bid to limit the use of fossil fuels, solar thermal energy can be used to cook food which is environmentally friendly and abundant in most of the developing world.

A solar cooker is a cooking device that uses energy from the sun to cook food (Mawire, 2009). Solar cookers have been in existence for more than a century with one of the first ones being reported in India by Adams (1878), but the progress in their adoption is very slow. Essentially, three types of solar

cookers exist and these are classified according to their different designs. The three types of solar cookers are direct focusing solar cookers, oven solar cookers and indirect solar cookers.

1.1.1. Direct focusing (concentrating) solar cookers

Direct focusing solar cookers also referred to as concentrating type of solar cookers use reflectors to focus and concentrate sunlight directly onto a usually smaller and darker cooking pot as compared to the reflector. The pot is either suspended or set on a stand at the focal region. These cookers consist of one or more reflectors and a framework that supports both the reflectors and the pot. Numerous arrangements of this cooker have been devised to allow the reflector to be tilted to always point towards the sun with the pot remaining at the focal region. The type of reflectors used for these cookers include; parabolic dish reflectors, spherical reflectors, plane mirror reflectors and parabolic trough reflectors. A direct focusing parabolic dish solar cooker is shown in Figure 1. Concentrator cookers work best in direct sunlight but in cloudy conditions and windy conditions their performance is poor.

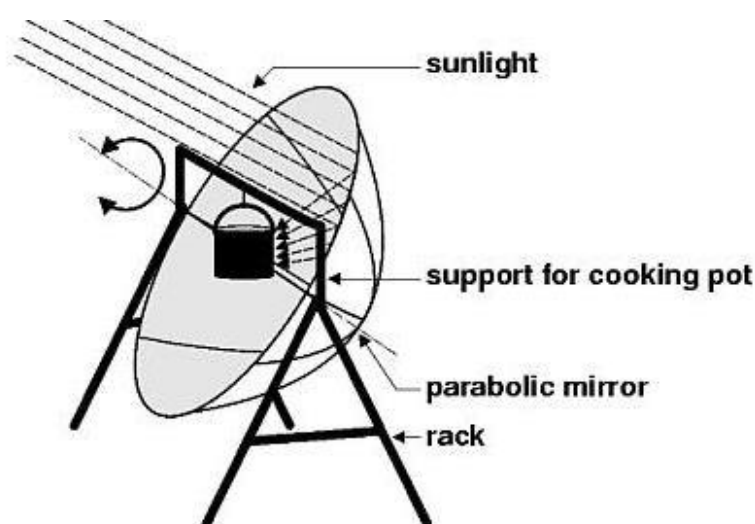


Figure 1: A schematic of an asymmetrical parabolic cooker. This configuration allows cooking to be done as close as possible to the vessel (Mawire, 2015).

1.1.2. Oven (hot box) solar cookers

Box-type solar cookers/ovens use the greenhouse effect for cooking food. A box cooker has a transparent glass or plastic top and may have one or more reflectors to enhance the performance of the cooker. The top is removable for placing cooking containers inside. The cooking containers and the bottom of the box cooker are dark-coloured or black for better absorption of solar radiation. The sides of the solar cookers must be insulated to avoid heat losses. The insulation material must not allow long-wave radiation to pass through it. The thermal insulation for the cooker must be able to withstand high temperatures. Figure 2 shows how cooking occurs in a solar box cooker. Sunlight rays, both direct and reflected (from the reflective material) enter the solar box cooker. These rays are

converted into heat energy which is utilised for cooking. The cooking container and the bottom of the box are black for better absorption of the radiation.

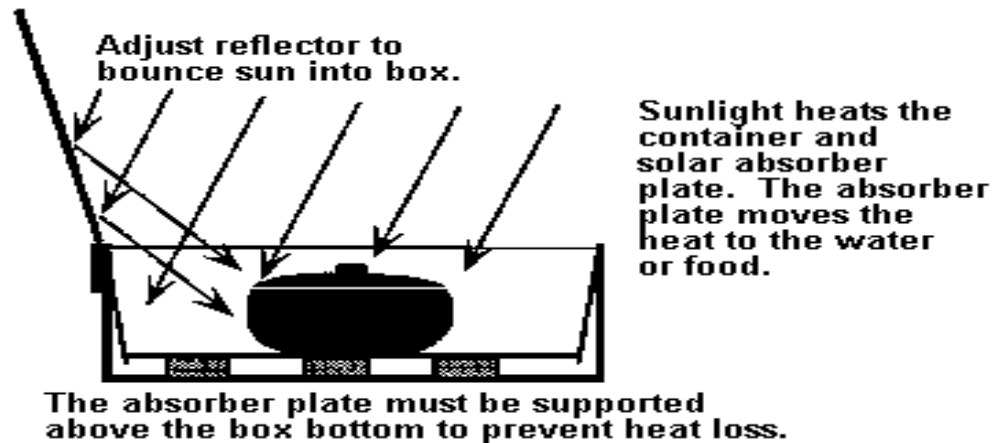


Figure 2: A schematic of box type cookers with a single reflector (Shaw, 2002)

Booster mirrors around the window can also be used to direct more solar radiation into the oven. A principal advantage of oven solar cookers over direct focusing cookers is that they can use both the direct and the diffuse components of solar radiation. A further advantage of these cookers is that no solar tracking is required to focus the solar radiation. Operating temperatures of about 200 °C can be achieved with these solar cookers when booster mirrors are utilised. These temperatures are adequate for cooking most types of food except for prolonged frying. Heat transfer into and within a solar box cooker occurs by conduction, convection and radiation. Although oven solar cookers do possess some advantages over direct focusing cookers, their main disadvantages are that they have low efficiencies, they require more time to cook food, they have limited capacity dependent on the size of the cooker, they have limited varieties and they cannot be used for indoor cooking.

1.1.3. Indirect solar cookers

Indirect solar cookers are solar cookers constructed such that the solar energy collectors are separated from the cooking vessels. A heat transfer medium is usually required to bring the collected energy into the cooking vessel. The cooking vessel can be placed further away from the solar energy collector allowing for an indirect cooking mode (Mawire, 2009). Solar energy collectors can be placed on the roof, while the cooking vessel can be placed indoors. In theory, the distance between the solar energy collector and the cooking vessel can be very large. However, practical challenges such as heat loss and the circulation of the heat transfer medium limits this distance. Close proximity between the cooking vessel and the solar energy collector allows for heat transfer through natural convection. Indirect solar cookers have the advantages of indoors cooking, stability, ease of use, controlled cooking and easy incorporation to a thermal energy storage (TES) unit.

Indirect solar cookers with different designs are shown in Figure 3, as presented by Muthusivagami et al. (2010). A major disadvantage of indirect solar cookers is that they are rather expensive to build and maintain. Another disadvantage is that some of the solar cookers, especially, those using solar concentrators require constant tracking.

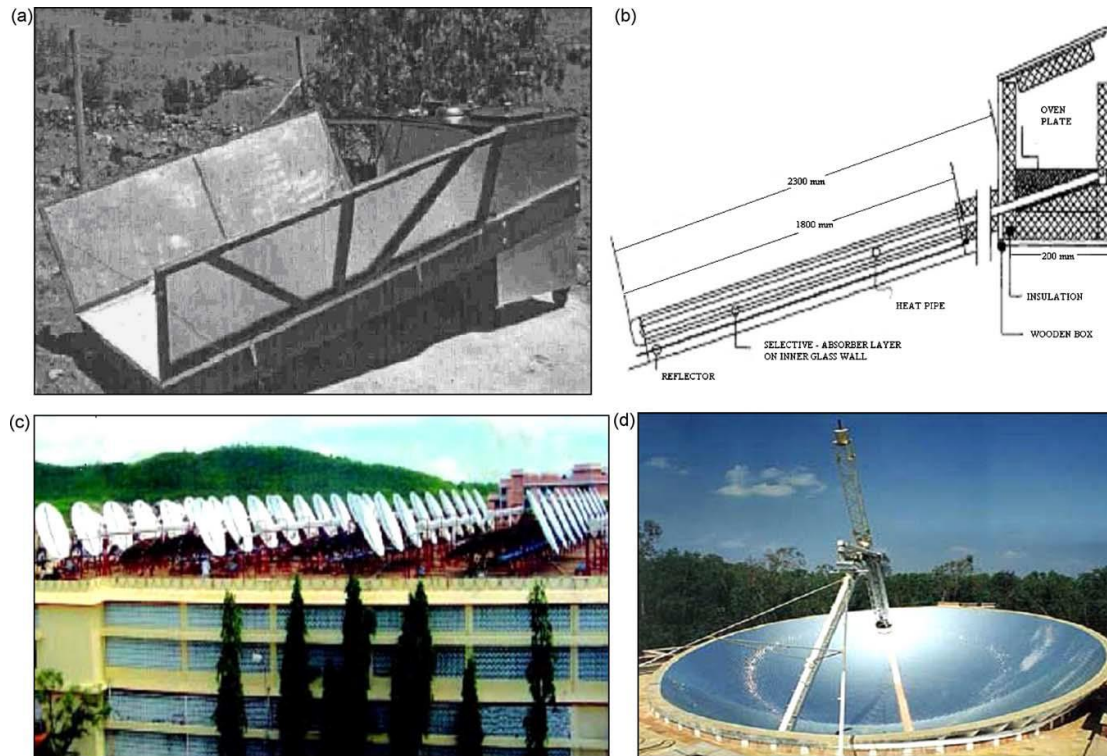


Figure 3: Indirect types of solar cookers (a) with flat plate collector, (b) with evacuated tube collector, (c) parabolic concentrators at Tirumala Tirupathi Devasthanam and (d) spherical reflectors at Auroville (Muthusivagami et al. 2010).

1.2. Thermal energy storage (TES) for solar cookers

The major disadvantage of solar cookers is that they cannot be used during periods when the sun is not available, for example at night or during cloudy periods. To cater for the intermittency of the solar energy resource, solar cookers can be designed with TES storage units to enhance their effectiveness during non-sunshine periods.

The viable options of storing thermal energy for solar cookers are sensible heat thermal energy storage (SHTES) and latent heat thermal energy storage (LHTES). In SHTES, heat is stored by heating a material (or extracted by cooling) without any change in its phase. The specific heat capacity of the material and the temperature change during the heating cycle determines the amount of heat that can be stored in a given volume. A variety of materials can be used for such systems, and these include water, heat transfer oils, inorganic molten salts, pebbles and rocks. With solids, the material is often in the porous form and heat is stored or extracted by the flow of a fluid through the solid pores or the bed voids.

LHTES is based on the heat absorbed or released when a storage material undergoes a phase change. A solid phase change material (PCM) is a material with a high heat of fusion, when melting at a certain temperature, is capable of storing large amounts of energy. This energy is then released when the material solidifies. Since heat is absorbed or released when the material changes phase, PCMs are classified as LHTES units. PCMs can be classified as organic, inorganic and eutectic (including metallic alloys). Organic PCMs include fatty acids and paraffins, while inorganic PCMs are usually hydrated salts. A eutectic PCM is a melting composition of two or more components.

2. A brief review on solar cookers with thermal energy storage

2.1. Solar cookers with sensible heat thermal energy storage (SHTES)

Direct focusing solar cookers using sensible heat storage are rather rare, and only a few designs using SHTES have been proposed which operate principally in the indirect mode. A portable solar cooker and water heater using a parabolic concentrator shown in Figure 5 was designed by Badran et al. (2010). The device was able to cook food and heat up water in the storage tank. An umbrella type of parabolic dish concentrator which uses oil TES material was designed by Chandra et al. (2013) to heat up the oil which was in thermal contact with the cooking surface. At night, water is poured through a funnel that leads into the oil storage vessel. The water in the pipes gets heated because of the hot oil inside the storage container. The water turns into vapour and comes out through pores which are used to cook rice.



Figure 5: Portable solar cooker and water heater designed by Badran et al. (2010).

The simulation investigation was done by Mawire et al. (2009) using an experimentally validated one dimensional model for SHTES material in a solar cooker shown in Figure 6. The study compared three SHTES material namely; fused silica, alumina and stainless steel. The thermal performance of these materials was evaluated in terms of the axial temperature distribution, the total energy stored, the total exergy stored and the transient charging efficiency. The results obtained indicated that not only was the value of the total amount of energy stored important for the thermal performance of oil-pebble-bed TES systems but also that the amount of exergy stored and the degree of thermal stratification should be considered. A high ratio of the total exergy to the total energy stored was suggested as a good measure of the thermal performance of the pebble material. From the simulations, it was concluded that fused silica possessed the best thermal stratification performance whilst stainless steel achieved the highest total energy stored at the expense of a greater drop in the energy from the peak value as charging progressed. Alumina, on the other-hand, was found to have the fastest energy storage rate and had the best exergy to energy ratio variation during the charging process which was comparable to that of fused silica at the end of the charging process.

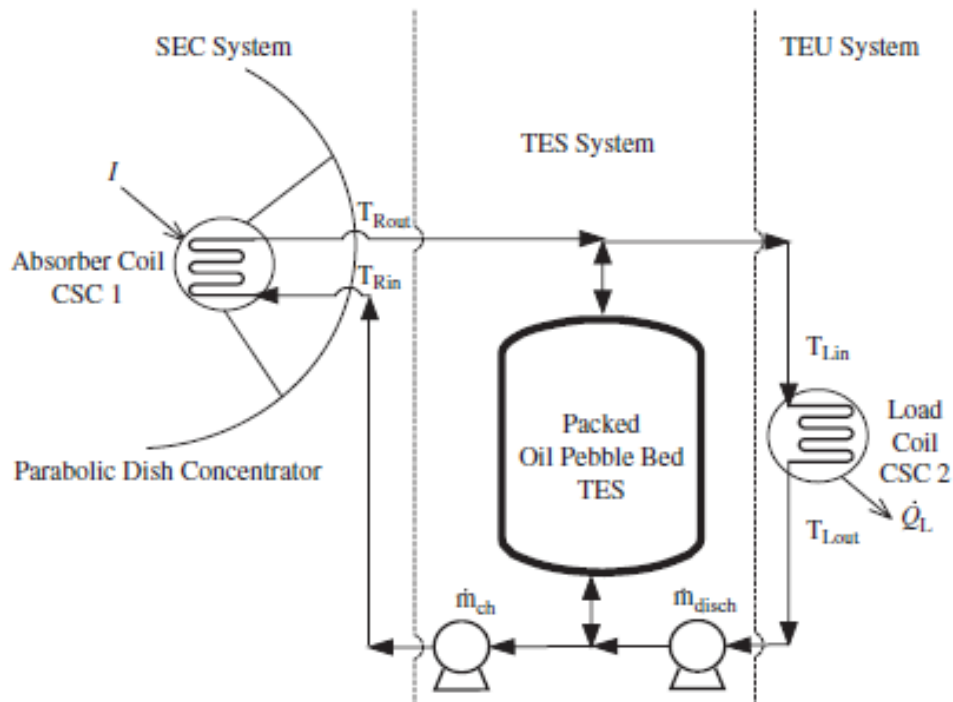


Figure 6: A conceptual diagram of the solar TES and cooking system proposed by Mawire et al. (2008) showing solar energy capture (SEC), thermal energy storage (TES) and thermal energy utilisation (TEU).

Charging experiments of an oil based heat storage tank coupled with a low cost small scale solar parabolic trough for cooking purposes were done by Mussard and Nydal (2013) using the system

shown in Figure 7. Two tests were carried; one with an uninsulated absorber and the other with an insulated absorber. The results showed that at low temperatures, the absorber without insulation was much more effective. When the storage temperature approached 200 °C, the insulated tube became more effective. An SK-14 direct focussing solar cooker without heat storage was experimentally compared with a solar parabolic trough solar cooker using a storage unit (Mussard et al. 2013). The SK-14 cooker performed better than the solar cooker with storage due to the non-optimised design of the cooking surface which could be improved to match that of an electrical cooker.

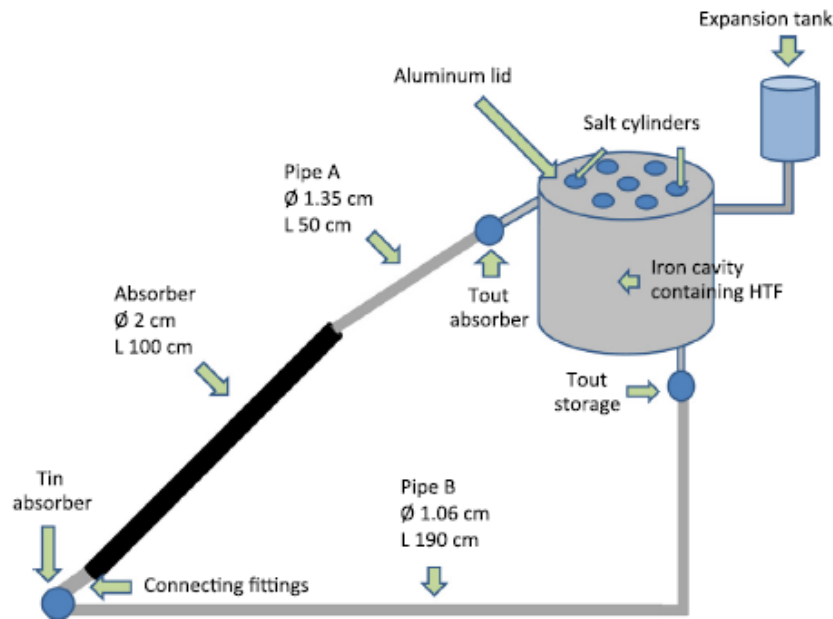


Figure 7: Schematic view of the oil-based storage coupled with a self-circulated loop.

Designs of oven solar cookers or solar box cookers using sensible heat storage are also limited and a few designs have been made. A hot box solar cooker which used engine oil as a storage material was designed, fabricated and tested so that cooking could be performed at late evening times (Nahar, 2003). A photograph of the hot box storage solar cooker is shown in Figure 8 (Muthusivagami et al., 2010). The device was a double-walled solar hot box. The outer box was made of a galvanized steel sheet and the inner box was also a made of a double-walled aluminum sheet tray. The space between the inner trays was filled with 5.0 kg of used engine oil, and it was completely sealed. The space between the outer tray and the outer box was filled with glass wool insulation and separated by a wooden frame. The inner tray was painted black with black board paint. Nahar (2003) found out that the maximum stagnation temperature achieved inside the cooking chambers of the hot box solar cooker with storage material was the same as that of the hot box solar cooker without storage during day time, but it was 23 °C more in the storage solar cooker from 17:00 hrs to 24:00 hrs. The efficiency of the hot box storage solar cooker was found to be 27.5%. Cooking trials were also conducted with rice and green vegetables using the hot box storage cooker and with a hot box solar cooker without

storage from 17:30 hrs. The food inside the hot box storage cooker was cooked perfectly by 20:00 hrs, while the food inside the hot box cooker without storage was not cooked at all.



Figure 8: A photograph of the hot box storage cooker designed by Nahar (2003) (Muthusivagami et al., 2010)

The experimental thermal performance evaluation of a box type solar cooker using stone pebbles as TES material was done in Nepal (Shrestha and Byanjankar, 2007). For comparisons purposes, a cooker without stone pebbles was tested with a solar cooker with stone pebbles. The experimental results of both no-load testing and load testing showed that with stone pebbles inside the cooker, the time for cooking food could be delayed by considerable amount of time of about two hours after noon thus making the cooker suitable for evening meals due to the stored heat. Alozie et al. (2010) compared the performance of three solar hot boxes namely; (a) a solar hot box cooker without collectors, (b) a solar hot box cooker with collectors and (c) a solar hot box cooker with heat storage stone pebbles. Results indicated that the storage type of cooker could keep temperatures high enough at around 90 °C by 18:00 hrs for the possibility of evening cooking.

Oven type of solar cookers with SHTES have disadvantages of achieving low temperatures due to low efficiencies, slow cooking speeds and their limited capacity depending of the size of the cookers.

The most popular designs of solar cookers with SHTES are indirect solar cookers and substantial research has been done on these kinds of cookers. Flat plate indirect solar cookers, evacuated tube indirect solar cookers and concentrating type of indirect solar cookers using SHTES have been designed and a few of these designs are presented here.

A flat plate collector natural convection solar cooker with short term coconut oil TES was designed by Harakasingh et al. (1996). A double-glazed flat-plate collector covered with a selective surface was used as the power source for the solar cooker. Coconut oil was used as the heat transfer fluid and at the highest part of the thermo-syphon loop there was an oil bath in which two cooking pots were immersed to facilitate good heat transfer between the working fluid and the cooking pots.

Temperatures of approximately 150°C could be achieved between 10:00 hrs and 14:00 hrs under high solar radiation conditions. A flat plate collector indirect solar cooker using a vegetable oil as the heat transfer fluid and an oil/pebble bed TES system which also uses the thermo-syphon principle is shown in the photograph of Figure 9 (Schwarzer and daSilva, 2003). The oil was heated up in the collector with reflectors and moved by a natural flow mechanism to the cooking unit. Manually controlled valves guided the oil flow-rate either to the pots or to the storage tank. This type of solar cooker could be in-cooperated into a kitchen. The major advantages of this solar cooker were the possibility of indoor cooking, the use of a thermal storage tank to keep the food warm for longer periods of time for night cooking and the high temperatures of the working fluid reached in a short period of time allowing fast cooking as well as frying and roasting.



Figure 9: Indirect flat plate collector solar cooker with TES designed by Schwarzer and daSilva (2003)

Solar cookers based on conventional flat-plate solar collectors suffer from the drawback of the performance deteriorating due to the reversed cycles during night and cloudy periods of the day. The further disadvantages are that they are expensive to construct and the non-removable pots make cleaning and dishing of food difficult. Evacuated tube solar collectors (ETSCs) have a number of advantages over other types of solar collectors. These advantages include; the need for solar tracking is removed since they operate with direct as well as diffuse solar radiation, high temperatures can be achieved, cooking can take place in the shade or inside a building because of the spatial separation of collecting part and oven unit, their thermal conductance is extremely high and the heat transfer between the evaporator and the condenser section is nearly isothermal.

Kumar et al. (2001) designed the community type solar pressure cooker based on an ETSC. It consisted of an evacuated tubular solar collector and a pressure cooker which acted both as a cooking unit and a TES unit. Both units were coupled together by a heat exchanger. The incident solar irradiance fell onto the collector and heated up the working fluid inside the tubes. The vaporized fluid rose upwards to the heat exchanger, and transferred energy by condensation to the water flowing in the secondary loop of the heat exchanger. The condensed fluid then returned back to the

collector tubes and the process of heat transfer continued. Batch type of cooking was suggested by the experimental results. In Australia, Morrison et al. (1993) developed an indoor type of solar cooker using evacuated heat pipes with a pressurized water heat storage tank with an appeal similar to a normal electrical hot plate cooker. The cooker used a sophisticated system whereby steam generated in an evacuated tubular absorber was transferred via a long pipe system into a storage vessel connected to the cooking plates. The design developed by Esen (2004) of an evacuated tube solar collector using different heat transfer refrigerants in the heat pipes with an oil TES system is shown in Figure 10. The oil reservoir of a capacity of 9 litres was used for heat storage allowing the cooker to be preheated, and the foods to be kept warm, after cooking. The maximum temperature obtained in a pot containing 7 litres of edible oil was 175 °C. The cooker was successfully used to cook several foods and cooking processes were performed with the cooker in 27–70 min periods.

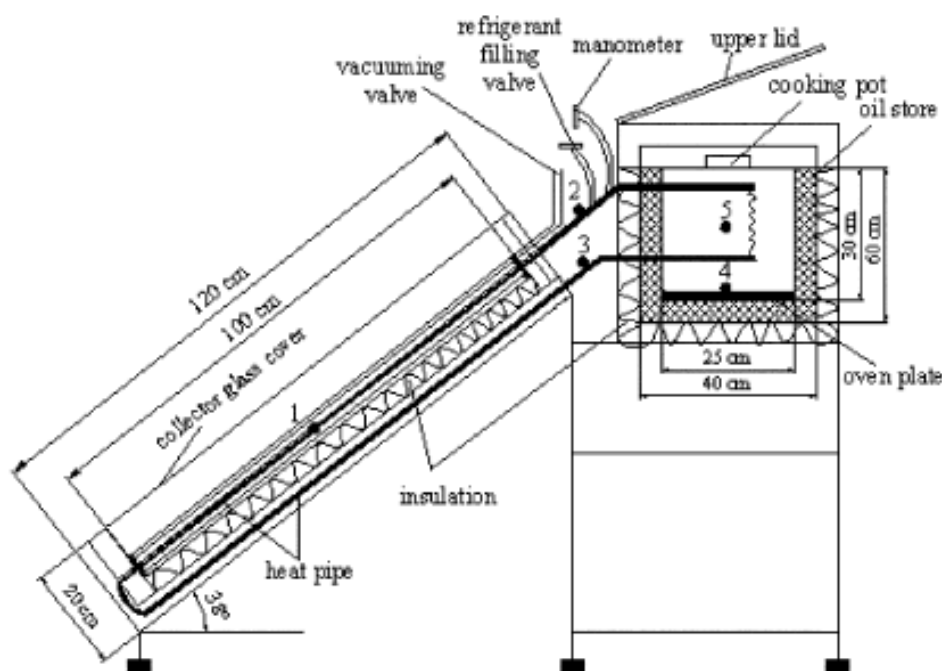


Figure 10: Cross-sectional view of the evacuated collector tube with integrated heat pipes and an oil thermal storage system developed by Esen (2004).

Evacuated tube indirect solar cookers with thermal energy storage are rather complex and expensive to fabricate. Added to this disadvantage, the tubes tend to deteriorate with time thus reducing their overall performance. Concentrating type of solar collectors can achieve higher temperatures than the other types of solar collectors hence it is possible to perform high temperature cooking applications like baking and frying. A hybrid indirect solar cooker with an oil TES system and a parabolic dish concentrator was designed by Prasanna and Umanand (2011). A schematic diagram showing the hybrid solar cooking system is shown in Figure 11. The energy source was a combination of solar thermal energy and liquefied petroleum gas (LPG). Solar thermal energy was transferred to the kitchen by means of a circulating fluid. The transfer of solar heat was a two-fold process whereby the

energy from the collector was transferred first to an intermediate oil storage tank, and this energy was subsequently transferred from the storage tank to the cooking load. During periods when the sun was not available, stored heat, LPG or electricity could be used to cook foods such that cooking could be carried out at any time during the day.

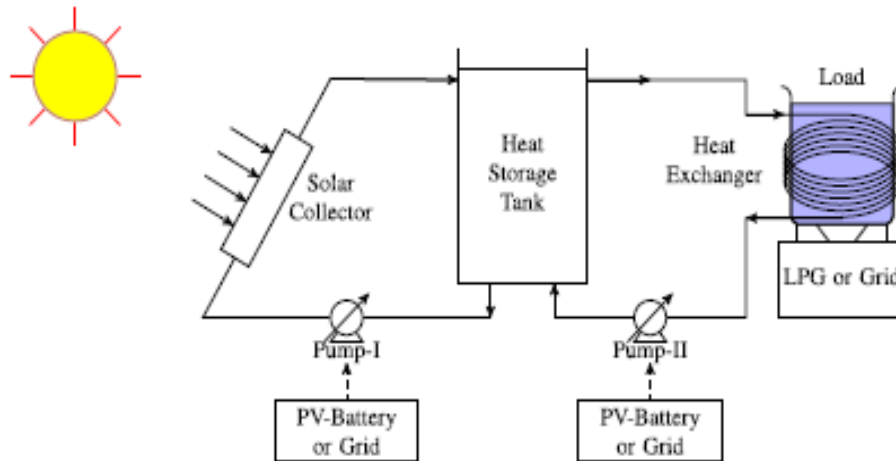


Figure 11: Block diagram of hybrid solar cooking system (Prasanna and Umanand, 2011).

An innovative design of a hawkeye solar cooker was designed by students at the Universities of Iowa and California (Hawkeye solar cooker, 2013) which used sand as a sensible heat TES unit. A compound parabolic reflector was used to concentrate the solar radiation onto an absorbing box. The cooker was able to cook food and store heat. Instead of using a heat transfer fluid in indirect concentrating solar cookers, a secondary reflector could be used to focus the solar radiation onto a cooking device or onto a cooking device with a TES unit. Nyahoro et al. (1997) performed charging and discharging simulations using cast iron and granite charging blocks and the results obtained showed that cast iron had more energy stored and less energy lost during a charging and discharging sequence. The results also indicated that the height of the storage block should be at least one-fifth of the diameter of the block after different heights and diameters were simulated.

2.2. Solar cookers with latent heat thermal energy storage (LHTES)

Latent heat TES based on phase change material has the advantages of a higher energy storage density and an isothermal behaviour during phase change as compared to SHTES material. This means that there is a significant decrease in the storage volume when using LHTES material as compared to SHTES material.

Direct focusing solar cookers using LHTES are an emerging technology, and there are only very few recent research studies that have been done on these types of solar cookers. An experimental investigation of a solar cooker based on a parabolic dish collector with a PCM storage unit for Indian climatic conditions was performed by Chaudhary et al. (2013). Figure 12 shows a schematic diagram and a photograph of the receiver of the solar cooker. The solar cooker with the PCM TES unit was kept on the absorber plate of a parabolic dish concentrator. During day time, acetanilide PCM stored

heat and during the evening, the solar cooker was kept in an insulator box, and the PCM delivered heat to the food. To enhance the performance of 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 along with glazing. Results obtained indicated that the solar cooker with outer surface painted black along with glazing performed better when compared to the other two cases.

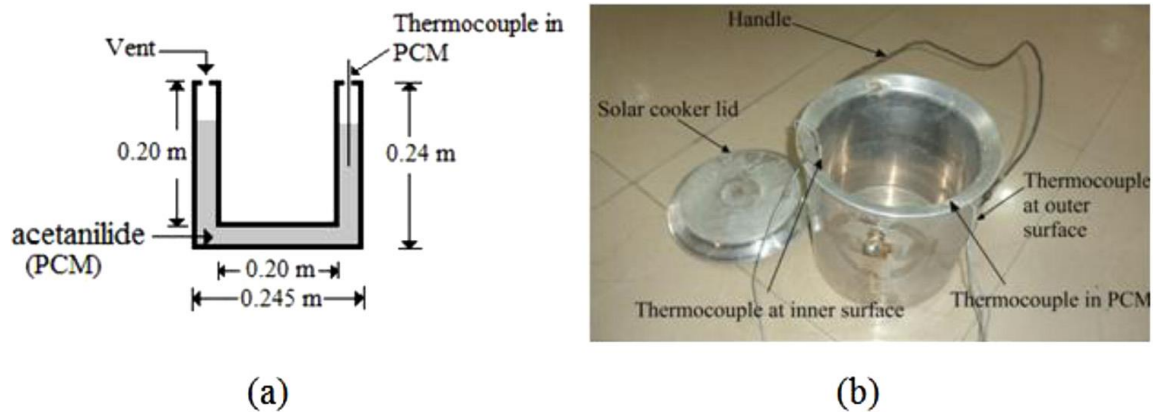
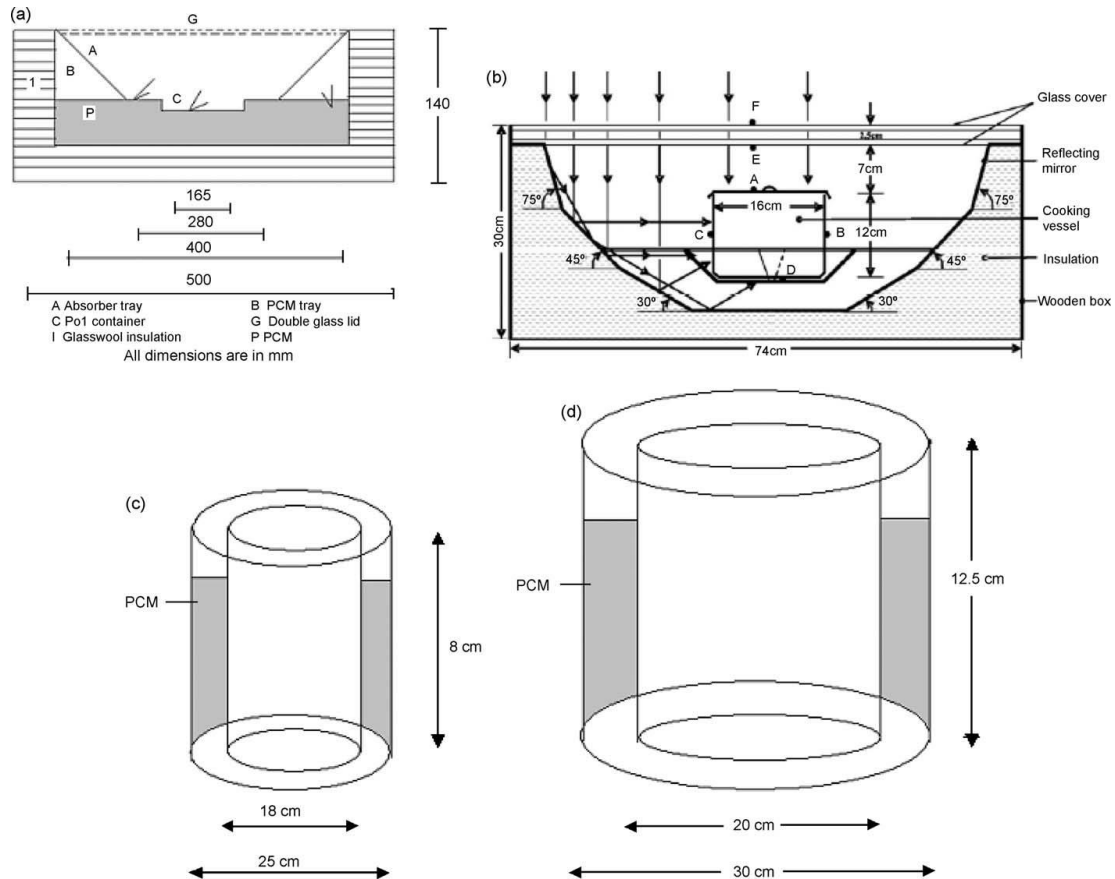


Figure 12: (a) Schematic diagram (b) Photograph of the solar cooker receiver designed by Chaudhary et al. (2013).

A portable solar cooker of a standard concentrating parabolic type that incorporated a daily PCM TES unit was evaluated by Lecuona et al. (2013). The storage unit was made by using two conventional coaxial cylindrical cooking pots, an internal one and a larger external one. The space between the two coaxial pots was filled with PCM forming an intermediate jacket. A model was developed to evaluate the thermal performance of the cooker which was validated with experimental results. Two types of PCMs were evaluated which were technical grade paraffin and erythritol. Results obtained indicated that cooking lunch for a family was possible with the simultaneous storage of heat during the day. Keeping the utensil afterwards, inside an insulating box indoors allowed for cooking dinner with the retained heat, and also allowed for using the heat for breakfast in the next day. Other types of direct focusing solar cookers using PCM storage have also been reported (Foong et al., 2011; Arunasalam et al., 2012; Abinaya and Rajakumar, 2013). Direct focusing solar cookers with PCM storage have disadvantages of the PCM being relatively expensive as compared to SHTES, thermal degradation of the PCM after numerous charging and discharging cycles, poor heat transfer due to the low thermal conductivity of the PCM material, and the need of a solar tracking mechanism.

Buddhi and Sahoo (1997) designed and tested the solar cooker shown in Figure 13a with LHTES for cooking food late in the evening. In their design, the PCM was filled below the absorbing plate. Commercial grade stearic acid was used as the PCM. In this design, the rate of heat transfer from the PCM to the cooking pot during the discharging mode of the PCM was slow, and more time was required for cooking food in the evening. Figure 13b shows the design by Domanski et al. (1995) of a solar hot box cooker with LHTES. The possibility of cooking during non-sunshine hours using PCMs

as storage media was investigated. Two concentric cylindrical vessels made from aluminum were connected together at their tops using four screws to form a double-walled vessel with a gap between the outer and inner walls. The gap between the outer and the inner vessels was filled with 1.1 kg of stearic acid (melting temperature 69.8°C) or 2 kg of magnesium nitrate hexahydrate (melting temperature 89.8°C) which left sufficient space for expansion of the PCMs during melting. The cooker performance was evaluated in terms of charging and discharging times of the PCMs under different conditions. Results obtained indicated that the performance depended on the solar irradiance, mass of the cooking medium and the thermo-physical properties of the PCM. The overall efficiency of the



cooker during discharging of the PCM was found to be 3–4 times greater than that for steam and heat-pipe solar cookers, which can be used for indoor cooking.

Figure 13: Oven type solar cookers with latent heat storage: (a) Buddhi et al. model, (b) Domanski et al. model, (c) Sharma et al. model and (d) Buddhi et al. model.

Sharma et al. (2000) designed and developed a cylindrical PCM storage unit for a box type solar cooker to cook food late in the evening as shown in Figure 13c. The PCM surrounded the cooking vessel, hence the rate of heat transfer between the PCM and the food was high. The designed PCM container had two hollow concentric aluminum cylinders and the space between the cylinders was filled with acetamide (melting point 82.8°C , latent heat of fusion 263 kJ/kg) as the PCM. To enhance the rate of heat transfer between the PCM and the inner wall of the PCM container, eight fins were

welded at the inner wall of the PCM container. Results obtained from the experimental tests showed that by using 2 kg of acetamide as the PCM, a second batch of food could be cooked if it was loaded before 3:30 pm during the winter season. The researchers also recommended that the melting temperature of the PCM should be between 105 °C and 110 °C for evening cooking, and thus there was a need to identify a storage material with an appropriate melting point and quantity which could be used to cook food late in the evening. Buddhi et al. (2003) developed a latent heat storage unit shown in Figure 13d for a box type of solar cooker with three reflectors. They used acetanilide (melting point 118.9 °C, latent heat of fusion 222 kJ/kg) as a PCM for night cooking. From the experimental results, the authors concluded that cooking experiments were successfully conducted for evening time cooking up to 20:00 hrs with 4.0 kg of PCM used in the storage unit.

The major drawbacks of oven solar cookers with PCM storage units are the low heat transfer rates and the low operating temperatures thus different heat transfer enhancements mechanisms have to be employed to improve their efficiencies.

Hussein et al. (2008) developed a novel indirect solar cooker shown in Figure 14 with outdoor elliptical cross-section wickless heat pipes coupled to a flat-plate solar collector with an integrated indoor PCM thermal energy storage and cooking unit. Two plane reflectors were used to enhance the solar radiation incident onto the collector, while magnesium nitrate hexahydrate (melting temperature 89 °C and a latent heat of fusion of 134 kJ/kg) was used as the PCM inside the indoor cooking unit of the cooker. Different experiments were performed with the solar cooker without loading and with different loads at different loading times to study the benefit of the elliptical cross-section wickless heat pipes and the PCM in the indirect solar cooker. The PCM was evaluated in terms of cooking food at noon, cooking food in the evening and in terms of keeping food warm at night and early in the morning. The experimental results indicated that the solar cooker could be used to successfully cook different kinds of meals at noon, afternoon and evening times. The cooker could also be used for heating or keeping meals hot at night and early in the morning.

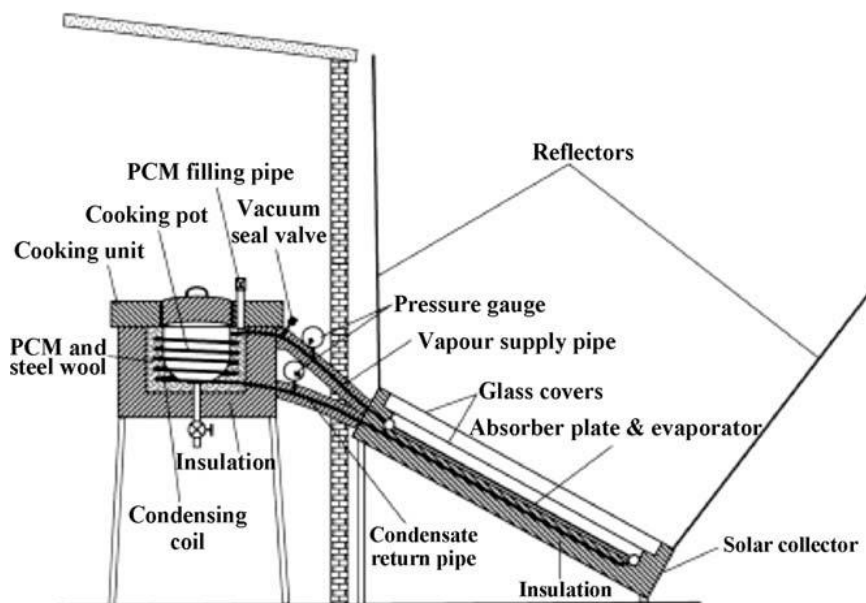


Figure 14: Latent heat storage type flat plate solar cooker using magnesium nitrate hexahydrate as PCM developed by Hussein et al. (2008).

An indirect solar cooker based on an evacuated tube solar collector (ETSC) with a PCM storage unit was developed by Sharma et al. (2005). A schematic diagram of the indirect solar cooker is shown in Figure 15. The cooker consists of an ETSC, a closed loop pumping line-containing water as the heat transfer fluid (HTF), a PCM storage unit, a cooking unit, a pump, a relief valve, a flow meter and a stainless steel tubular heat exchanger. The PCM storage unit had two hollow concentric aluminum cylinders and the space between the cylinders was filled with 45 kg erythritol (melting point 118 °C, latent heat of fusion 339.8 kJ/ kg). A pump circulated the heated water (HTF) from the ETSC through the insulated pipes to the PCM storage unit by a using a stainless steel tubular heat exchanger that was wrapped around the cooking unit. During sunshine hours, heated water transferred its heat to the PCM and stored in it in the form of latent heat through the stainless steel tubular heat exchanger. The stored heat was utilized to cook food in the evening or when sun intensity was not sufficient to cook food. Results of the experimental tests performed concluded that evening and noon time cooking were possible. Evening time cooking was also found to be faster than noon time cooking. Experimental results also indicated that this solar cooker yielded satisfactory performance despite of the low heat transfer. A modified design of the heat exchanger in the TES unit was suggested to enhance the rate of heat transfer in that solar cooker.

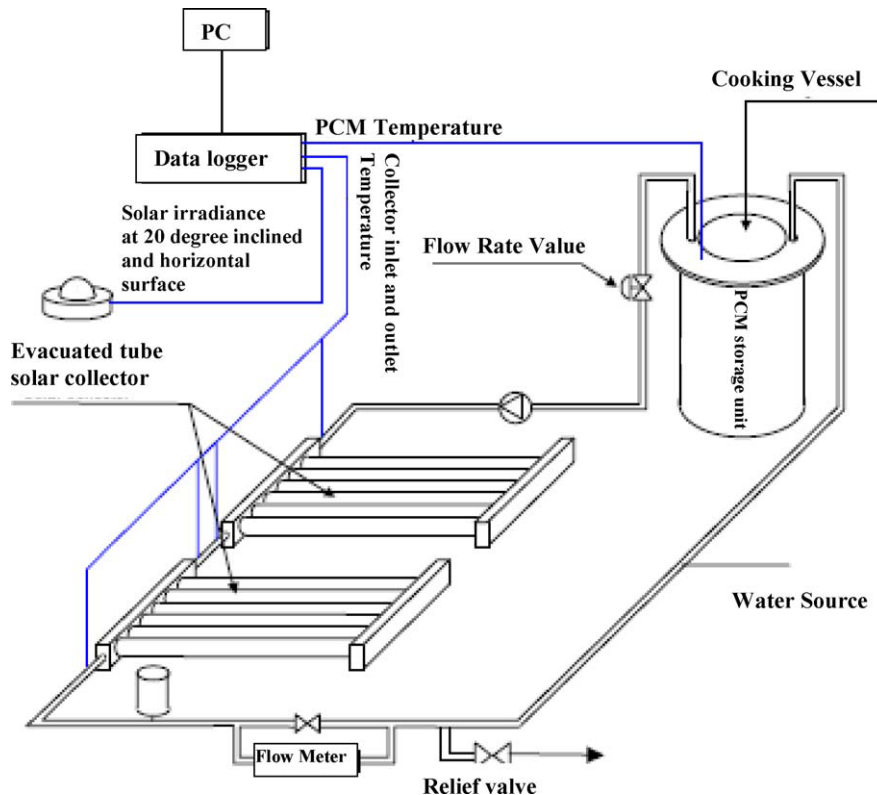


Figure 15: Schematic diagram of the indirect solar cooker based on evacuated tube solar collector with a PCM storage unit designed by Sharma et al. (2005).

Besides using flat plate collectors or ETSCs, concentrating collectors may be employed with a LHTES unit for indirect solar cooking applications. One such design has been discussed earlier (Mussard and Nydal, 2013). Murty et al. (2007) designed and developed an inclined heat exchanger unit for an SK-14 parabolic solar concentrator (PSC) for off-place cooking. The principal objective of this study was to use an inclined HTF column as a heat exchanger unit, and to evaluate the thermal performance of a PSC assisted with an inclined cylindrical heat exchanger unit for off-place cooking with and without phase change material (PCM). Experiments were conducted for cooking foods on a normal day with commercial-grade sodium acetate (melting point is 104 °C and latent heat of fusion is 230 kJ/kg) and acetanilide (melting point is 115.42 °C and latent heat of fusion is 189.4 kJ/kg) as the LHTES materials. The cooking experiments were conducted with the PCMs as TES media, during charging and discharging of the PCMs. It was observed that the cooking time was less during discharging of the PCMs.

Indirect solar cookers using PCMs have major drawbacks of a poor heat transfer, complexity in design and the expense in their construction.

3. Research gaps in solar cookers with thermal energy storage

- i. There have been limited research studies on solar cookers with TES systems using heat transfer oils. Heat transfer oils are particularly favourable since temperatures above the boiling point of water (100 °C) can be achieved which are suitable for frying and baking. Besides this, storage tanks using oil are simplified since they do not have to be pressurized as with the case of water which is cheaper and readily available.
- ii. The use of locally available TES materials in a particular region or country for enhancing the performance of solar cookers is rather limited.
- iii. Packed bed storage systems using oil heat transfer fluids for domestic cooking applications have been rarely reported in recent literature. The packed bed storage configuration has better heat transfer characteristics than other types of configurations such as the shell and tube especially when latent heat thermal energy storage systems are considered.
- iv. Storage type of cooking vessels have been rarely reported. These vessels can store heat during periods of high solar radiation, and use it during non-sunshine periods.
- v. Hybrid solar cooking and TES storage systems using another energy source have been rarely reported. These systems are more practical especially when there are extended periods of low solar radiations. The alternative energy source can be used for cooking.
- vi. TES applications of metallic phase change materials (PCMs) for higher volumetric storage densities and higher thermal conductivities that have appeared in recent literature are rather limited.

4. Best previous work on thermal energy storage for solar cookers

In order to address some of the research gaps identified, our previous work focused mainly on oil and oil/pebble-bed sensible heat thermal energy storage systems for an indirect solar cooking application.

In the 2009, Applied Energy paper (**Impact Factor: 8.426 (2018), cited 56 times in Scopus, Mawire et al. 2009**), we presented one of the first ever simulated performance of sensible heat storage materials for pebble bed TES systems for a solar cooking application. The results of the different simulations indicated that not only was the value of the total amount of energy stored important for the thermal performance of oil/pebble-bed systems but also the total exergy stored and the thermal stratification should be considered. A high ratio of the total exergy to the total energy stored was suggested as a good measure of thermal performance. From the simulations, it was concluded that fused silica possessed the best thermal stratification performance, whilst stainless steel achieved the highest total energy stored at the expense of a greater drop from the peak value as charging progresses. Alumina, on the other-hand, was found to have the fastest energy storage rate and had the best exergy to energy ratio variation during the charging process which was comparable to fused silica at the end of the charging process.

In 2014, the Energy for Sustainable Development paper, (**Impact Factor: 3.307 (2018), cited 45 times in Scopus, Mawire and Taole (2014)**), presented the experimental energy and exergy performance of a solar receiver for a domestic parabolic dish concentrator for teaching purposes. The thermal performance was evaluated using energy and exergy analyses. The exergy factor parameter was proposed for quantifying the thermal performance. The exergy factor was found to be high under conditions of high solar radiation and under high operating temperatures. The heat loss factor of the receiver was determined to be around 4.6 W/K. An optical efficiency of around 52 % for parabolic dish system was determined under high solar radiation conditions. This experimental setup could be used as teaching tool for people with little or no knowledge about solar dish concentrators due its simplicity and the basic mathematical formulations applied.

The 2011 Applied Energy paper, (**Impact Factor: 8.426 (2018), cited 35 times in Scopus, Mawire and Taole (2014)**) presented the first ever comparison of experimental thermal stratification parameters for an oil/pebble-bed thermal energy storage system of an indirect solar cooker during charging. Six different experimental thermal stratification evaluation parameters during charging for an oil/pebble bed TES system were presented. The six parameters evaluated were the temperature distribution along the height of the storage tank at different time intervals, the charging energy efficiency, the charging exergy efficiency, the stratification number, the Reynolds number and the Richardson number. Temperature distribution along the height of the storage tank at different time intervals and the stratification number were the only parameters found to describe thermal stratification quantitatively adequately.

The experimental characterisation of a thermal energy storage system using temperature and power controlled charging was presented in the 2008 Renewable Energy paper (**Impact Factor: 5.439 (2018), cited 34 times in Scopus, Mawire and McPherson (2008)**). Results from temperature control experiments indicated that the proposed control structure performed quite well since very strict control of the outlet charging temperature was not necessary. The results also indicated that as the set temperature was changed, offset errors were created. The input power to an electrical hot plate simulating the collector/concentrator was also controlled to simulate the daily sinusoidal variation in the amount of solar radiation. A combined feedforward and feedback (integral) control structure was implemented for power control. The temperature profile of the pebble bed TES was also measured during the charging experiments. Thermal stratification was evident in the pebble bed storage as was shown by the results. Changes in the set temperature points and artificially imposed disturbances affected the profile of the pebble bed storage. The developed control strategies could be used to characterise TES systems for solar applications without designing an actual solar concentrator.

In 2008, the Solar Energy Materials and Solar Cells paper (**Impact Factor: 6.019 (2018), cited 32 times in Scopus, Mawire et al. (2008)**), the first ever simulated energy and analyses of the charging of an oil-pebble bed thermal energy storage system for a solar cooker were presented. Energy balance equations were used to model a solar energy capture (SEC) system and an oil-pebble bed TES system for a proposed solar cooker. The predictions of the models were used to perform energy and exergy analyses of the TES system using two different charging methods. The constant-temperature charging method resulted in a larger degree of thermal stratification and energy stored as compared to the constant-flowrate charging method. However, for lower solar radiation conditions, the energy and exergy rates for the constant-temperature method were slightly lower than those for the constant-flowrate method. Greater exergy rates and exergy efficiencies were obtained when using the constant-temperature method at high solar radiation conditions. The exergy efficiencies were significantly smaller than the energy efficiencies for both methods. It was found that increasing the flowrate led to an increase in the exergy efficiency and this occurred at the expense of reducing the charging temperature. This was because the rate of heat transfer was increased with an increase in flowrate. At high solar radiation conditions, the constant-temperature method was seen to perform better than the constant-flowrate method in terms of the exergy and energy efficiencies. At low solar radiation conditions, low charging temperatures were suggested and the constant-flowrate method was found to be more viable during these conditions.

5. Recent work on thermal energy storage for solar cookers

In recent times, our research group has started looking more into locally available materials, for thermal energy storage for solar cooking applications. Our recent work mainly focussed on experimental work on the characterisation of both locally available sensible heat and latent heat storage materials in the medium temperature range of 100-250 °C for solar cooking applications.

In 2014, an experimental performance of thermal energy storage oils for solar cookers during charging was presented in the paper published in Applied Thermal Engineering (**Impact Factor:**

4.022 (2018), cited 22 times in Scopus, Mawire et al. (2014)). Charging experiments to evaluate the thermal performance of three thermal energy storage oils for solar cookers were presented. The three thermal oils evaluated were Sunflower Oil, Shell Thermia C and Shell Thermia B. Energy and exergy based thermal performance parameters were evaluated. A new parameter, the exergy factor, was proposed which evaluated the ratio of the exergy content to the energy content. Sunflower Oil performed better than the other thermal oils under high power charging. Thermal performances of the oils were comparable under low power charging.

In the 2016, Journal of Energy Storage paper, **(Impact Factor: 3.516 (2018), cited 18 times in Scopus, Mawire (2016))**, the performance of Sunflower Oil as sensible heat storage medium for domestic applications was evaluated experimentally. The thermal performance of Sunflower Oil was evaluated during charging, 24 h heat retention and discharging cycles. Results of charging revealed that high temperature charging was the most viable option. Heat retention results during 24 h showed that high temperatures resulted in more heat losses during the cool-down heat retention processes. An optimal heat retention temperature was also suggested by the results. An optimal discharging flow-rate was also suggested by the discharging results. This was a compromise between obtaining a high rate of heat transfer and using the stored energy more effectively.

The 2017 Applied Thermal Engineering paper **(Impact Factor: 4.022 (2018), cited 6 times in Scopus, Shobo and Mawire (2017))** presented experimentally a comparison of the thermal performances of acetanilide, meso-erythritol and an In-Sn alloy, as phase change materials (PCMs) for medium temperature applications, inside separate, spherical aluminium capsules. Meso-erythritol showed the best charging performance. Sub-cooling affected the quality of heat discharged by acetanilide and meso-erythritol. The In-Sn alloy was found to be a superior PCM for medium temperature heating applications as compared to the other two PCMs.

In 2018, the Journal of the Brazilian Society of Mechanical Sciences and Engineering **paper (Impact Factor 1.743, 2018, cited twice in Scopus, Shobo et al. (2018))** presented rapid thermal cycling experimental results of three phase change materials (PCMs) for cooking applications. The suitability of the use of acetanilide, meso-erythritol and In-48Sn as phase change materials (PCMs) in latent heat thermal storage systems (LHTES) for cooking applications was investigated under rapid charging and heat retrieval conditions. In-48Sn showed the greatest thermal stability, while acetanilide showed the least. Acetanilide and meso-erythritol exhibited large degrees of super-cooling making them undesirable to be used in a LHTES unit for cooking applications under rapid heating and cooling cycles. Though the cost implication of utilizing In-48Sn was much higher as compared with the other two PCMs, its good cycling stability and its average solidification temperature being within the desired cooking temperature made it a preferred PCM candidate under fast heat retrieval conditions than acetanilide and meso-erythritol. The International Journal of Green Energy paper **(Impact Factor 1.307, 2018, cited twice in Scopus, Mawire (2018))** published in 2018, performed experimental energy and exergy analyses of a discharging heat exchanger for a small hot-oil domestic storage tank. Experimental results were presented in terms of the discharging energy rates (power) and the discharging exergy rates for low (~4 ml/s) and high discharging flow rates (~8 ml/s). Water heating

energy rates, which were respectively maximized at approximately 600 W and 1200 W at low and high flow-rate discharging, were found to be higher than the discharging energy rates, which respectively maximized at 450 W and 900 W. These results indicated that the energy rates did not accurately evaluate the thermal performance of the discharging heat exchanger since the energy heating rate of the water was greater than that for the oil that heats it up, which was thermodynamically inconsistent. The exergy factor was proposed as a good design parameter for discharging heat exchangers.

Also in 2018, the Sustainable Energy Technologies and Assessment paper, **(Impact Factor 3.456, 2018, Cited 6 times in Scopus, Lugolole et al. (2018))** presented experimental results on the thermal performance comparison of three sensible heat thermal energy storage systems during charging cycles. Two packed storage systems using Sunflower Oil as the heat transfer fluid with two particle diameters (10.5mm and 31.9 mm) were compared with an oil only storage tank. The oil storage system charged up fastest, followed by the small pebbles thermal energy storage (TES) and lastly by the large pebbles TES due its lower thermal mass. The small pebbles TES had a faster rate of temperature rise than the big pebbles which experienced temperature drops. The oil TES system showed the fastest rise and drop of the stratification number due to its lower thermal mass. Generally, the slowest rate of drop in the stratification number profiles was seen with the large pebbles TES system for all flow-rates. The small pebbles TES performed better in terms of the thermal performance parameters evaluated in this study.

In 2019, the Journal of Energy Storage paper, **(Impact Factor: 3.516 (2018), Cited once in Scopus, Mawire et al. (2019))** presented an experimental comparison of the thermal performance of an eutectic solder (Sn63/Pb37) with that of three organic PCMs: erythritol, adipic acid, high density polyethylene (HDPE), inside similar spherical aluminium capsules is presented. Erythritol exhibited superior charging characteristics than the other PCMs in both the static and the dynamic modes. However, subcooling hampered the discharging performance of erythritol at high heat retrieval rates as the latent heat was discharged at temperatures lower than 100 °C. Sn63/Pb37 possessed stable charging and discharging performances in both the static and dynamic modes and showed the potential of being an ideal PCM for medium temperature applications. The solder's performance was second to that of erythritol even at low heat retrieval rates with latent heat discharged at the highest temperatures. Adipic acid presented relatively better charging and discharging performances than HDPE. Sn63/Pb37 showed good potential as a metallic PCM candidate for domestic thermal energy storage applications.

Also in 2019, Lugolole et al. (2019) presented the experimental analyses of sensible heat thermal energy storage systems during discharging in Sustainable Energy Technologies and Assessments **(Impact Factor 3.456, 2018, Lugolole et al. (2019))**. The discharging performance of a sunflower oil TES tank was compared with two sunflower oil/rock-bed TES tanks with two different granite rock pebble sizes. The average particle diameters of the rock pebbles were 10.5mm and 31.9mm respectively, with respective void fractions of 0.39 and 0.43 in the TES tanks. The TES systems were initially charged before the commencement of the discharging experiments. The temperature profiles,

energy rates, exergy rates, exergy recovery efficiency and stratification number profiles were evaluated during discharging cycles at flow rates of 4 mls^{-1} , 8 mls^{-1} and 12 mls^{-1} , respectively. The results obtained showed that the discharging times, discharging energy rate, exergy rates, exergy recovery efficiency and the TES tanks' de-stratification characteristics were all dependent on the HTF flow rates. The TES tanks showed better stratification with the lowest flow rate of 4 mls^{-1} than at the higher flow rates. The increase in de-stratification was due to the faster thermal mixing effect at the higher flow rates. The small pebbles TES experienced the greatest thermal de-stratification followed by the oil-only TES and finally by the big pebbles TES at the higher flow rates (8 mls^{-1} and 12 mls^{-1}). The greatest thermal exergy recovery was obtained with the TES tank filled with the large granite pebbles at all the flow rates. The results showed that the discharging performance of the oil-only TES was enhanced by the addition of the granite pebble bed particularly with the pebbles of an average size of 31.9 mm.

6. Future work on thermal energy storage for solar cookers

A combined thermal energy storage system for medium temperature applications will be evaluated experimentally and numerically. The combined system will be used for an indirect solar cooker to enhance its effectiveness during periods of low or no sunshine (cloudy and night periods). The combined system consists of a packed bed system of latent heat storage material and sensible heat storage material contained in a single storage tank. Latent heat storage material has advantages of a higher energy storage density and an isothermal behaviour during the release and storage of heat but its major disadvantages are its expensiveness, exhibition of sub-cooling and poor thermal conductivity. On the other-hand, sensible heat storage is cheaper, has better thermal conductivity and is readily available but its main disadvantage is the much lower energy storage density. Combining the two storage systems, will result in a cheaper storage system which possesses the advantages of both systems.

A single storage system consisting of one phase change material for latent heat storage and one sensible heat storage system will be tested experimentally using Sunflower Oil as the heat transfer fluid, which is available locally in South Africa. Three different locally available phase change materials and three different locally available sensible heat storage materials will be tested experimentally in the storage tank composed of one phase change material and one sensible heat storage material. Different storage ratios will also be tested. To optimize the system, numerical models will be developed and these will be validated with experimental results. Parametric studies for optimization will be carried with commercially available engineering and computational fluid dynamics approach. The possibility of using multiple phase change materials and multiple sensible heat storage materials will also be investigated numerically. Very little recent literature has been published on this concept.

One MSc student has done experimental tests on a combined system and graduated with a distinction in July 2019. Two other MSc students are currently doing experimental tests with different phase change materials. The first MSc student is comparing three different phase change material

packed bed systems. The second MSc student is researching experimentally on cascading different phase change materials with different melting temperatures in a single storage tank. Two and three system phase change material cascaded storage systems will be investigated.

A hybrid solar-electric cooking system will be characterized and optimized. The system has partly been developed. Different solar receivers will be tested experimentally and models for the system will be developed. The aim is to use low-wattage heat to charge up the storage tank as well as to use it to cook foods during periods of low sunshine. During periods when the sun is available, solar energy would be used to cook food thus reducing the demand for electrical energy for cooking. Simultaneous solar and electrical operation will also be tested. Four modes of operation are possible with our proposed design, (a) a solar only mode when sufficient solar radiation is available to cook the food, (b) a solar only mode with storage during non-peak periods when the solar energy is available and no cooking is done (c) a solar-electric mode during periods of low solar radiation such that electrical energy can be used to boost up the solar energy stored and (d) an electrical only mode when there are extended periods of no sunshine. The system is currently using an oil based thermal energy storage system. Research on suitable phase change materials (PCMs) to enhance the storage capacity is currently being conducted. MSc and PhD students will be engaged in the project.

The system consists of all-glass evacuated solar tube (EST) based compound parabolic concentrators (CPC) and a combined thermal energy storage system for medium temperature applications. The medium solar heat from the CPC solar collector is transferred to a combined heat storage system by circulating oil through a finned U-shaped tube which is inserted within the EST. The combined heat storage system will be used for an indirect solar cooker to enhance its effectiveness during periods of low or no sunshine (cloudy and night periods). The combined system consists of a packed bed system of latent heat storage material and sensible heat storage material contained in a single storage tank.

An EST based CPC solar collector has the advantages of being simpler in structure, it needs no solar tracking, and it is thermally stable for the temperatures in the range of 100 to 200 °C. Latent heat storage material has advantages of a higher energy storage density and an isothermal behaviour during the release and storage of heat but its major disadvantages are its expensiveness, exhibition of sub-cooling and poor thermal conductivity. On the other-hand, sensible heat storage is cheaper, has better thermal conductivity and is readily available but its main disadvantage is the much lower energy storage density. Combining the two storage systems, will result in a cheaper storage system which possesses the advantages of both systems. A single storage system consisting of one phase change material for latent heat storage and one sensible heat storage system will be tested experimentally. To optimize the system, a theoretical mathematical procedure to predict the optical performance of different geometries of the CPC will be proposed, and numerical models to evaluate the thermal performance will be developed and validated with experimental results. Very little recent literature has been published on this concept.

Solar food drying combined with a thermal energy storage (TES) system to increase drying capacity will be investigated. The aim of this project is to implement a thermal energy storage (TES) system on a solar powered food dryer developed by the 'Applied Fluid Mechanics and (Aero) Acoustics (AFMAA)' research group of KU Leuven, Group T Leuven campus. The TES system will heat up during the day and gives this heat back to the dryer during periods when solar radiation is not or only has limited availability, e.g. during night or cloudy periods. Therefore, the combination of a solar dryer with a TES system greatly increases the drying capacity, meaning more food can be preserved for the local community ensuring more food security. As the dryer is only powered by solar energy, this project will promote the use of renewable energy, a must with respect to the global issues of climate change. Moreover, the dryer will also avoid the use of wood for drying, meaning deforestation will also be reduced. The TES system will be designed and extensively tested by the Department of Physics and Electronics of North-West University (NWU) and afterwards it will be commercialised by the company "Dryers for Africa" who will put the system on the market.

7. Conclusions

An overview of the three main types of solar cookers with their basic operating principles was presented in this lecture. Basic operating principles of direct focusing, oven and indirect solar cookers were outlined. Solar cookers using both sensible heat thermal energy storage (SHTES) and latent heat thermal energy storage (LHTES) were briefly reviewed and discussed. Advantages and disadvantages of the different types of solar cookers with TES were also highlighted. The most viable options for solar cookers with TES for developing countries are the oven type of solar cookers and direct focusing solar cookers since there are relatively cheap to fabricate and maintain. On the other hand, when issues of efficiency and safety are concerned, indirect solar cookers with TES are more viable and these can be implemented for community scale cooking since they are relatively expensive to construct. Solar cookers with TES offer an alternative to polluting fossil fuels and LPG (Liquid Petroleum Gas) in rural areas of developing countries. Past, recent and future work to be done by the solar thermal research group has also been presented.

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Solar Cookers with Thermal Energy Storage: A Sustainable Cooking Solution for Developing Countries

Prof. Ashmore Mawire

29 August 2019



Outline of Presentation

1. Introduction
2. Solar Cookers
3. Thermal Energy Storage
4. Research gaps in Solar Cookers with TES
5. Best Previous Work on TES for Solar Cookers
6. Recent Work on TES for Solar Cookers
7. Future Work
8. Conclusions
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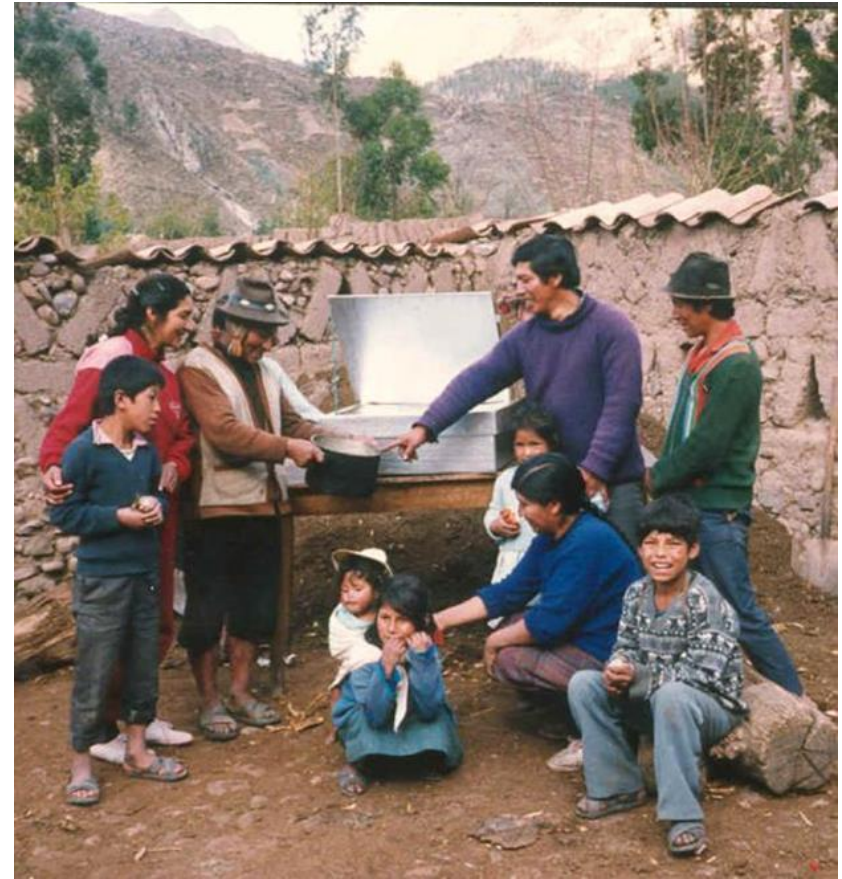


1. Introduction : Why use solar cookers?

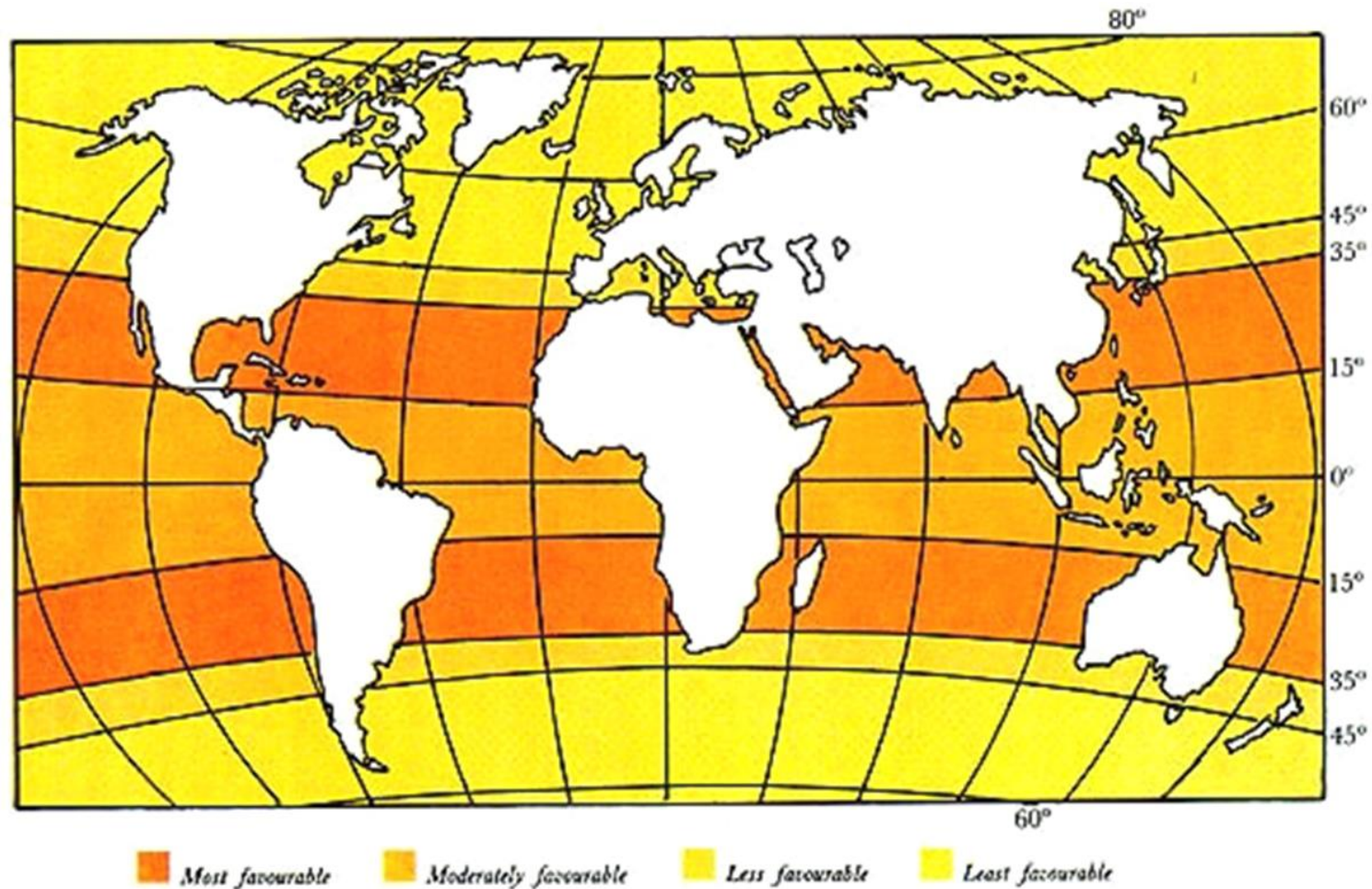
- Half the world's people burn wood or dried dung to cook their food.
- Nearly 1.2 billion people, a fifth of the world's population, do not have access to clean drinking water.
- Over 1 million children die yearly because of un-boiled drinking water.
- Wood cut for cooking purposes contributes to the 16 million hectares of forest destroyed annually.
- Half the world's population is exposed to indoor air pollution, mainly the result of burning solid fuels for cooking and heating.
- No electricity access for cooking foods for people in rural communities in developing countries

1. Introduction: Benefits of Solar Cookers

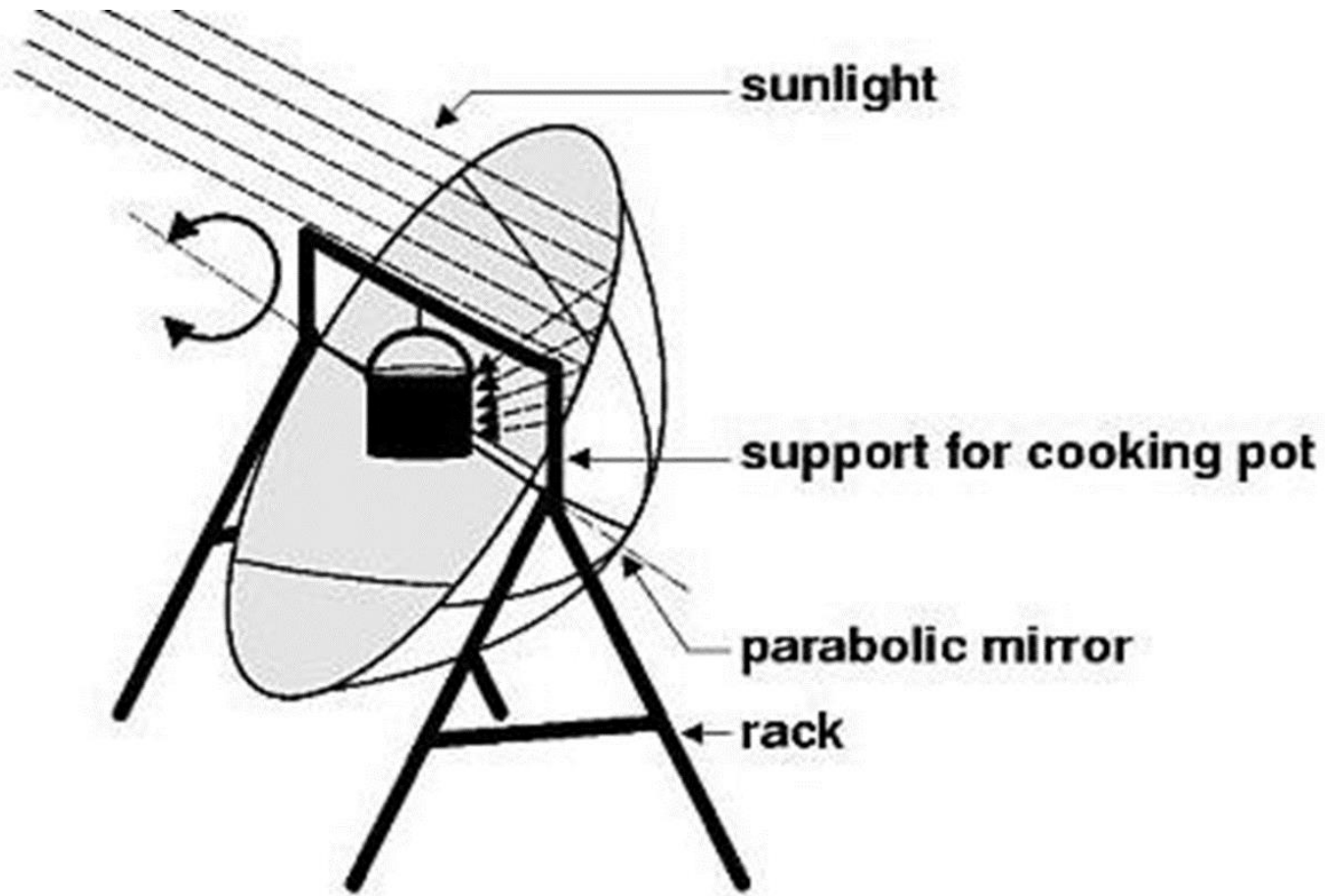
- Consumes no fuels/wood
 - No loss of trees & habitat
 - Trees sequester carbon
- Generates no air pollution
- Generates no greenhouse gases
- Produces no smoke
 - Cooking smoke kills over 1.6 million people each year, mostly women & children, according to a recent report
- Eliminates fire dangers



1. Introduction: Worldwide Solar Radiation Distribution



2. Solar Cookers: Direct Focusing (Concentrating) Solar Cooker



2. Solar Cookers: Direct Focusing (Concentrating) Solar Cooker Characteristics



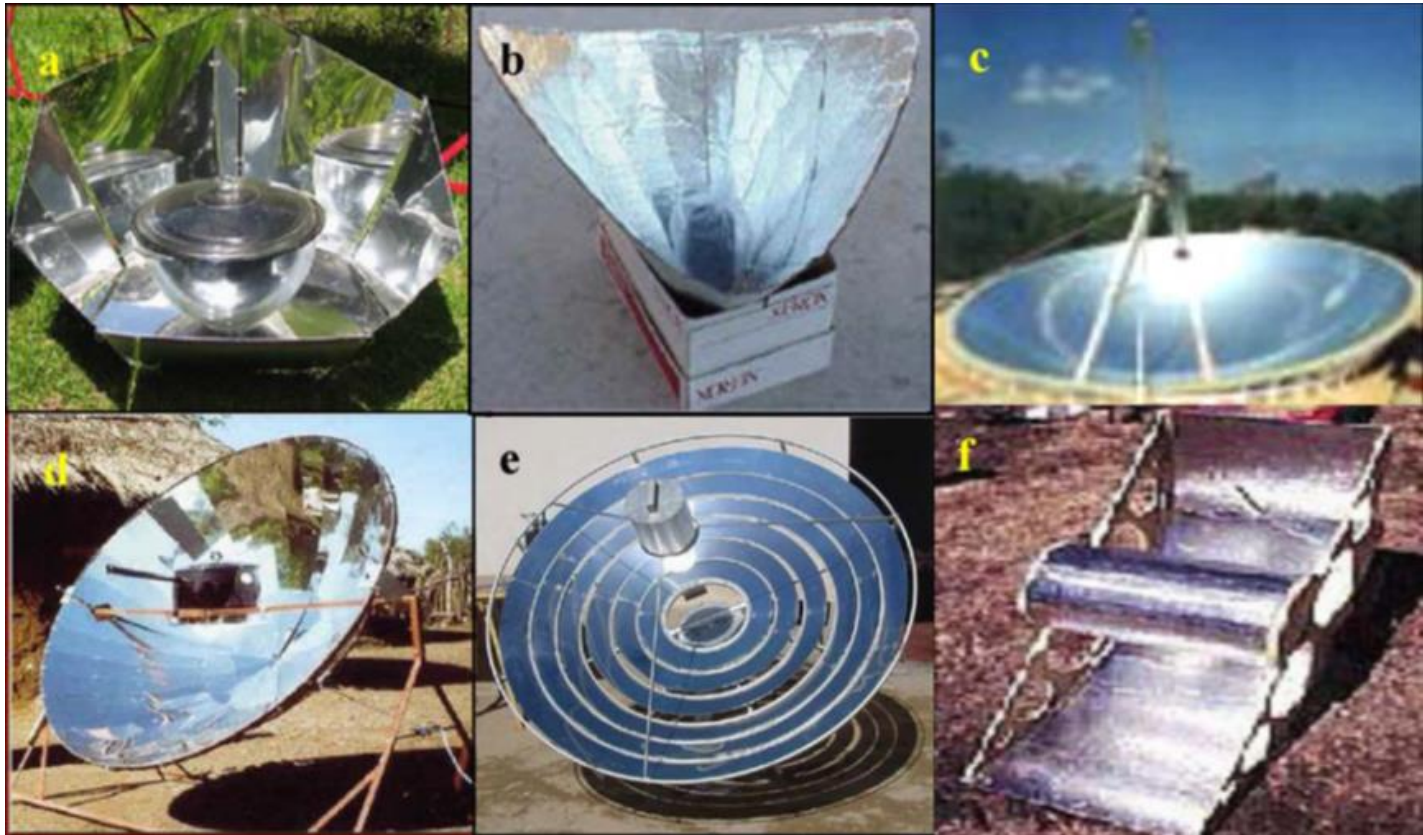
- Highly focused light and high temperatures
- Cooks nearly as fast as a conventional oven
- Costly and complicated to make and use – have to turn frequently to follow the sun
- Potentially hazardous-high solar flux-Use Sunglasses!!

2. Solar Cookers: Direct Focusing (Concentrating) Solar Cooker Characteristics



- Uses only the direct component of solar radiation thus it is ineffective during low solar conditions.
- Poor performance during windy conditions due to heat losses and indoors cooking not possible
- Fast cooking speed when boiling, frying and roasting under high solar radiation conditions

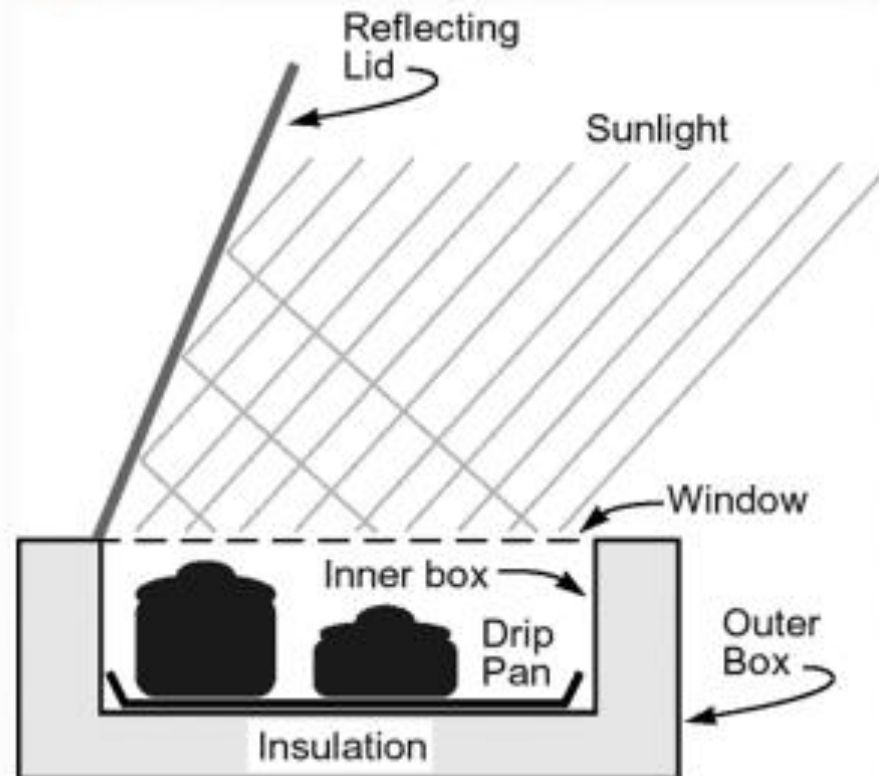
2. Solar Cookers: Types of concentrating solar cookers



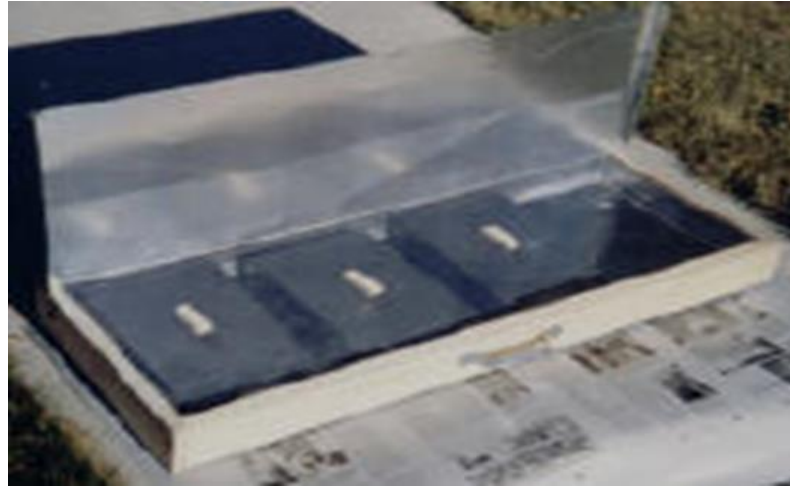
Direct focussing types of solar cookers: (a) Panel cooker, (b) Funnel cooker, (c) Spherical reflector, (d) Parabolic reflector, (e) Fresnel concentrator and (f) Cylindro-parabolic concentrator.

2. Solar Cookers: Oven (Box Type) Solar Cooker

Principle of a Solar Box Cooker



2. Solar Cookers: Oven (Box Type) Solar Cooker Characteristics



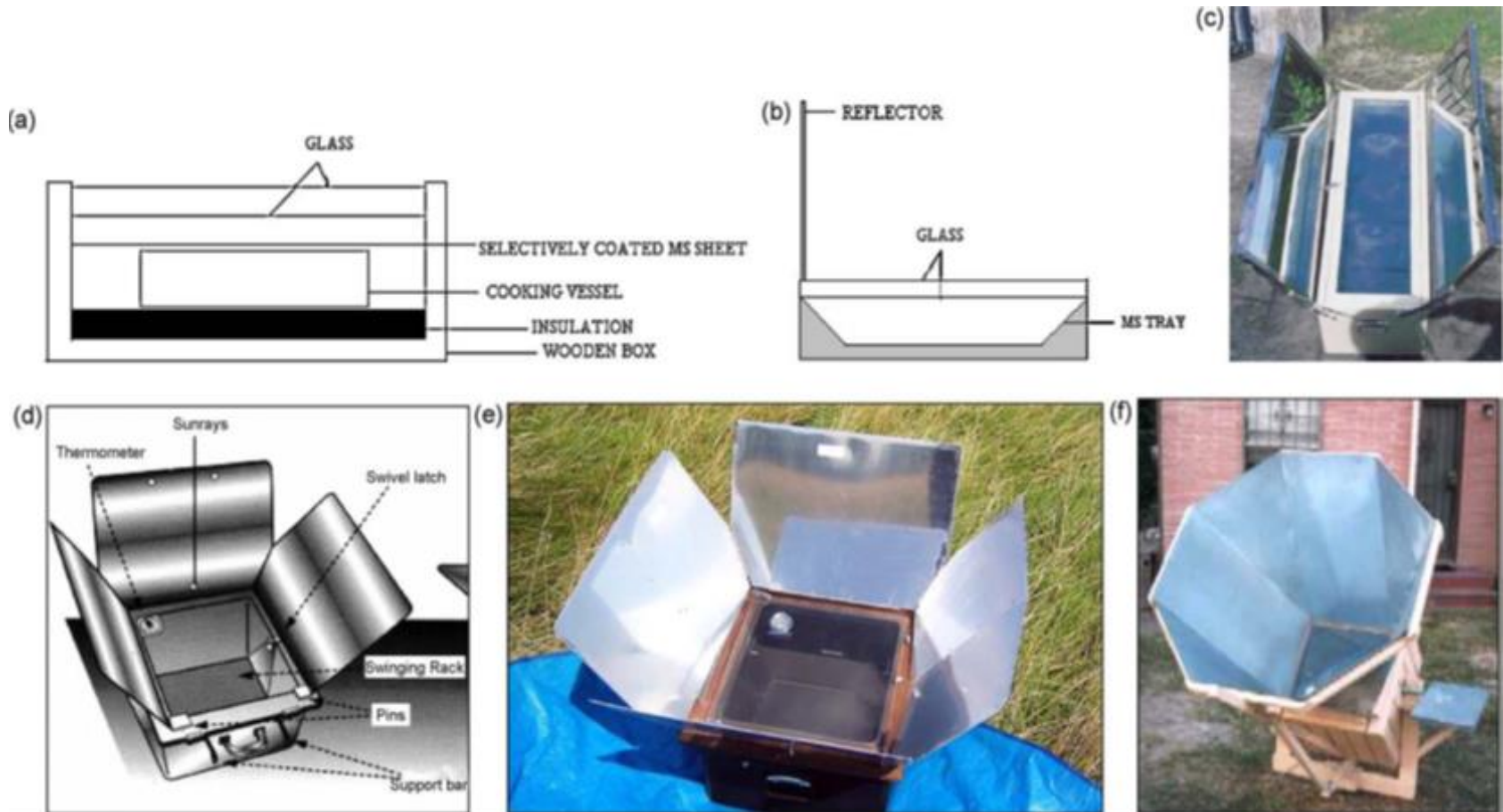
- Among easiest and most popular to build and use
- Lid of a cardboard box reflects light onto pots under glass
- Advantage of slow, even cooking of large quantities of food.(This is a disadvantage if fast cooking speeds are required)

2. Solar Cookers: Oven (Box Type) Solar Cooker Characteristics



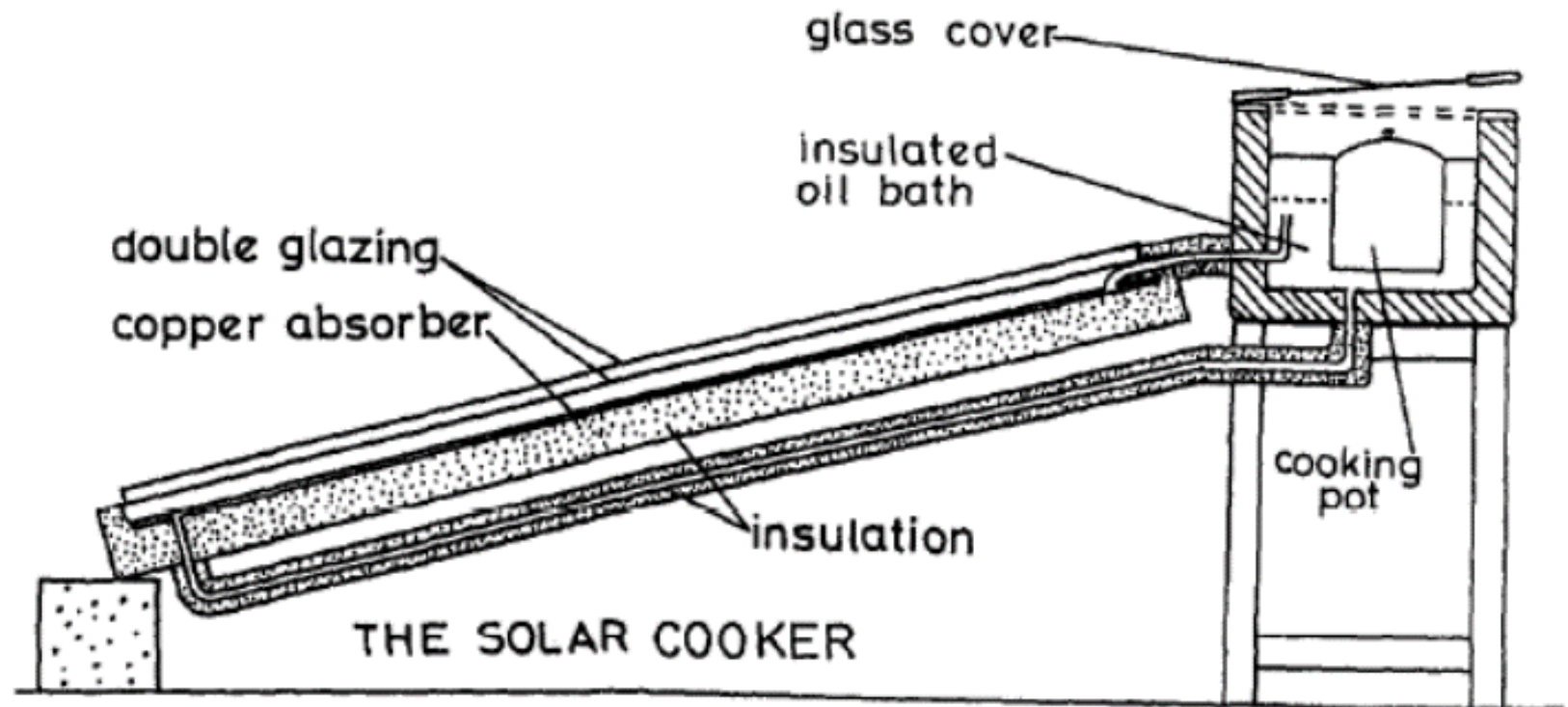
- Cheap easy to use
- Max temp 120 °C
- Minimum solar tracking
- Low efficiency and slow cooking speed
- Limited capacity depending on design
- Indoor cooking not possible

2. Solar Cookers: Types of solar box cookers

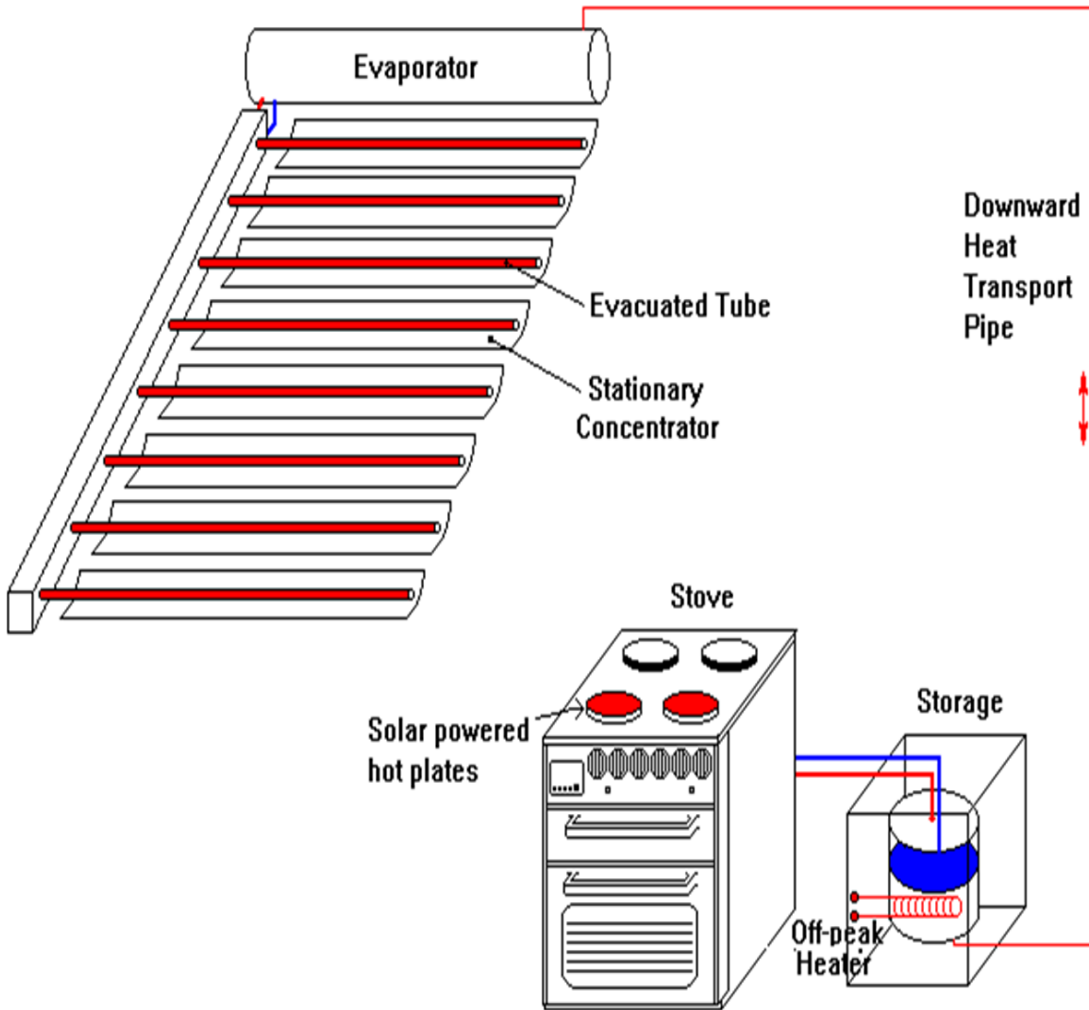


Oven types of solar cookers: (a) without reflector, (b) with a single reflector, (c) with double reflectors, (d) with three reflectors, (e) with four reflectors and (f) with eight reflectors.

2. Solar Cookers: Indirect Solar Cooker

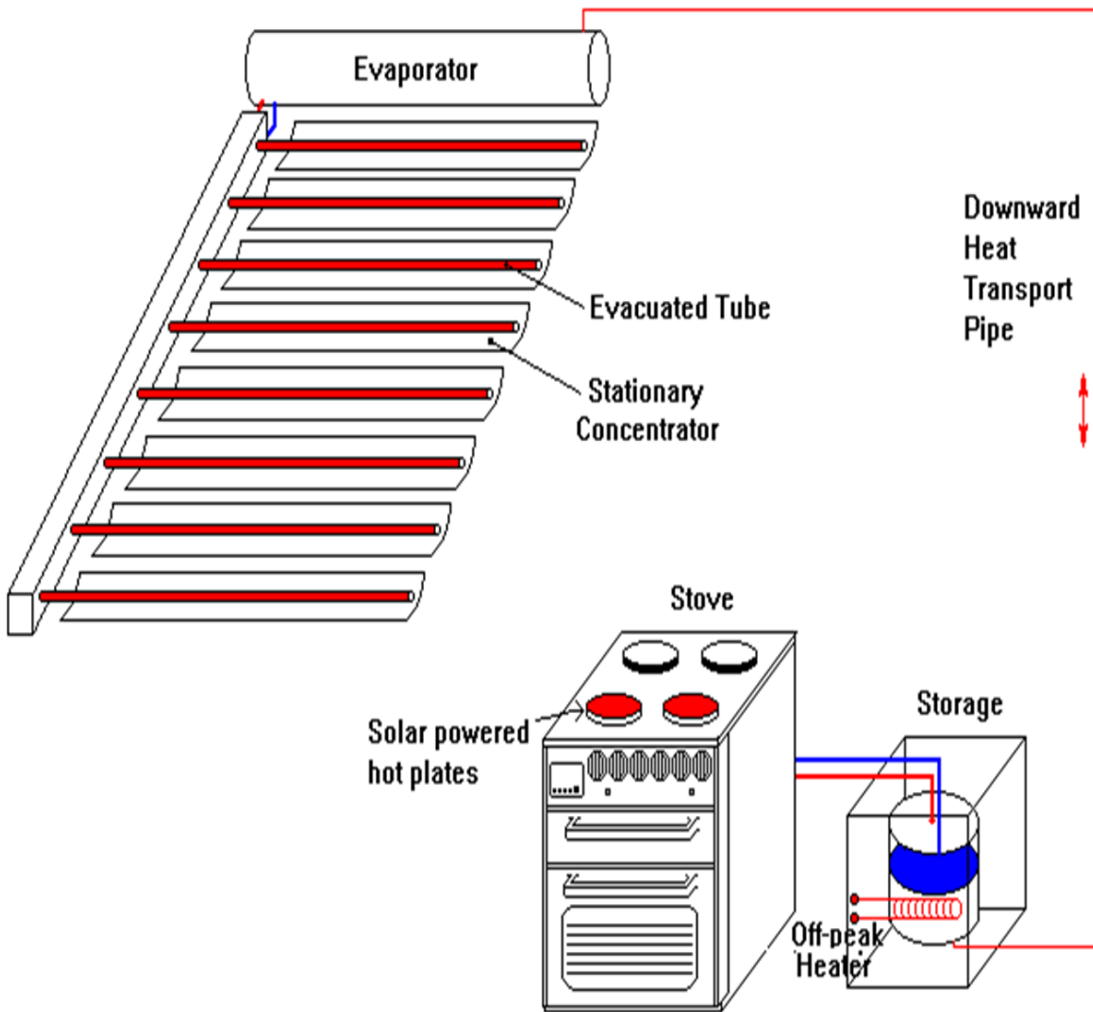


2. Solar Cookers: Indirect Solar Cooker Characteristics



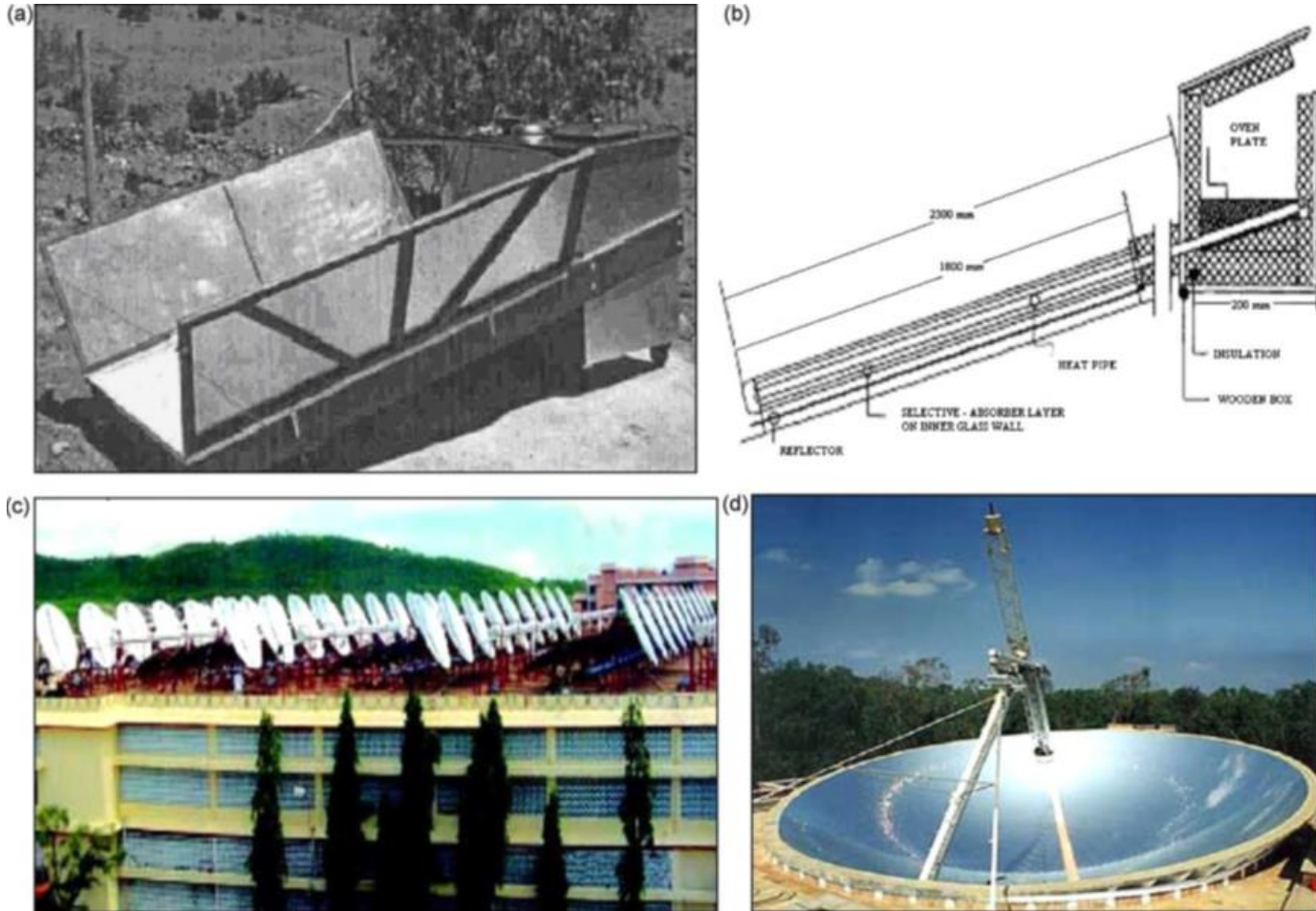
- Solar energy collectors are separated from the cooking vessels
- A heat transfer medium is usually required for heat transfer to and from the collector to the cooking vessel
- An indirect cooking mode is possible for indoors cooking (Mawire, 2009).

2. Solar Cookers: Indirect Solar Cooker Characteristics



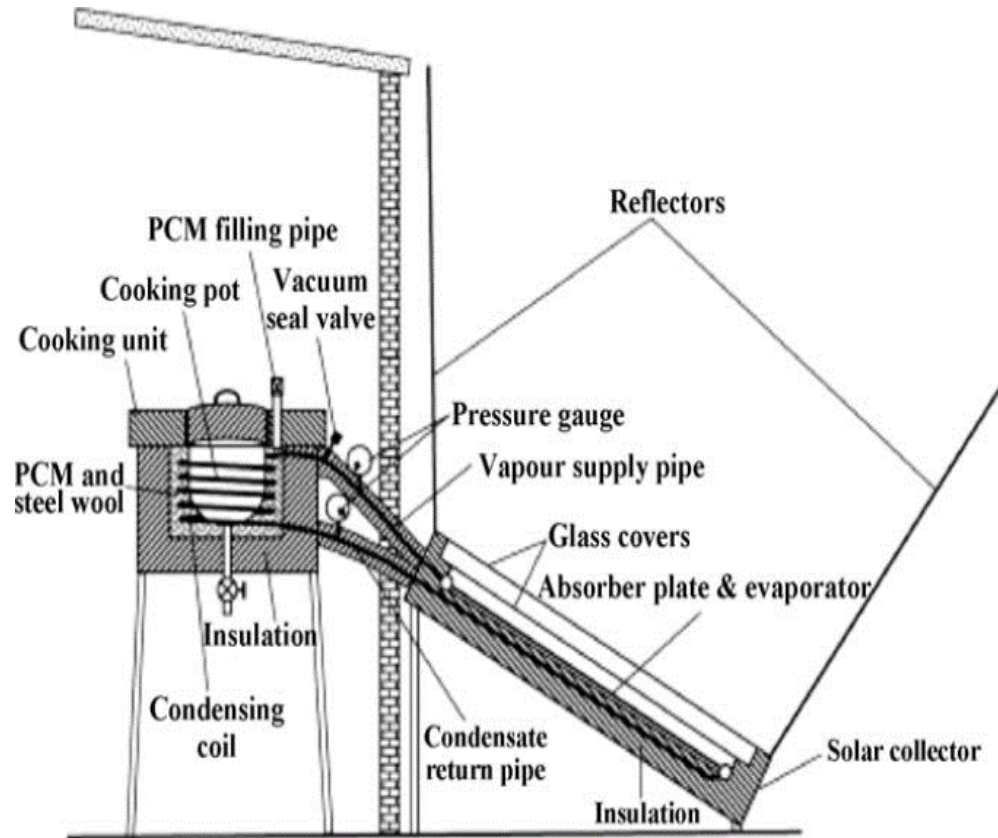
- Heat losses due to pipes and other heat transfer accessories
- Expensive- pipes , heat exchangers, pumps and other accessories required.
- Stable, easy to use, controlled cooking speed.
- Easy to integrate with thermal energy storage for evening and night cooking

2. Solar Cookers: Types of Indirect Solar Cookers



Indirect types of solar cookers (a) with flat plate collector, (b) with evacuated tube collector, (c) parabolic concentrators at Tirumala Tirupathi Devasthanam and (d) spherical reflectors at Auroville

3. Thermal Energy Storage: Why TES for Solar Cookers?



- Solar energy not available at night and during cloudy and rainy periods.
- TES can be used during these periods.
- Indoors cooking is possible with the use of TES systems.
- Cooking speed of solar cookers without storage is rather slow and it can be faster with TES.
- Possibility of controlled cooking like an electrical cooker when using storage

3. Thermal Energy Storage: Sensible Vs Latent Heat

Sensible Heat

- Sensible heat storage is cheap and readily available worldwide
- Based on the temperature rise in a thermal mass
- Sensible heat storage materials have greater thermal conductivities than phase change materials for latent heat storage systems

Latent Heat

- Expensive and limited availability, some PCMs have to be engineered in the laboratory
- Based mainly on the large latent heat of fusion released during solid to liquid phase transitions.
- Larger thermal energy storage density- High latent heat of fusion as compared to sensible heat storage materials

3. Thermal Energy Storage: Sensible Vs Latent Heat

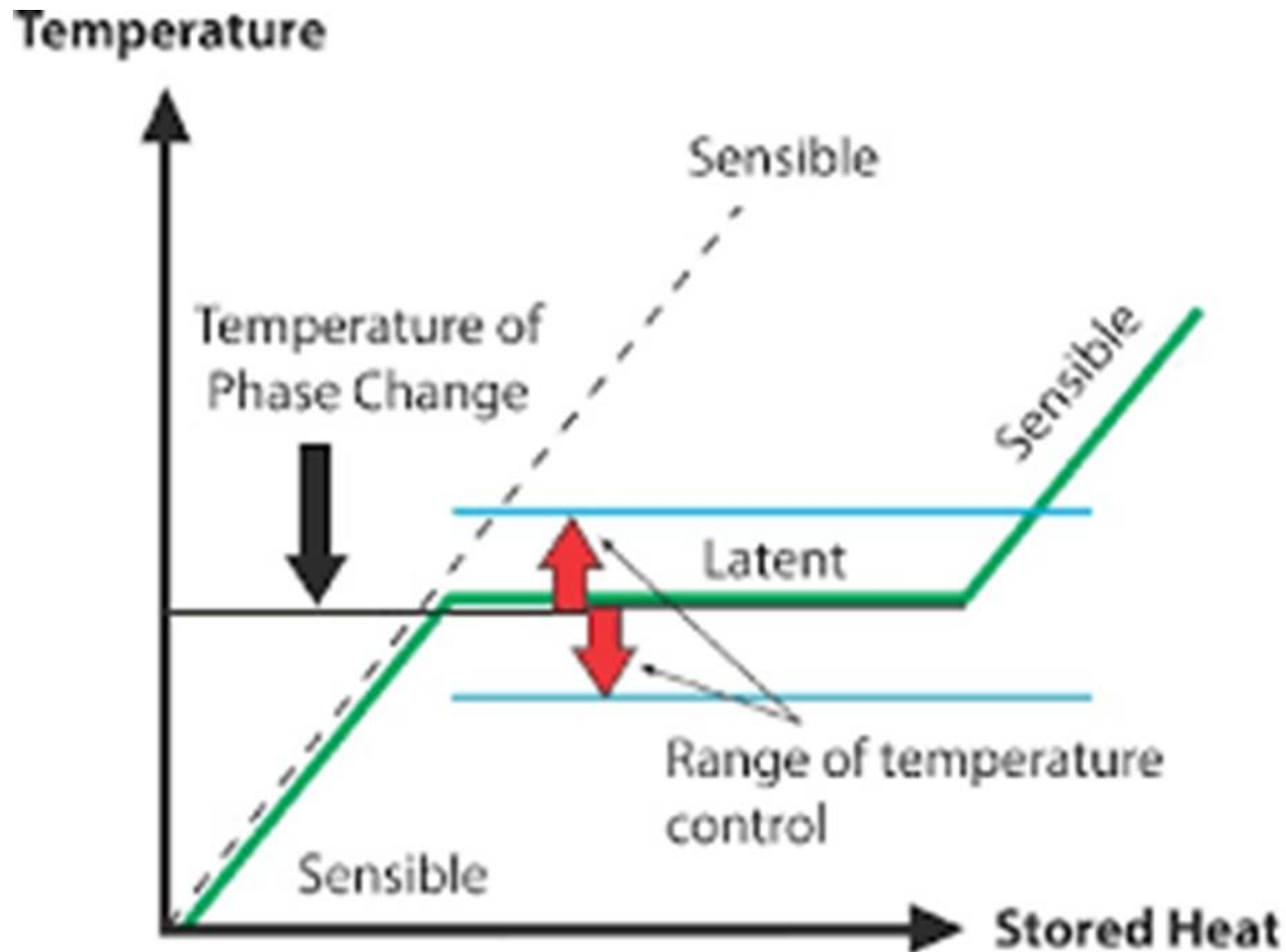
Sensible Heat

- Large storage space-
Lower energy storage density
- Thermal properties stable after many thermal cycles.
- Usually non toxic and environmentally friendly materials like air water, rocks

Latent Heat

- Large storage density, lower space requirements and compact energy storage.
- Thermal properties degrade after several thermal cycles.
- Some PCMs are toxic and environmentally unfriendly, however some possess suitable environmental qualities

3. Thermal Energy Storage: Sensible Vs Latent Heat



3. Thermal Energy Storage: Common Locally Available Sensible Heat Storage Materials



Granite Pebbles



Water



Sunflower Oil



Sand

3. Thermal Energy Storage: Common Locally Available Latent Heat Storage Materials



Adipic Acid



Erythritol



HDPE



Eutectic Solder

4. Research gaps in Solar Cookers with TES

1. Limited research studies on solar cookers with TES systems using heat transfer oils. Heat transfer oils are particularly favourable since temperatures above the boiling point of water (100 °C) can be achieved which are suitable for frying and baking.
2. Storage tanks using oil are simplified since they do not have to be pressurized as with the case of water which is cheaper and readily available.
3. The use of locally available TES materials in a particular region or country for enhancing the performance of solar cookers is rather limited.
4. Packed bed storage systems using oil heat transfer fluids for domestic cooking applications have been rarely reported in recent literature.

4. Research gaps in Solar Cookers with TES

5. The packed bed storage configuration has better heat transfer characteristics than other types of configurations such as the shell and tube especially when latent heat thermal energy storage systems are considered.
6. Storage type of cooking vessels have been rarely reported. These vessels can store heat during periods of high solar radiation, and use it during non-sunshine periods.
7. Hybrid solar cooking and TES storage systems using another energy source have been rarely reported. These systems are more practical especially when there are extended periods of low solar radiations. The alternative energy source can be used for cooking.
8. TES applications of metallic phase change materials (PCMs) for higher volumetric storage densities and higher thermal conductivities that have appeared in recent literature are rather limited.

5. Best Previous Work on TES for Solar Cookers

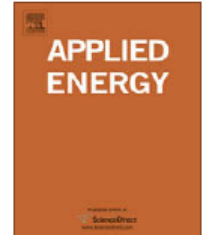
Applied Energy 86 (2009) 1246–1252



Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



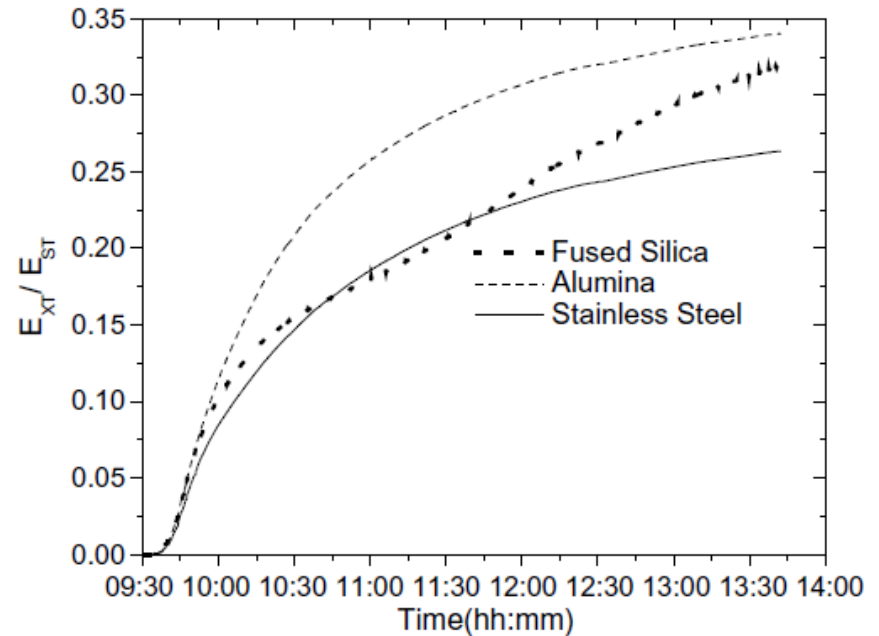
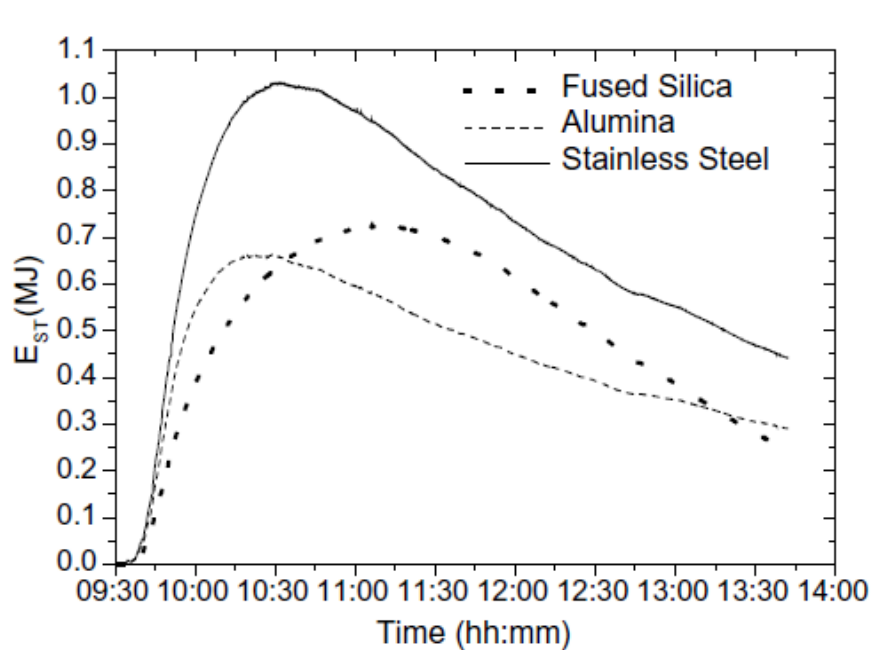
Simulated performance of storage materials for pebble bed thermal energy storage (TES) systems

A. Mawire*, M. McPherson, R.R.J. van den Heetkamp, S.J.P. Mlatho

Department of Physics and Electronics, North West University (Mafikeng Campus), Private Bag X2046, Mmabatho 2735, South Africa

- This work has been cited 57 times in Scopus , Applied Energy journal (Impact Factor: 8.426 (2018)).
- The work presented one of the first ever simulated performance of sensible heat storage materials for pebble bed TES systems for a solar cooking application.

5. Best Previous Work on TES for Solar Cookers



- The results concluded that fused silica possessed the best thermal stratification performance whilst stainless steel achieved the highest total energy stored at the expense of a greater drop from the peak value as charging progresses.
- Alumina, on the other-hand, was found to have the fastest energy storage rate and had the best exergy to energy ratio variation during the charging process which was comparable to fused silica at the end of the charging process.

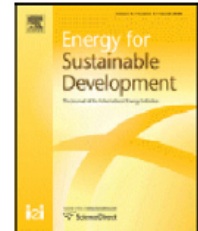
5. Best Previous Work on TES for Solar Cookers

Energy for Sustainable Development 19 (2014) 162–169



Contents lists available at ScienceDirect

Energy for Sustainable Development



Experimental energy and exergy performance of a solar receiver for a domestic parabolic dish concentrator for teaching purposes

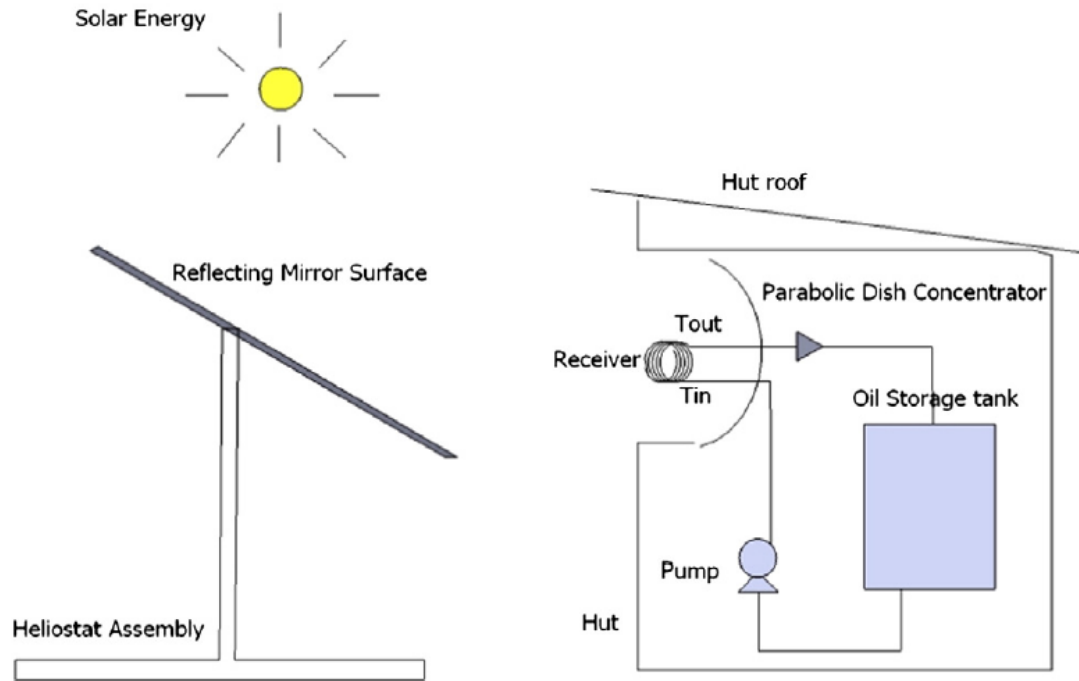


Ashmore Mawire *, Simeon H. Taole

Department of Physics and Electronics, North West University (Mafikeng Campus), Private Bag X2046, Mmabatho 2735, South Africa

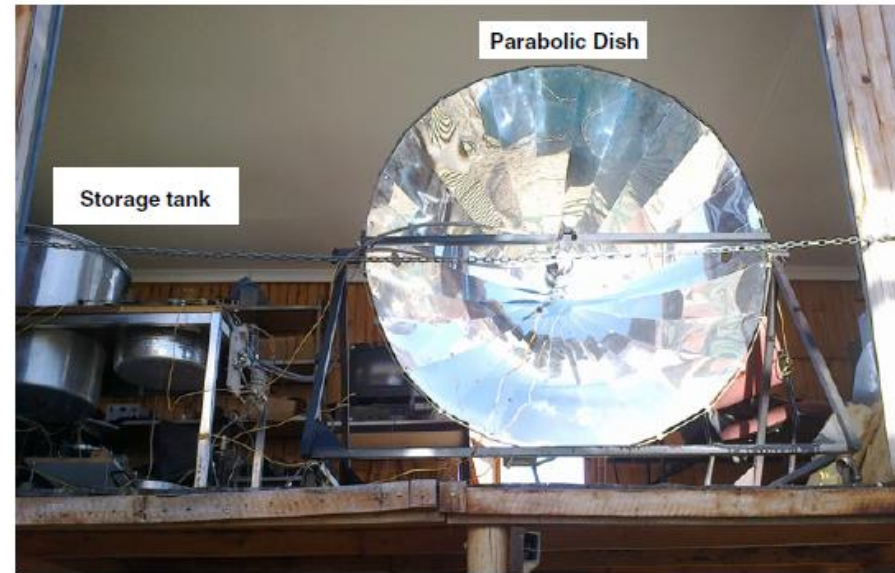
- This work has been cited 46 times in Scopus. The article was published in the Energy for Sustainable Development journal (Impact Factor: 3.307(2018)).
- The work presented a unique study on the experimental energy and exergy performance of a solar receiver for a domestic parabolic dish concentrator for teaching purposes.

5. Best Previous Work on TES for Solar Cookers



- The thermal performance was evaluated using energy and exergy analyses. The exergy factor parameter was proposed for quantifying the thermal performance.
- The exergy factor was found to be high under conditions of high solar radiation and under high operating temperatures.

5. Best Previous Work on TES for Solar Cookers



- The heat loss factor of the receiver was determined to be around 4.6 W/K. An optical efficiency of around 52% for parabolic dish system was determined under high solar radiation conditions.
- This experimental setup could be used as teaching tool for people with little or no knowledge about solar dish concentrators due its simplicity and the basic mathematical formulations applied.

5. Best Previous Work on TES for Solar Cookers

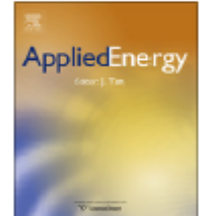
Applied Energy 88 (2011) 4766–4778



Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



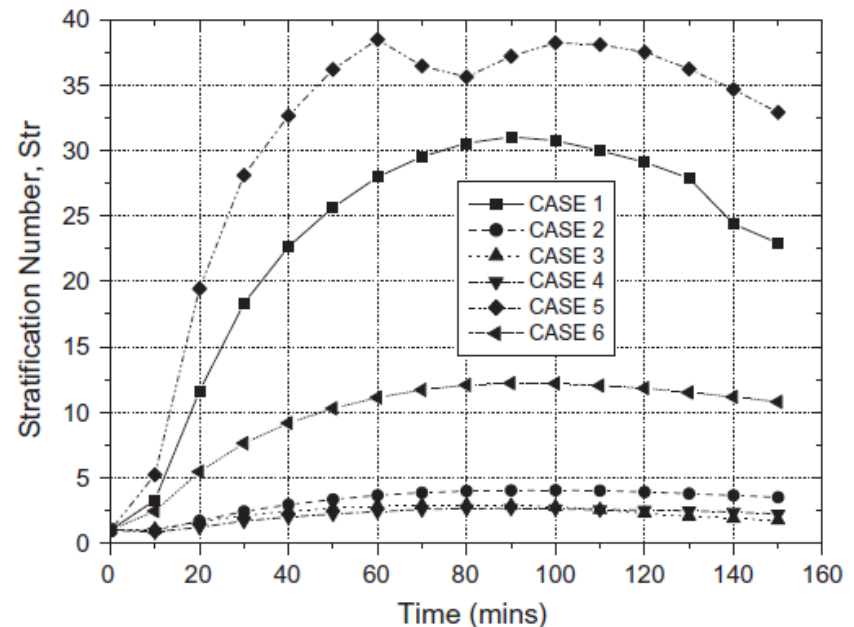
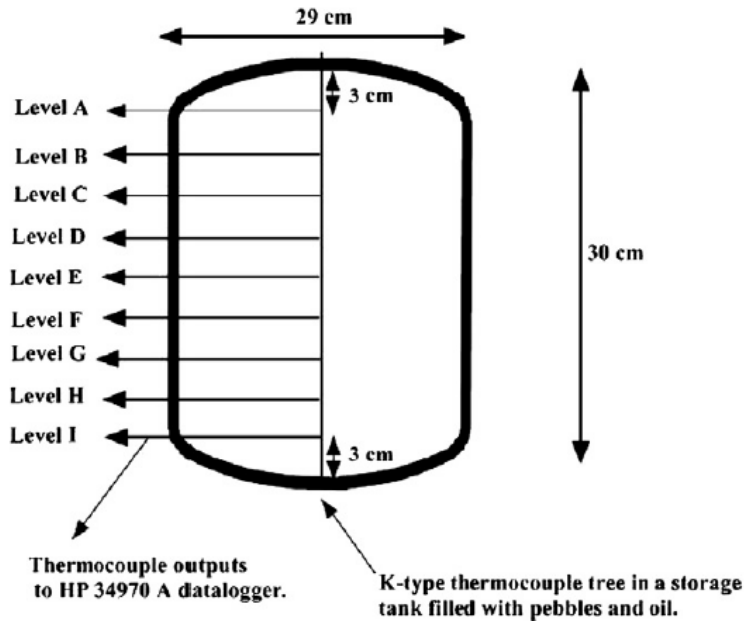
A comparison of experimental thermal stratification parameters for an oil/pebble-bed thermal energy storage (TES) system during charging

Ashmore Mawire *, Simeon H. Taole

Department of Physics and Electronics, North West University (Mafikeng Campus), Private Bag X2046, Mmabatho 2735, South Africa

- This work has been cited 35 times in Scopus. The article was published in the Applied Energy journal (Impact Factor: 8.426(2018)).
- The work presented the first ever comparison of experimental thermal stratification parameters for an oil/pebble-bed thermal energy storage system of an indirect solar cooker during charging.

5. Best Previous Work on TES for Solar Cookers



- Six parameters evaluated were the temperature distribution along the height of the storage tank at different time intervals, the charging energy efficiency, the charging exergy efficiency, the stratification number, the Reynolds number and the Richardson number.
- Temperature distribution along the height of the storage tank at different time intervals and the stratification number were the only parameters found to describe thermal stratification quantitatively adequately.

5. Best Previous Work on TES for Solar Cookers



Available online at www.sciencedirect.com



Renewable Energy 33 (2008) 682–693

**RENEWABLE
ENERGY**

www.elsevier.com/locate/renene

Experimental characterisation of a thermal energy storage system using temperature and power controlled charging

A. Mawire*, M. McPherson

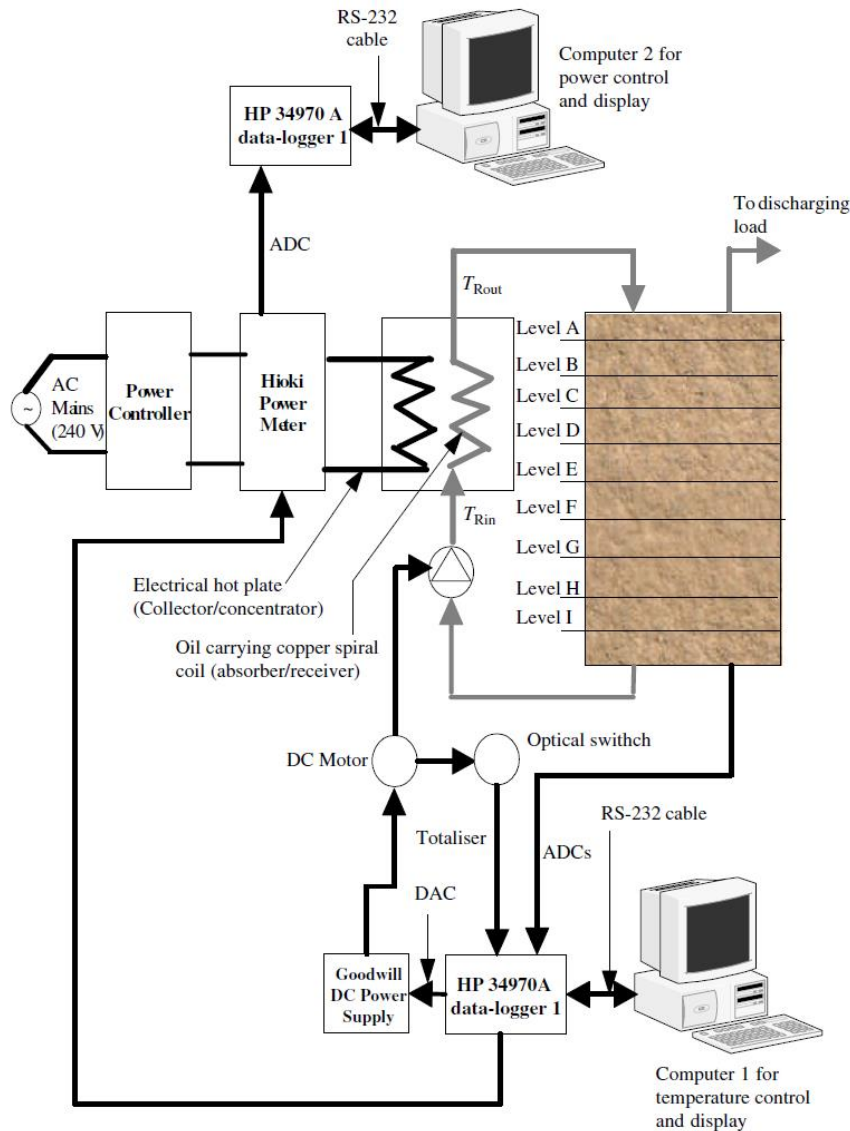
Department of Physics and Electronics, North West University (Mafikeng Campus), Private Bag X2046, Mmabatho 2735, South Africa

Received 1 September 2006; accepted 29 April 2007

Available online 12 June 2007

- This work has been cited 34 times in Scopus. The article was published in the Renewable Energy journal (Impact Factor: 5.439(2018)).
- This paper presented experimental characterisation of a thermal energy storage system using temperature and power controlled charging.

5. Best Previous Work on TES for Solar Cookers



- The TES was developed using a packed pebble bed. An electrical hot plate simulated the concentrator which heats up oil circulating through a copper coil absorber charging the TES system.
- Results of the charging experiments are used to characterise the storage system. The different experiments indicated various degrees of stratification in the storage tank.

5. Best Previous Work on TES for Solar Cookers

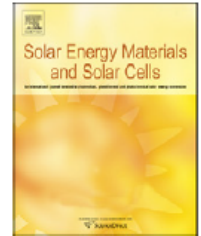
Solar Energy Materials & Solar Cells 92 (2008) 1668–1676



Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat



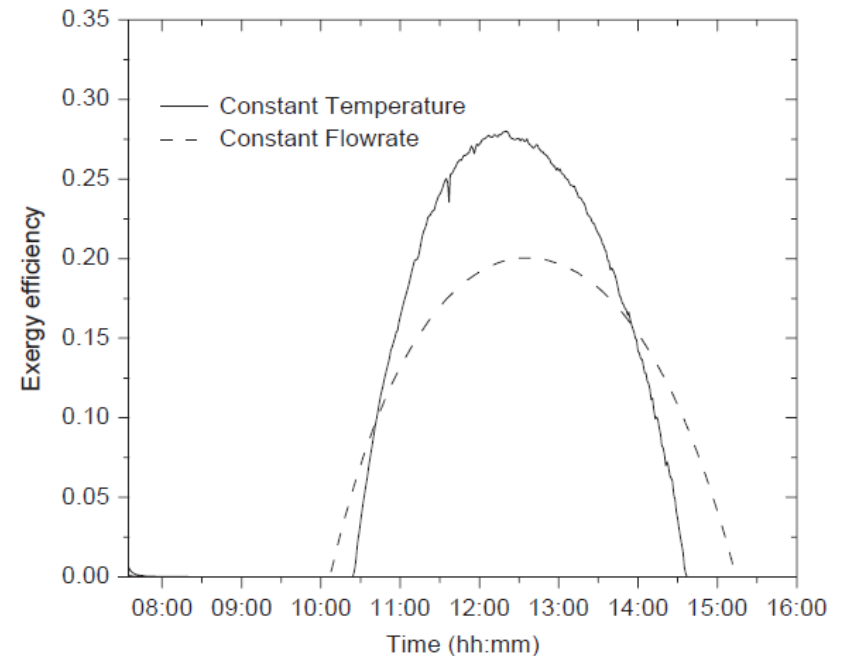
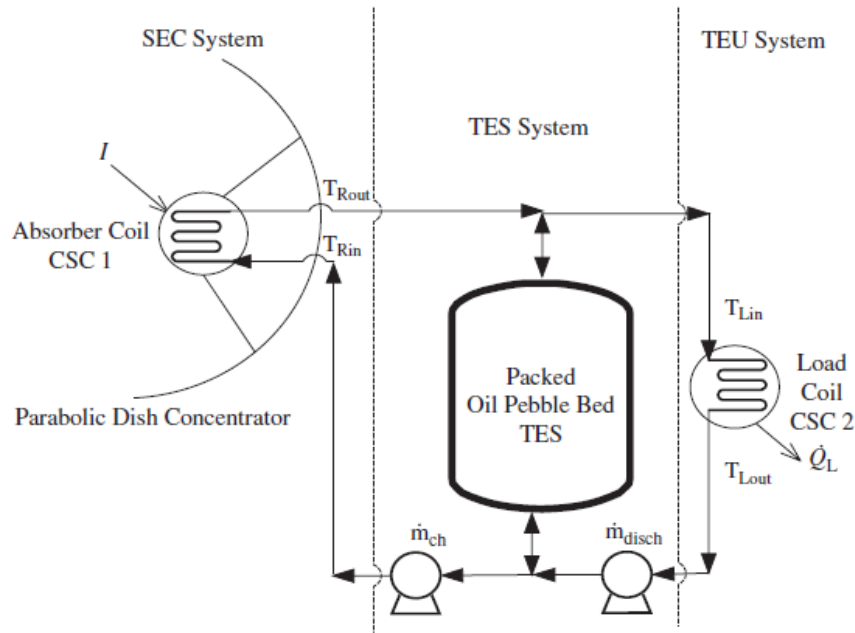
Simulated energy and exergy analyses of the charging of an oil–pebble bed thermal energy storage system for a solar cooker

A. Mawire*, M. McPherson, R.R.J. van den Heetkamp

Department of Physics and Electronics, North West University, Mafikeng Campus, Private Bag X2046, Mmabatho 2735, South Africa

- This work has been cited 32 times in Scopus. The article was published in the Solar Energy Materials & Solar Cells journal (Impact Factor: 6.019 (2018)).
- This paper presented the first ever simulated energy and analyses of the charging of an oil-pebble bed thermal energy storage system for a indirect solar cooker using two charging methods.

5. Best Previous Work on TES for Solar Cookers



- There were greater initial energy and exergy rates for the constant-flow rate method when the solar radiation is low.
- Energy efficiencies using both methods are comparable whilst the constant-temperature method results in greater exergy efficiency at higher levels of the solar radiation.

6. Recent Work on TES for Solar Cookers

Applied Thermal Engineering 73 (2014) 1321–1329



Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng



Performance comparison of thermal energy storage oils for solar cookers during charging

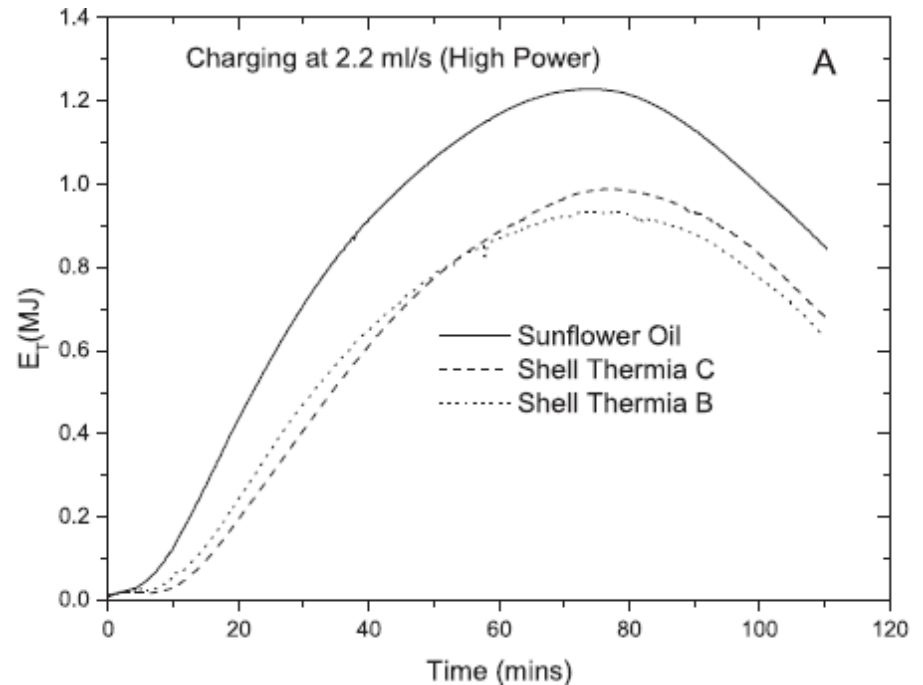
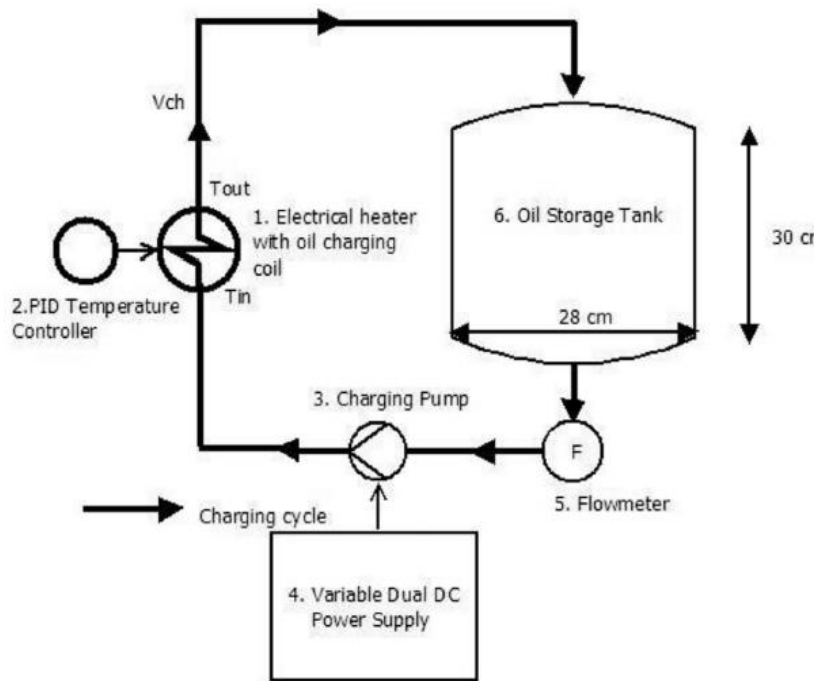


Ashmore Mawire*, Abigail Phori, Simeon Taole

Department of Physics and Electronics, North West University (Mafikeng Campus), Private Bag X2046, Mmabatho 2735, South Africa

- This work has been cited 23 times in Scopus. The article was published in the Applied Thermal Engineering journal (Impact Factor: 4.022 (2018)).
- This paper presented an experimental performance of thermal energy storage oils for solar cookers during charging

6. Recent Work on TES for Solar Cookers



- The three thermal oils evaluated were Sunflower Oil, Shell Thermia C and Shell Thermia B.
- Sunflower Oil performed better than the other thermal oils under high power charging. Thermal performances of the oils were comparable under low power charging.

6. Recent Work on TES for Solar Cookers

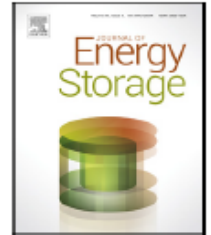
Journal of Energy Storage 5 (2016) 1–9



Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est



Performance of Sunflower Oil as a sensible heat storage medium for domestic applications

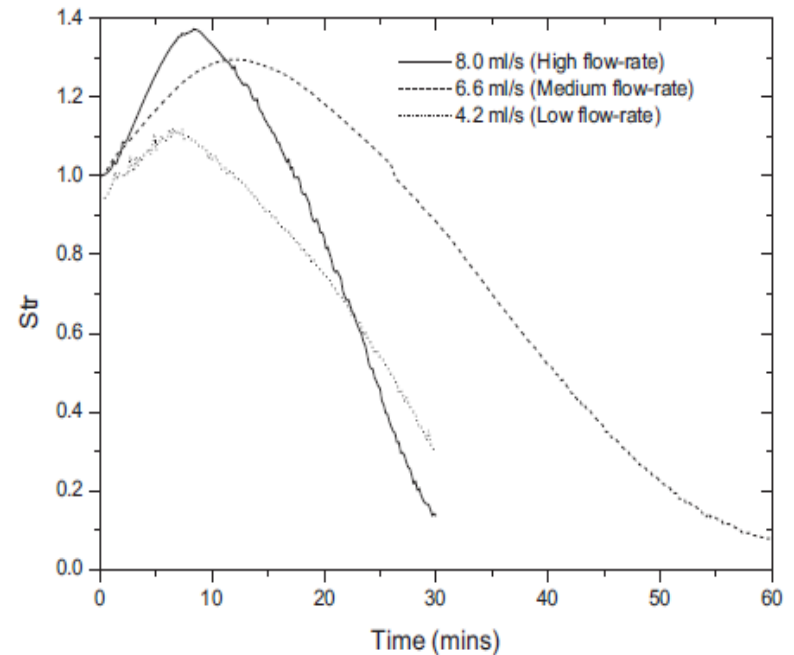
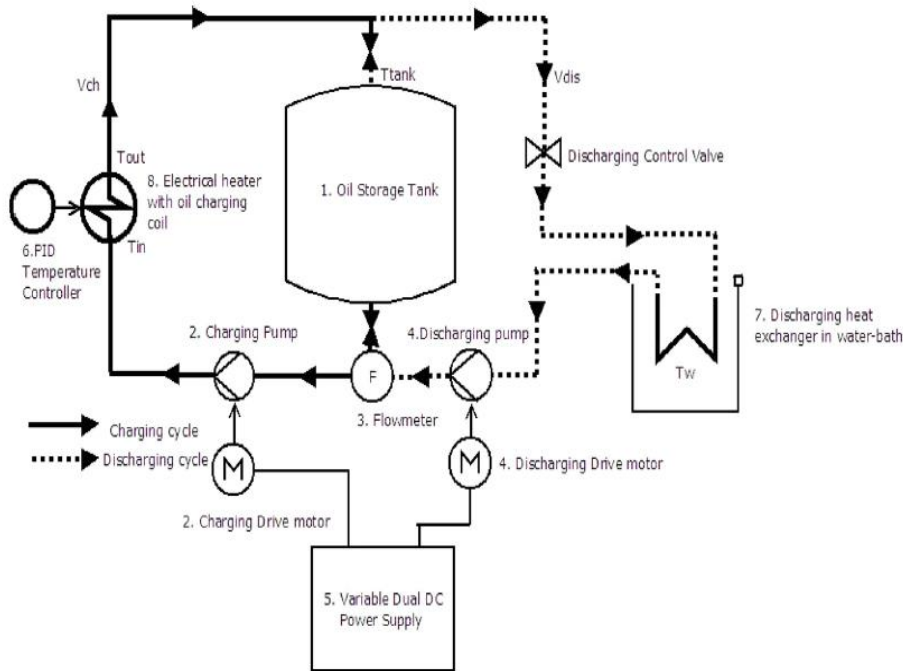


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- This work has been cited 19 times in Scopus. The article was published in the Journal of Energy Storage (Impact Factor: 3.516 (2018)).
- The performance of Sunflower Oil as sensible heat storage medium for domestic applications was evaluated experimentally.

6. Recent Work on TES for Solar Cookers



- An optimal heat retention temperature was suggested by the results.
- An optimal discharging flow-rate was also suggested by the discharging results. This is a compromise between obtaining a high rate of heat transfer and using the stored energy more effectively.

6. Recent Work on TES for Solar Cookers

Applied Thermal Engineering 124 (2017) 871–882



Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng



Research Paper

Experimental comparison of the thermal performances of acetanilide, meso-erythritol and an In-Sn alloy in similar spherical capsules



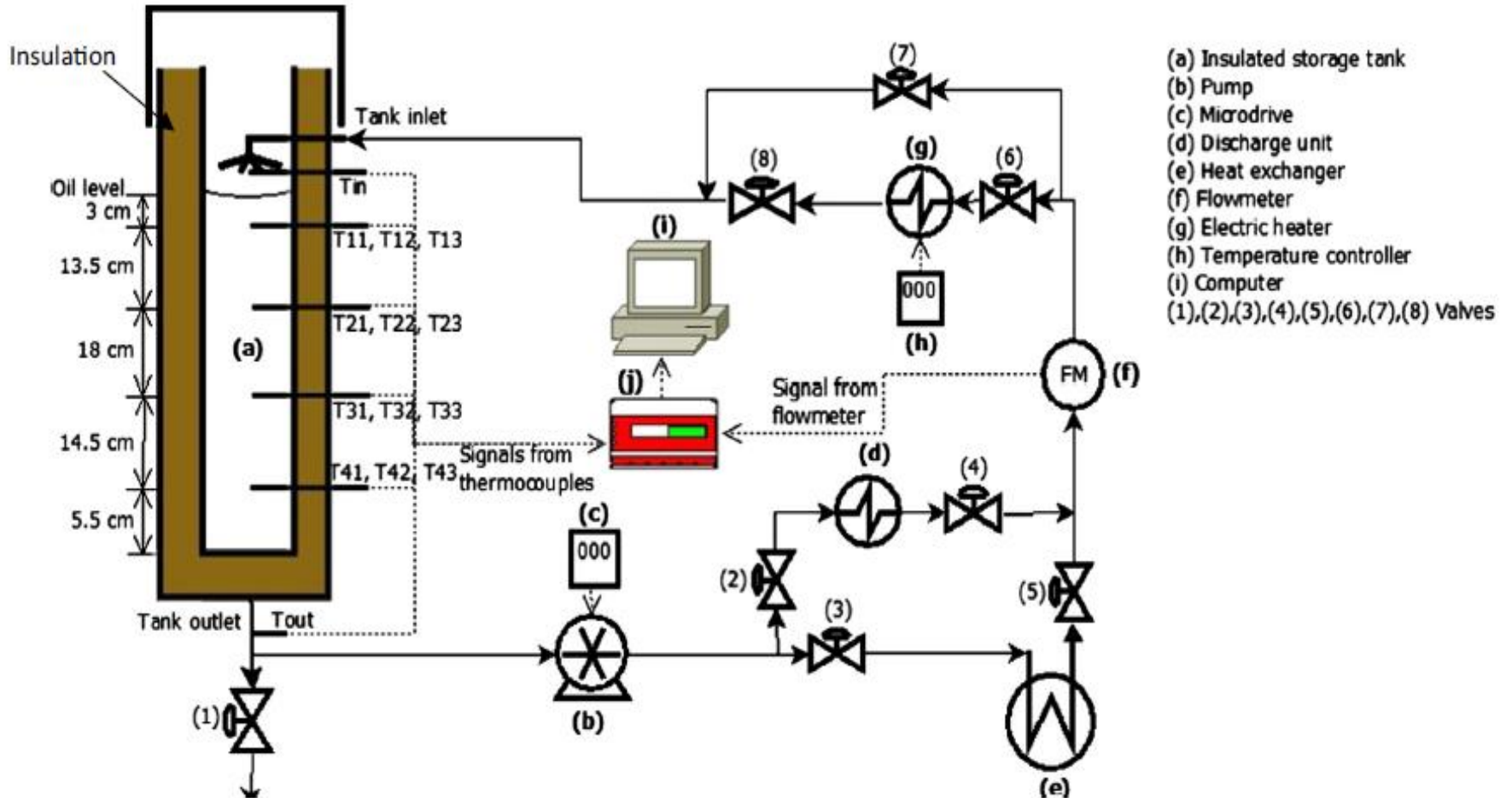
A.B. Shobo^{a,*}, A. Mawire^b

^a Department of Mathematics, Science and Sports Education, University of Namibia, Private Bag 5507, Oshakati, Namibia

^b Department of Physics and Electronics, Northwest University, Private Bag X2046, Mmabatho 2745, South Africa

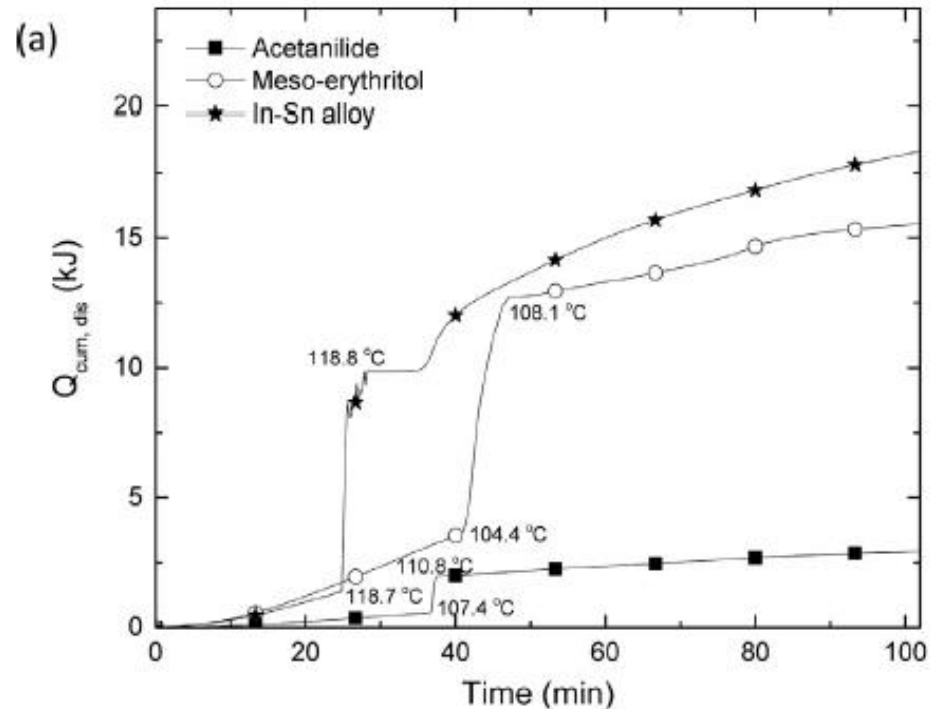
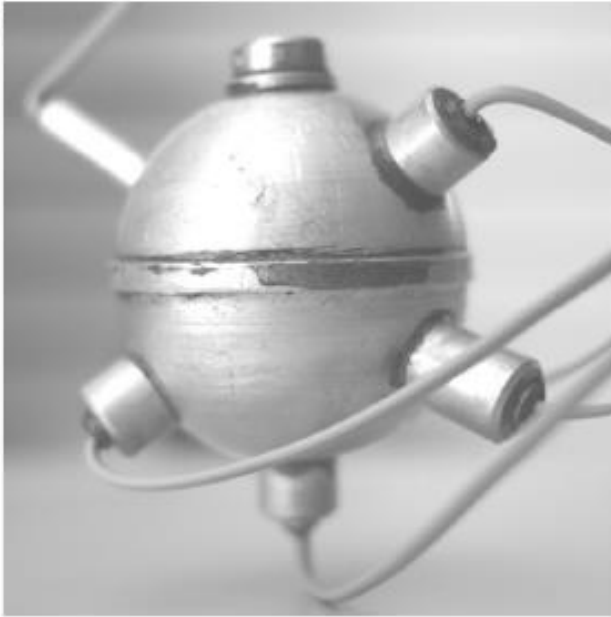
- This work has been cited 7 times in Scopus. The article was published in the Applied Thermal Engineering journal (Impact Factor: 4.022 (2018)).
- A comparison of the thermal performances of acetanilide, meso-erythritol and an In-Sn alloy, as phase change materials (PCMs) for medium temperature applications, inside separate, spherical aluminium capsules was presented.

6. Recent Work on TES for Solar Cookers



- Meso-erythritol showed the best charging performance.

6. Recent Work on TES for Solar Cookers



- The In-Sn alloy was found to be a superior PCM for medium temperature heating applications as compared to the other two PCMs.
- Sub-cooling affected the quality of heat discharged by acetanilide and meso-erythritol.

6. Recent Work on TES for Solar Cookers

Sustainable Energy Technologies and Assessments 30 (2018) 37–51



Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta



Thermal performance comparison of three sensible heat thermal energy storage systems during charging cycles



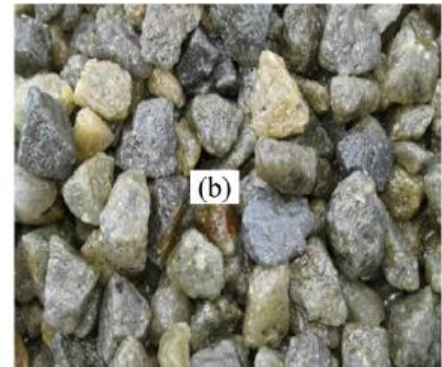
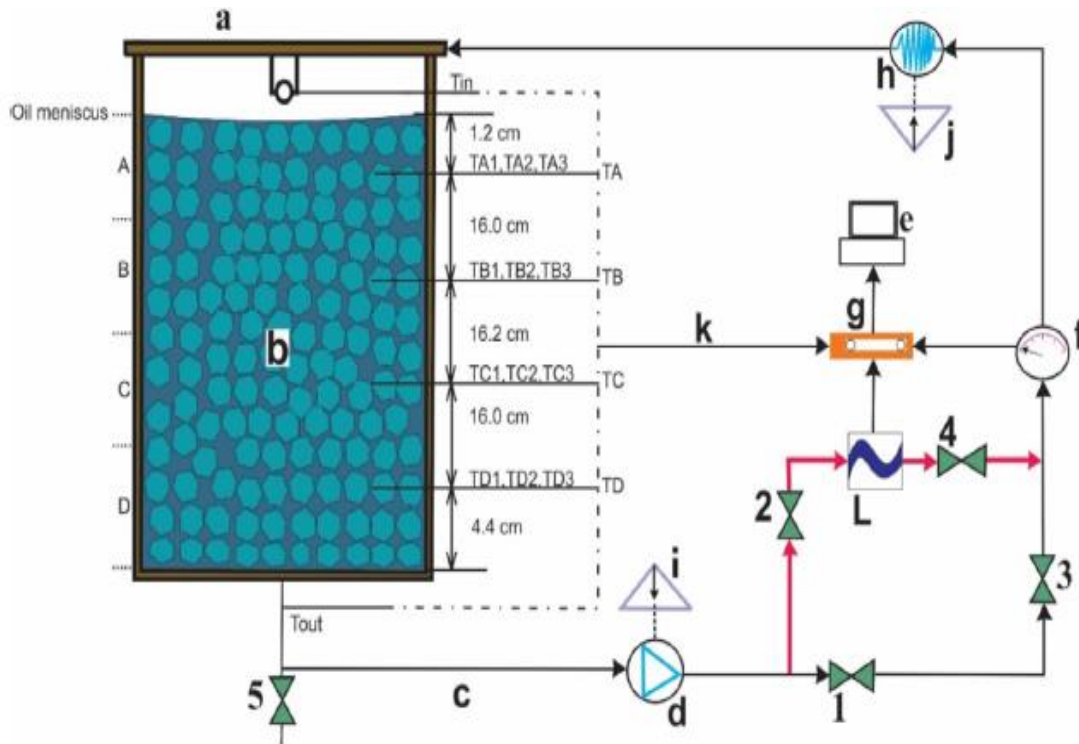
R. Lugolole^b, A. Mawire^{a,*}, K.A. Lentswe^a, D. Okello^b, K. Nyeinga^b

^a Department of Physics and Electronics, North West University, Private Bag X2046, Mmabatho 2735, South Africa

^b Department of Physics, Makerere University, P.O. Box 7062, Kampala, Uganda

- This work has been cited 8 times in Scopus. The article was published in the Sustainable Energy Technologies and Assessment journal (Impact Factor: 3.456 (2018)).
- Experimental results on the thermal performance comparison of three sensible heat thermal energy storage systems during charging cycles. Two packed storage systems using Sunflower Oil as the heat transfer fluid with two particle diameters (10.5mm and 31.9 mm) were compared with an oil only storage tank.

6. Recent Work on TES for Solar Cookers



- The oil storage system charged up fastest, followed by the small pebbles thermal energy storage (TES) and lastly by the large pebbles TES due its lower thermal mass.
- The small pebbles TES had a faster rate of temperature rise than the big pebbles which experienced temperature drops.
- The small pebbles TES performed better in terms of the thermal performance parameters evaluated in this study.

6. Recent Work on TES for Solar Cookers

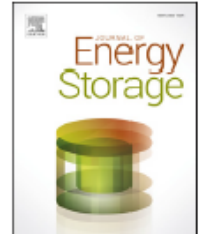
Journal of Energy Storage 23 (2019) 469–479



Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est



Performance comparison of four spherically encapsulated phase change materials for medium temperature domestic applications



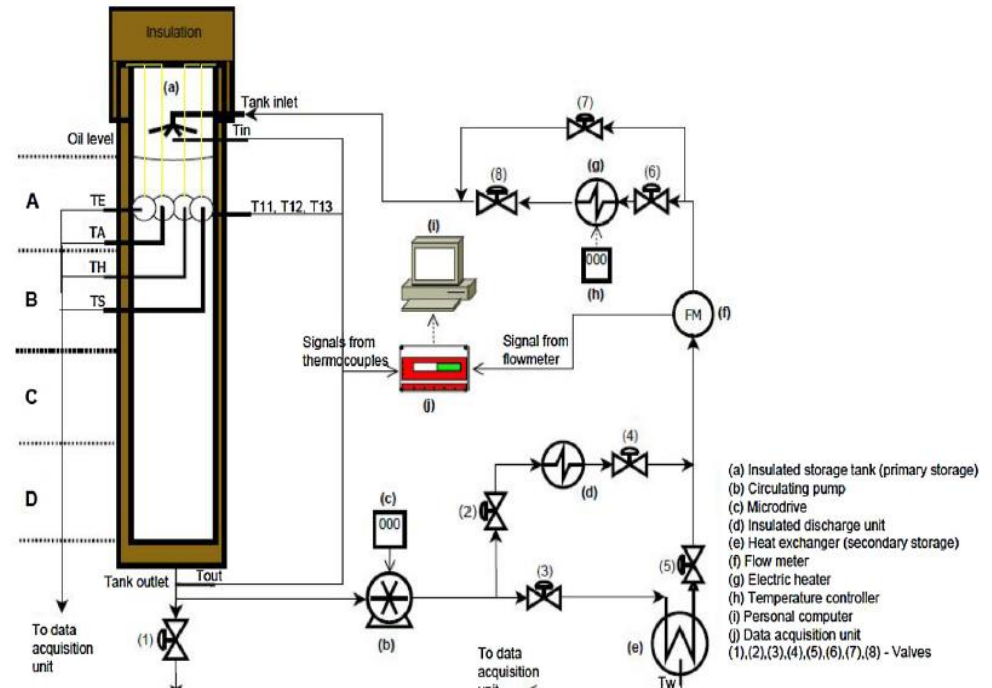
Ashmore Mawire^{a,*}, Katlego A. Lentswe^{a,b}, Adedamola Shobo^b

^a Department of Physics and Electronics, North West University (Mafikeng Campus), Private Bag X2046, Mmabatho 2735, South Africa

^b Department of Mathematics, Science and Sports Education, University of Namibia, Private Bag 5507, Oshakati, Namibia

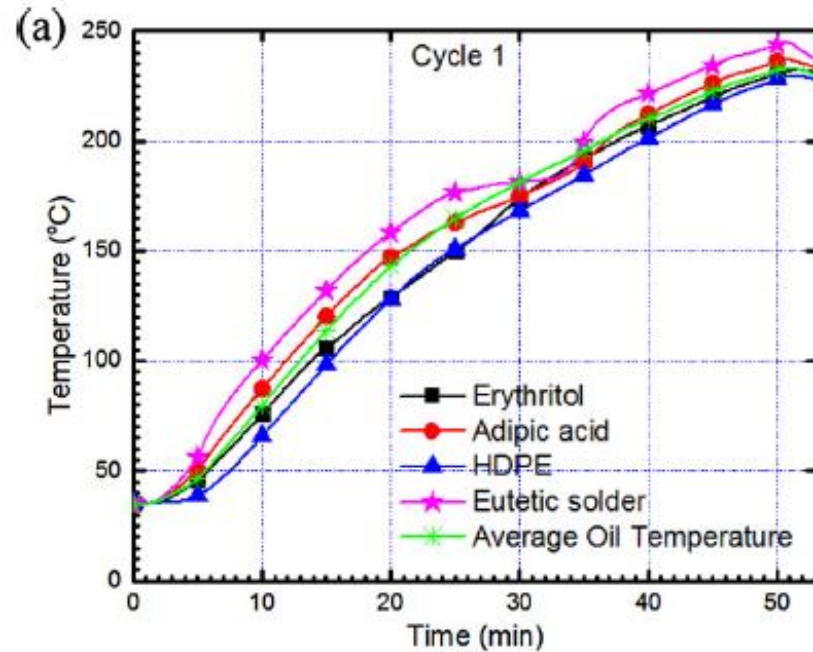
- The article was published in the Journal of Energy Storage (Impact Factor: 3.316 (2018), cited twice in Scopus)
- This paper presented an experimental comparison of the thermal performance of an eutectic solder (Sn63/Pb37) with that of three organic PCMs: erythritol, adipic acid, high density polyethylene (HDPE), inside similar spherical aluminium capsules

6. Recent Work on TES for Solar Cookers



- Static and dynamic tests were performed on the 4 PCMs
- Erythritol exhibited superior charging characteristics than the other PCMs in both the static and the dynamic modes. However, subcooling hampered the discharging performance of erythritol at high heat retrieval rates as the latent heat is discharged at temperatures lower than 100 °C

6. Recent Work on TES for Solar Cookers



- Sn63/Pb37 possessed stable charging and discharging performances in both the static and dynamic modes and showed the potential of being an ideal PCM for medium temperature applications.
- The solder's performance was second to that of erythritol even at low heat retrieval rates with latent heat discharged at the highest temperatures.
- Adipic acid presented relatively better charging and discharging performances than HDPE.

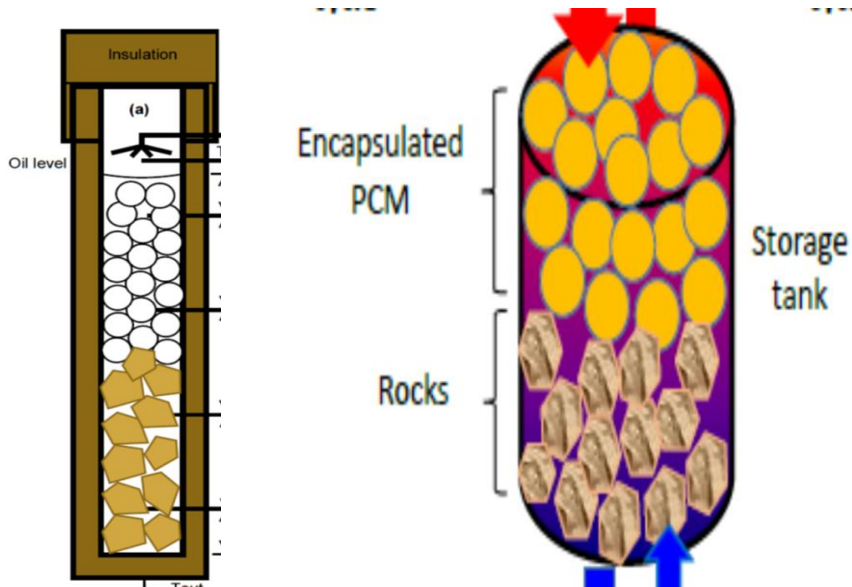
7. Future Work : A combined medium temperature domestic thermal energy storage

- The combined system will be used for an indirect solar cooker to enhance its effectiveness during periods of low or no sunshine (cloudy and night periods).
- The combined system consists of a packed bed system of latent heat storage material and sensible heat storage material contained in a single storage tank.
- Latent heat storage material has advantages of a higher energy storage density and an isothermal behaviour during the release and storage of heat but its major disadvantages are its expensiveness, exhibition of sub-cooling and poor thermal conductivity. On the other-hand, sensible heat storage is cheaper, has better thermal conductivity and is readily available but its main disadvantage is the much lower energy storage density. Combining the two storage systems, will result in a cheaper storage system which possesses the advantages of both systems.
- A single storage system consisting of one phase change material for latent heat storage and one sensible heat storage system will be tested experimentally using Sunflower Oil as the heat transfer fluid, which is available locally in South Africa. During periods when the sun is available solar energy would be used to cook food thus reducing the demand for electrical energy for cooking.

7. Future Work : A combined medium temperature domestic thermal energy storage

- Three different locally available phase change materials and three different locally available sensible heat storage materials will be tested experimentally in the storage tank composed of one phase change material and one sensible heat storage material.
- Different storage ratios will also be tested. To optimize the system, numerical models will be developed and these will be validated with experimental results.
- Parametric studies for optimization will be carried with commercially available engineering and computational fluid dynamics approach. The possibility of using multiple phase change materials and multiple sensible heat storage materials will also be investigated numerically. Very little recent literature has been published on this concept. The combined system will be used for an indirect solar cooker to enhance its effectiveness during periods of low or no sunshine (cloudy and night periods).

7. Future Work : A combined medium temperature domestic thermal energy storage



Dr. Adedamola Shobo



Dr. Denis Okello

- One MSc student involved in the project graduated with a distinction in July 2019, Katlego Lentswe
- Two MSc students are currently involved in project, Chidiebere Ekwomadu and Tlotlo Lefenya
- Collaborator- Dr. Denis Okello, Makerere University, Uganda
- Co-Investigator, Dr. Adedamola Shobo, University of Namibia

7. Future Work : A hybrid solar-electric TES and cooking system

- A hybrid solar-electric thermal energy storage and cooking system
- During periods when the sun is available solar energy would be used to cook food thus reducing the demand for electrical energy for cooking.
- Simultaneous solar and electrical operation will also be tested.
- Four modes of operation are possible with our proposed design, (a) a solar only mode when sufficient solar radiation is available to cook the food, (b) a solar only mode with storage during non peak periods when the solar energy is available and no cooking is done (c) a solar-electric mode during periods of low solar radiation such that electrical energy can be used to boost up the solar energy stored and (d) an electrical only mode when there are extended periods of no sunshine.
- The system is currently using an oil based thermal energy storage system. Research on suitable phase change materials (PCMs) to enhance the storage capacity is currently being conducted.
- MSc and PhD students will be engaged in the project.

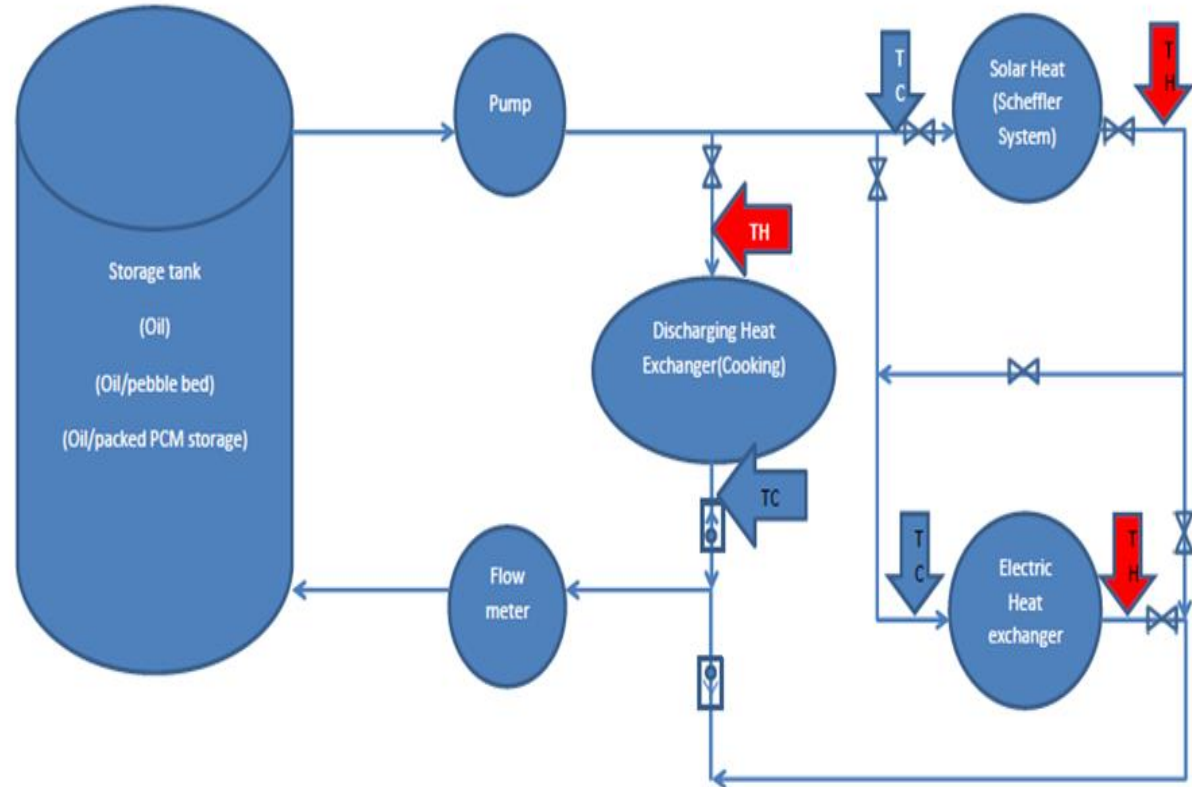
7. Future Work : A hybrid solar-electric TES and cooking system



Collaborator, Prof. Jo Darkwa
University of Nottingham
UK



Co-Investigator,
Dr. Adedamola Shobo,
University of Namibia



7. Future Work : Performance of a compound parabolic concentrator based solar system with combined heat storage for domestic medium temperatures

- The system consists of all-glass evacuated solar tube (EST) based compound parabolic concentrator (CPC) and a combined thermal energy storage system for medium temperature applications. The medium solar heat from the CPC solar collector is transferred to a combined heat storage system by circulating oil through a fined U-shaped tube which is inserted within the EST.
- The combined heat storage system will be used for an indirect solar cooker to enhance its effectiveness during periods of low or no sunshine (cloudy and night periods). The combined system consists of a packed bed system of latent heat storage material and sensible heat storage material contained in a single storage tank.
- An EST based CPC solar collector has the advantages of being simpler in structure, it needs no solar tracking, and it is thermally stable for the temperatures in the range of 100 to 200 degrees celcius.

7. Future Work : Performance of a compound parabolic concentrator based solar system with combined heat storage for domestic medium temperatures

- Latent heat storage material has advantages of a higher energy storage density and an isothermal behaviour during the release and storage of heat but its major disadvantages are its expensiveness, exhibition of sub-cooling and poor thermal conductivity. On the other-hand, sensible heat storage is cheaper, has better thermal conductivity and is readily available but its main disadvantage is the much lower energy storage density.
- Combining the two storage systems, will result in a cheaper storage system which possesses the advantages of both systems. A single storage system consisting of one phase change material for latent heat storage and one sensible heat storage system will be tested experimentally.
- To optimize the system, a theoretical mathematical procedure to predict the optical performance of different geometries of the CPC will be proposed, and numerical models to evaluate the thermal performance will be developed and validated with experimental results.
- Very little recent literature has been published on this concept.

7. Future Work : Performance of a compound parabolic concentrator based solar system with combined heat storage for domestic medium temperatures



Collaborator, Prof. Runsheng
Tang, Solar Research
Institute
Yunnan Normal University
China



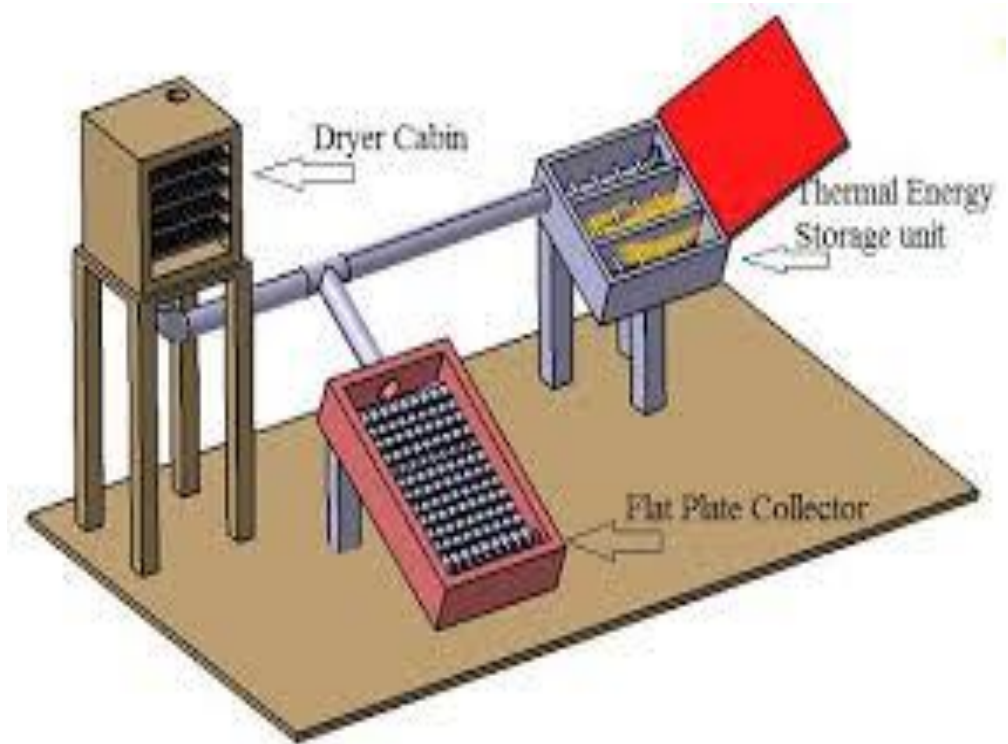
7. Future Work :Solar food drying combined with a thermal energy storage (TES) system to increase drying capacity

- The aim of this project is to implement a thermal energy storage (TES) system on a solar powered food dryer developed by the 'Applied Fluid Mechanics and (Aero) Acoustics (AFMAA)' research group of KU Leuven, Group T Leuven campus. The TES system will heat up during the day and gives this heat back to the dryer during periods when solar radiation is not or only limited available, e.g. during night or cloudy periods.
- The combination of a solar dryer with a TES system greatly increases the drying capacity, meaning more food can be preserved for the local community ensuring more food security. As the dryer is only powered by solar energy, this project will promote the use of renewable energy, a must with respect to the global issues of climate change.
- Moreover, the dryer will also avoid the use of wood for drying, meaning deforestation will also be reduced. The TES system will be designed and extensively tested by the Department of Physics and Electronics of North-West University (NWU) and afterwards it will be commercialised by the company "Dryers for Africa" who will put the system on the market.

7. Future Work :Solar food drying combined with a thermal energy storage (TES) system to increase drying capacity



Collaborator, Prof. Maarten
Vanierschot
Mechanical Engineering
Technology
KU LEUVEN University
Belgium



8. Conclusions

- An overview of the three main types of solar cookers with their basic operating principles was presented in this lecture. Basic operating principles of direct focusing, oven and indirect solar cookers were outlined.
- Advantages and disadvantages of the different types of solar cookers with TES were also highlighted.
- The most viable options for solar cookers with TES for developing countries are the oven type of solar cookers and direct focusing solar cookers since there are relatively cheap to fabricate and maintain.
- On the other-hand when issues of efficiency and safety are concerned, indirect solar cookers with TES are more viable and these can be implemented for community scale cooking since they are relatively expensive to construct.
- Solar cookers with TES offer an alternative to polluting fossil fuels and LPG (Liquid Petroleum Gas) in rural areas of developing countries.
- Past , recent as well as future work to done by the solar thermal research group has been presented.

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- Former and current postgraduate and undergraduate students.
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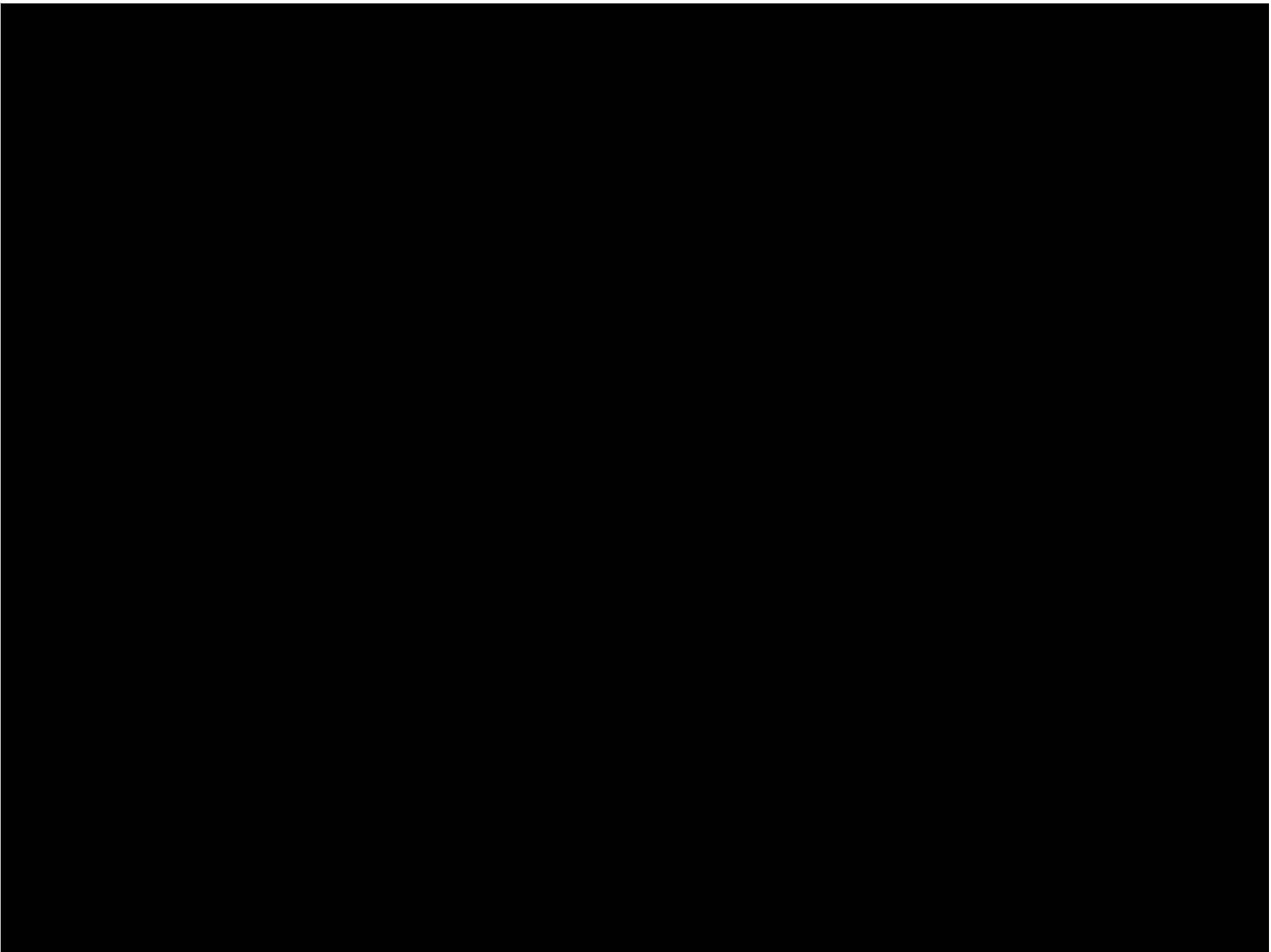
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Renewable Transformation Challenge 2019 - Winner announced!

19. August 2019

Solar-powered home cooking system, designed to replace traditional fuel-based systems, wins 2nd Elsevier-ISES Renewable Transformation Challenge

US-based Team SUNSPOT recognized for award that honors innovation in renewable energy

London, August 19, 2019 - Elsevier (<https://www.elsevier.com>), a global information analytics business specializing in science and health, and the International Solar Energy Society (<https://www.ises.org/home>) (ISES), are pleased to announce that 'Sunspot Solar Electric Cooking' by Team SUNSPOT is the winner of the second Renewable Transformation Challenge.

The Renewable Transformation Challenge (<https://www.elsevier.com/physical-sciences-and-engineering/energy/journals/renewable-transformation-challenge>), launched in 2017, aims to honor and showcase outstanding work that actively supports the transformation to a world powered by renewable energy, and has the potential to widen access to energy – particularly in developing countries. The Challenge was open to individuals and organizations in both not-for-profit and commercial sectors worldwide.

'Team SUNSPOT is honored to be selected as the winner of this year's Renewable Transformation Challenge,' said Douglas Danley, Team Leader and Co-founder of SUNSPOT (<https://sunspotpv.com/about>). 'The combination of innovative micro-financing, efficient consumer-grade electric cooking appliances and low-cost photo-voltaic modules have made it possible to introduce the solar-electric cooking system, which can compete with traditional biomass stoves.'



Paul Carroll and Douglas Danley (right) stand alongside the Sunspot Solar Electric Cooker. Danley, Carroll and team members Teresa Danley, and Vladimir Brunstein (not pictured) were this year's winners of the Elsevier-ISES Renewable Transformation Challenge (Credit: Douglas Danley).

The scale of the problem that Danley and his team set out to solve is massive. According to the World Bank, three billion people across the world are still using basic biomass fuels (like wood or dung) for cooking¹. This has a significant negative impact on the individuals' health, their environment, and their social and economic potential. Reducing the use of biofuels around the world will mean less deforestation and that time currently used to collect or create fuel, could be better spent on more socially beneficial activities like education and commerce.

**Thank you
Dankie
Kealeboga**

