Methanol fuel stoves as a clean technology for domestic cooking in South Africa

TS Marebane

orcid.org/0000-0001-8077-6543

Dissertation accepted in fulfilment of the requirements for the degree *Master of Science in Geography and Environmental Management* at the North-West University

Supervisor: Prof H Annegarn

Co-supervisor: Prof S Piketh

Co-supervisor: Prof RP Burger

Graduation July 2021

29570433

Declaration

I, Tlhomaro Marebane, hereby declare that the dissertation '**Methanol fuel stoves as a clean technology for domestic cooking in South Africa'** is my own, and further information included has been acknowledged with appropriate references. It is submitted to fulfil the requirements for the degree *Master of Science in Geography and Environmental Management*. This dissertation has not been submitted to any other institution.

Parts of this dissertation were presented at a national conference, as shown below:

Marebane, T.S., Burger, R.P., Annegarn, H.J., Piketh, S.P., 2020. 'Methanol fuel stoves as a clean technology for domestic cooking in South Africa', *NACA Annual Conference*, online, 16-20 November 2020.

Dedication

This work is dedicated to the Marebane family, my dearest parents,
Nape ‘a Gosebo and Mahloko ‘a Mogotle.

Abstract

Methanol is a potential domestic fuel for South African low-income households that could provide a clean and fire-safe alternative to paraffin. Poorly designed paraffin stoves emit harmful substances black carbon fine particulate matter and are prone to accidental fires. The use, thermal performance and safety of methanol stoves need to be contextualised for South Africa. This study evaluates methanol cookstoves' thermal and emission performance. It highlights the cookstove as a clean technology for domestic cooking to replace paraffin wick stoves. A standard test method for methanol cookstoves has been developed by a South African Bureau of Standards (SABS) Working Group; the proposed test methods were evaluated and documented in the laboratory as part of this thesis research. Three commercially available methanol cookstoves are evaluated using the draft standard test method. A non-pressurised paraffin stove serves as the baseline. The energy loss rate by combined radiative and convective processes is evaluated by measuring the heating and cooling rate using the methanol cookstoves. By combining the heating curve with the derived heat loss rate, we deduce the corrected *total cooking power* of the fuel/stove combination. Cooking power from methanol combustion is investigated using water heating tests. The *equivalent time to boil* (time to raise 1 L of water from 20ºC to 100°C) is calculated from the heating rate curve. The hood method is employed to capture the flue gases for the analysis of CO and CO_2. The Relative Carbon monoxide Emission (RCE) (new term, defined in the body text) ratio is calculated and compared to the SABS 2% limit value in SANS (1906). Safety tests and evaporation losses during storage are investigated. Different pot finishes (shiny aluminium and black stainless steel) and sizes are used to investigate the influences of pot size and colour on the thermal and emission performance of the stoves. Fuel leakages and safety against conflagration were evaluated by upsetting the stoves through 90º and 180º from the horizontal plane. The results show minor heat losses from radiation and convection during regular operation from both stoves. Hence, the external finish of the pots had a negligible influence on the cooking power. Condensation forming on the bottom of the pot posed a noticeable perturbation leading to inconsistencies in the *corrected total cooking power* of the stoves. Pot size had a significant influence on the stove performance. In terms of thermal performance, the methanol stoves performed within specifications for the South African market.

With the aluminium pot at high power, two methanol fuel stoves (STV01 and STV02) and the paraffin wick stove generated thermal power of more than 1 kW irrespective of pot size. With the small pot, STV03 could not reach the required 1 kW, producing about 0.97 kW. Overall, the paraffin stove produced the highest thermal power with all pot types, followed by STV02, STV01 and STV03. Two methanol fuel stoves (STV01 and STV02) and the paraffin wick stove generated more than 580 W irrespective of pot size. STV03 was unable to reach the 580 W requirement producing ~528 W with the small pot. The paraffin stove generated the highest cooking power of 752 W with the large pot, followed by STV02 with 659 W with the small pot. With the stainless steel at high power, The paraffin stove produced the highest thermal power irrespective of the pot size and type. STV03 was unable to produce thermal power above 1 kW with any pot size. STV01 generated a thermal power of 1.10 kW with the medium pot, while STV02 generated 1.12 and 1.17 kW with large and small pots. The equivalent time to boil is less than 10 minutes per litre for all three methanol stoves, an acceptable performance range. With the shiny pots, STV01 reported the largest turn-down ratio (best controllability) with large (TDR = 3.7) and medium pots (TDR = 3.1), followed by STV02 and the paraffin stove, both producing TDR values of ~2, irrespective of pot size STV03 produced the poorest TDR, producing TDR of 2 with the medium pot only.STV01 and STV02 reported the largest TDRs with all three black pot sizes. Two of the methanol stoves and the paraffin stove reported Relative Carbon monoxide Emission (RCE) of values exceeding the 2% limit allowed for indoor combustion stoves. **At high power**, only STV03 has an RCE that complies with the 2% CO/CO_2 emission limit set in SABS 1906 (a paraffin stove standard for the safety and emission limits. Overall, the paraffin stove recorded the lowest combustion efficiency, with RCE reaching ~5% with the small shiny pot and 8% with the medium black pot. Further design improvements are needed to bring the carbon monoxide emissions within the health safety limits. Nevertheless, the methanol stoves' overall carbon monoxide emissions are lower than for the reference paraffin stove technology. For all the stoves, the power setting lever requires design improvements to reduce the touching temperature below 42°C. The overall assessment is that methanol-fuelled stoves are a viable alternative to paraffin-fuelled stoves concerning performance and safety.

Keywords: Methanol cookstove, safety, thermal performance, emission performance.

Table of Contents

List of Tables

List of Figures

Abbreviations and Acronyms

°C	Degree Celsius
CO	Carbon monoxide
CO_2	Carbon dioxide
HTP	Heterogeneous Testing Protocol
KTP	Kitchen Testing Protocol
RCE	Relative Carbon monoxide Emission
SABS	South African Bureau of Standard
SANS	South African National Standard
TDR	Turn Down Ratio
UTP	Uncontrolled Test Protocol
WBT	Water Boiling Test
WHT	Water Heating Test

Glossary

Conduction: "Heat transfer through stationary matter by physical contact". *https://cnx.org/contents/Ax2o07Ul@23.18:Q1FnCAex@9/14-4-Heat-Transfer-Methods*

Cooking power: The quantum of heat energy per unit time transferred to a cooking vessel and its contents.

Emissions: Excessive release of particles and or gases into the atmosphere or ambient air leading to poor indoor air quality. '*Gases or particles released into the air that can contribute to global warming or poor air quality.'* https://www.epa.ie/footer/a-zglossaryofenvironmentalterms/

Low power: ***"****Operation of a stove at a minimum (or nearly minimum) rate of energy use".* https://www.iso.org/obp/ui/#iso:std:iso:iwa:11:ed-1:v1:en

High power: *"Operation of a stove at a maximum (or nearly maximum) rate of energy use" https://www.iso.org/obp/ui/#iso:std:iso:iwa:11:ed-1:v1:en*

Radiation: The transfer or release of energy from an object to the surrounding matter.

Relative Carbon monoxide Emission (RCE): The ratio of the volumetric concentration of CO to the sum of the volumetric concentrations of CO and CO_2, averaged over a temperature rise interval from 30°C to 80°C.

Safety: "Ability of a cookstove to be operated at an acceptable level of risk of harm". https://www.iso.org/obp/ui/#iso:std:iso:19867:-1:ed-1:v1:en

Standard test protocol: "An original draught or record from a document, a plan for carrying out a scientific experiment or medical treatment" (Zhang et al., 2017:1347).

Standard: "A document which is established by consensus and approved by a recognised institution, provides common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context" (Zhang et al., 2017:1347).

Specific Time to Boil: The time that would be taken to raise the temperature of one litre of water by 80°C.

Turn-down ratio: The cooking powers of an appliance at high power and low power settings

Thermal power: The rate of energy release from the complete combustion of the consumed fuel.

Thermal efficiency: "*The ratio of energy retained by water (in the pot) to the energy released by the fuel combustion. The energy absorbed by the pot itself is not regarded as part of the function. [%]*" (Makonese 2011: xv).

Acknowledgements

* First and foremost, I would like to thank God the Almighty for the strength, endurance, and abilities that got me this far.
* I would like to give many thanks to my family for their support throughout the journey.
* I would also like to express my unending sincere gratitude to my supervisor, Professor Harold Annegarn, for nurturing, patience, guidance and support throughout this study.
* The success of this study is due to financial and academic support provided by the National Research Fund (NRF) and Climatology Research Group (CRG) of North-West University.
* I am grateful to the South African Bureau of Standards (SABS) Working Group for their efforts to develop the draft standard.
* I am always indebted to the ‘triangle’ Tshepo Papi Khanye and Ntwakgolo Butiza Marebane for their utmost support (day and night availability).

1 Introduction

1.1 Introduction and problem statement (context and background)

Energy efficiency and availability play an essential role in the human environment. It has since become a critical basic need for humans to maintain a living as much as they need water and air (oxygen) to live (Nkosi, 2017). There are different energy sources and fuels such as electricity, solar, wood, dung, biogas, paraffin, Liquefied Petroleum Gas (LPG) and coal. Electricity is the most efficient energy preferred globally; however, it is not accessible to everyone, especially in developing and non-developed countries. Wood, bio-gas, coal, dung and LPG are the energy sources most used within low-income settlements in developed and developing countries (Balmer, 2007; Dasgupta et al., 2013; Chidhindi et al., 2019). An estimated 3 billion residents in low-income settlements within developing such as China, Brazil, and South Africa use solid fuels and petroleum fuel products for domestic cooking, lighting and heating (WHO, 2014; Amegah & Jaakkola, 2016; Quinn et al., 2018). Over the African sub-Saharan, approximately 730 million (90%) of the population within low-income settlements is dependent on these fuels to meet their basic energy needs (Ludwig et al., 2003; IEA & World Bank (2014); Nkosi, 2017; Pailman et al., 2018).

South Africa is a developing country with a population of about 60 million, of which 3.5 million households have been declared energy-poor. The households declared energy poverty are households with limited or no access to safe and affordable energy sources. Other definitions of energy poverty refer to an expenditure of more than 10% of household income on energy services (Lloyd, 2002; Kimemia et al., 2014; Hernández, 2016; Stats SA, 2020). Approximately 80% of these households reside within low-income settlements. The main types of fuels used vary spatially; firewood is used almost in the entire country, while dung and coal are used mainly in the Highveld region (Mpumalanga, Gauteng, and Free state) (Ismail & Khembo, 2015; Nkosi, 2017). About 98% and 76% of households in rural areas of KwaZulu-Natal and North West province use firewood. The use of firewood is practised in almost every rural part of Limpopo province. Several low-income and informal settlements in the Gauteng and Western Cape province have been reported that about 99% of the households use biomass and paraffin for cooking and space heating (Lloyd, 2002). Paraffin is used equally in townships and rural places. The dependency on these fuels is an essential element of life in South African low-income settlements, and it will remain unchanged for the unforeseeable future (Lloyd, 2002).

Various studies done in South African low-income settlements report high indoor particulate matter concentrations during and after cooking. The high concentrations observed were due to open fires (Albers et al., 2015; Department of Environmental Affairs (DEA), 2016), incomplete combustion, low-grade fuels, lack of emission reduction infrastructure and inadequate coal stove-operation skills (Albers et al., 2015; Nkosi, 2017). The use of these fuels with poor combustion behaviour within dwellings has resulted in poor indoor air quality in many low-income households. Biomass stoves using wood as fuel account for approximately 0.0018 to 4.0 g/kg of suspended fine particulate matter (PM) and 0.19 to 7.94 g/kg of total suspended PM (Nkosi, 2017).

Paraffin is one of the most 'convenient' fuels for households within low-income settlements (Gevaart-Durkin et al., 2013). Approximately 40-50% of South Africa's population uses paraffin for domestic purposes (Kruger, 2006; Makonese et al., 2012). It has usage of about 14%, 21%, and 13% for space heating, cooking and lighting, respectively (Muller et al., 2003; Makonese et al., 2012). Paraffin is widely distributed within the markets, making it a readily available and inexpensive fuel compared to other energy carriers such as Liquefied Petroleum Gases (LPG) and electricity. LPG is considered cheap and efficient, but it is not widely or reliably available, while electricity is the most efficient yet most expensive (Peck et al., 2000; Kimemia et al., 2014). Paraffin stoves have been introduced as an intervention to minimise the use of biomass fuels in various countries (Barnes & Qian, 1992; Makonese et al., 2012). Paraffin has usage of 0.7% in urban and 7.5% in rural areas for only cooking purposes worldwide (WHO, 2018). South Africa has adopted paraffin without explicitly replacing solid and biomass fuel usage (Barnes & Qian, 1992; Alberts et al., 1997; Makonese et al., 2012).

The use of petroleum products, particularly paraffin, has been reported to be a challenge and risky (Masekameni et al., 2015). Paraffin is habitually referred to as a clean fuel as it does not produce visible smoke like solid fuels. However, various studies have reported that paraffin does produce harmful emissions (Makonese et., 2012). Incomplete combustion in poorly designed paraffin stoves results in enhanced CO and black carbon particulate matter emissions (Masekameni et al., 2015). The challenge of paraffin usage is not limited to poor indoor air quality but also involves fatalities and injuries from accidental fires caused by paraffin stoves (Makonese et al., 2012) and the ingestion of the fuel by children. Every year, shack fires are reported within informal and low-income settlements due to unsafe lighting, heating, and cooking practices. Children are said to constitute the majority of shack fire victims (Kimemia, 2012). Fuel spillage during refuelling or tilting a stove while ignited may result in fires and severe burn injuries.

Wick stoves have an inherent problem of the fuel tank heating up when operating for a long-time (over 30 minutes), resulting in the stove conflagrating. Paraffin is frequently confused with consumable drinks such as water and sodas when the fuel is (improperly) stored in used beverage bottles. Children, one to three years old, are the most susceptible to such ingestion incidents (Matzopoulos & Carolissen, 2006; Schwebel et al., 2009). While paraffin is poorly absorbed in the gastrointestinal tract, secondary consequences of severe pneumonitis may occur if the victim vomits and paraffin enters the respiratory tract (Tibbutt, 2011). Parrafin adds an unpleasant scent and taste to food (Tait et al., 2013).

Paraffin has several favourable properties as a domestic fuel. Paraffin has a high thermal efficiency when used in pressurised stoves. It is affordable, is widely available, and can be purchased in small quantities. Because it can be easily stored, it is a useful substitute energy for electricity or alternative stand-by during power cuts. In areas where biomass (firewood) for cooking is scarce or in dense informal settlements where open solid fuel combustion cannot occur, paraffin and compact paraffin stoves provide a viable alternative cooking technology (Tait et al., 2013).

Many intervention strategies and technologies such as standards, clean fuels and improved cookstoves were introduced in the past decades to replace or reduce the use of paraffin and traditional biomass stoves (MacCarty et al., 2010). Standards for stove designs and fuels were also established to ensure the quality and efficiency of the stoves. The standards are drafted by a country's Bureau of Standards and enforced by the state/ government. A standard involves testing the safety of use, thermal efficiency and pollutant emission of a particular stove using a specific fuel (Gallagher et al., 2016). Several standards for cooking technologies such as SANS (1906) and SANS (666) have been developed and enforced in South Africa. Every standard has a protocol that is used to evaluate the performance of the appliance. These standard protocols are either laboratory-based or field-based. Laboratory-based protocols include a Water Boiling Test (WBT) and the Heterogeneous Test Protocol (HTP) (HTP 1.05, 2012). Field-based protocols are the Kitchen Test Protocol (KTP) (KTP 4.0, 2018) and the Uncontrolled Test Protocol (UTP) (Robinson et al., 2011). Gas analysers for measuring pollutants expected from typical fuels are used to determine the emissions (MacCarty et al., 2010). The tests are used to evaluate whether the stove meets the standard requirements. A paraffin stove standard was developed in the 1990s following numerous reports of paraffin poisoning in children and shack fires within low-income settlements. These paraffin-related issues continue despite introducing standards that force manufacturers to develop alternative technologies and energy sources with minimal environmental and health risks (Lloyd & Truran, 2008; Kimemia, 2012).

Methanol has been identified as a potential alternative clean fuel to solid fuels and paraffin in South Africa (Masekameni et al., 2015). Although this fuel is already available in the market to a limited extent, detailed investigations of methanol stove performance are yet to be conducted in the South African context. The use and performance of methanol stoves need to be investigated and contextualised for South Africa. This study evaluates the safety, thermal and emission performance and safety of three different methanol cookstoves. The South African Bureau of Standard is yet to develop a standard for testing the use and performance of methanol appliances.

Given that there are no standard test methods for methanol stoves, there is a need to develop a standard based on a South African context. A standard test method will be developed in this study. Based on the standard test method, the following metrics are reported: thermal efficiency, thermal power, cooking power, controllability (turn-down ratio) and Relative Carbon monoxide Emissions. Safety aspects such as the surface temperature of touchable parts, evaporation loss, stove upset, sharp points/edges, and portability are evaluated. Lastly, the extent to which thermodynamic processes such as radiative cooling and conductive heat loss affect the performance of methanol stoves is reported.

1.2 Aim & objectives

This study aims to evaluate the safety, thermal and emission performance of selected methanol fuelled stoves and reference paraffin fuelled stove. This evaluation of the stoves' performance will aid in designing and enforcing cooking methanol cookstoves that are safer and cleaner for low-income households. The study will achieve this aim through the following objectives:

a) Develop a standard test method for thermal performance, emissions of CO, safety and durability of methanol cookstoves.
b) Investigate the radiative and conductive heat losses in determining cooking power.
c) Use the standard test method to evaluate three commercial designs of methanol cookstoves for:
   i) Safety
   ii) Thermal performance (heat transfer, combustion efficiency)
   iii) CO and CO_2 emissions
   iv) Influence of pot size and external finish (shiny aluminium (Al) or matt black) on the thermal and emission performance of the stove/fuel/pot combination.

1.3 Exclusions

Issues of affordability, marketing, social acceptance and methanol toxicity, all essential aspects for any large scale implementation of this new technology, were outside the scope of this thesis.

1.4 Study justification/significance

This study will help evaluate the methanol fuel stoves as an alternative to paraffin stoves that have been responsible for many of the shack fires that regularly occur in South African informal settlements. Furthermore, the study will help provide information on modifications to improve the methanol stove's performance to meet the required standard and users' preferences. It will, as a result, enhance the adoption of methanol fuel as an alternative energy carrier in low-income South African homes.

With the increase in demand for clean fuels and stoves countrywide, there is a clear need to develop standard protocols to improve cookstove certification procedures and capacity building within research and technical institutions. The standard protocols will be essential in testing newly developed cookstove models and extending the knowledge on clean fuels and cookstoves. This study will assist stakeholders to adopt and the government to enforce clean fuel and cookstove standards currently under development by the South African Bureau of Standards (SABS) and the International Organisation for Standardisation (ISO). This will ease implementing a certification protocol for newly designed cookstoves intended to be distributed in the markets (Rajabu et al., 2014). The results will aid in designing and evaluating methanol cookstoves that are safer and cleaner for low-income households and whether their performance characteristics will provide a cost-competitive alternative to the less safe paraffin stoves dominating the market.

1.5 Chapter outline

Chapter 1: Introduction

This chapter provides a brief background on energy sources and energy availability within South African low-income settlements. The importance of introducing clean and safe cooking technologies for domestic usage is emphasised. The chapter outlines the aim, objectives, significance and justification of the study.

Chapter 2: Literature review

In this chapter, a detailed review of the literature is provided. It covers standards in a global and South African context, unsafe cookstoves, new cookstove technologies, and cookstoves testing. It includes discussing the development of standard testing protocols and how they are used in testing centres to certify technologies.

Chapter 3: Methodology.

This chapter describes the processes and testing protocols used to perform the stove evaluations. The South African Bureau of Standards Working Group procedure for developing a draft methanol stove standard is outlined. The Water Heating Test used for testing thermal and emission performance is described, together with the methods for testing safety and use of the methanol stoves.

Chapter 4: Results and discussion

This chapter discusses the results of the use and performance of the methanol fuelled stoves and reference paraffin stove. It provides the comparison of the methanol stoves to paraffin wick stoves. The safety of the stoves is also analysed, showing strengths and weaknesses.

Chapter 5: Summary and Conclusion

This concluding chapter provides a summary and conclusions of the study. It highlights the objectives covered and how these objectives were achieved and answered in Chapters 3 and 4. It provides recommendations for future studies.

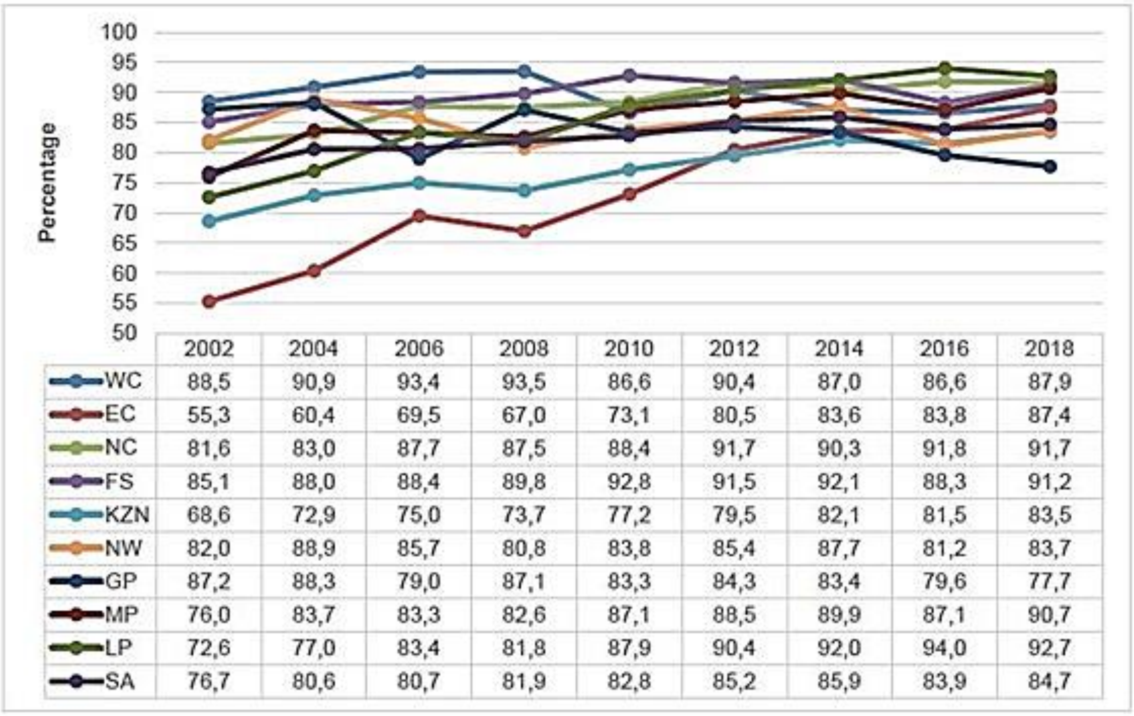
2 Literature Review

2.1 Household energy in South African low-income settlements

Implementing clean energy policies and efficient technologies intended to facilitate a transition to cleaner, safer fuels and technologies requires an in-depth understanding of the energy profiles within low-income settlements (van der Kroon et al., 2013; Nkosi, 2017). Enhanced facilitation in energy source transition can assist with improving the living conditions of low-income residents. The transition in energy sources involves switching from traditional cookstoves and fuels to improved and new technologies that are more efficient, cleaner and safe. (Reddy & Reddy, 1994; Nkosi, 2017). Little understanding of the dynamics of using different or combining energy sources can lead to assumptions that electrification of the dwellings in low-income settlements will mitigate the energy-related problems. Several factors play a role in determining the fuel type and appliances to be used. The factors include the availability of the fuel, reliability of the available appliances, cultural behaviour, health impacts, and economic stability (Davis, 1998; Heltberg, 2004).

In South Africa, energy poverty is a significant concern within low-income settlements. In 2000, the government launched various support programmes to provide poor people with free basic services to meet their household needs. A *free basic electricity* support programme was implemented in 2003 to help poor households meet their basic energy needs such as cooking, lighting, and heating. 50 kWh is provided for free to all South Africans qualifying as poor households (Runsten, 2015). Between 2002 and 2018, the national household dependency on electricity usage increased from 76.7% to 84.7%. There was a corresponding reduction in wood and paraffin use - wood usage reduced from 20% to 7.7% and paraffin from 16.1% to 3.6% (Stats SA, 2019).

Although wood and paraffin usage decreased, the programme did not have enough progress due to insufficient grid availability at many locations. Another limitation was that the amount of *free basic electricity* provided is insufficient to sustain households for at least a month. Consequently, several people continued to use other primary alternative energy sources (Visagie, 2008). Provinces found to have a high percentage of households with access to mains electricity are Limpopo (92.7%), Northern Cape (91.7%) and Free State (91.2%). The provinces with the lowest electricity access were North West (83.7%), KwaZulu-Natal (83.5%) and Gauteng (77.7%) (Stats SA, 2019) (Figure 2-1). The increase in lack of electricity over these four provinces is associated with swift immigration from rural provinces and a consequent increase in informal households.



	2002	2004	2006	2008	2010	2012	2014	2016	2018
WC	88,5	90,9	93,4	93,5	86,6	90,4	87,0	86,6	87,9
EC	55,3	60,4	69,5	67,0	73,1	80,5	83,6	83,8	87,4
NC	81,6	83,0	87,7	87,5	88,4	91,7	90,3	91,8	91,7
FS	85,1	88,0	88,4	89,8	92,8	91,5	92,1	88,3	91,2
KZN	68,6	72,9	75,0	73,7	77,2	79,5	82,1	81,5	83,5
NW	82,0	88,9	85,7	80,8	83,8	85,4	87,7	81,2	83,7
GP	87,2	88,3	79,0	87,1	83,3	84,3	83,4	79,6	77,7
MP	76,0	83,7	83,3	82,6	87,1	88,5	89,9	87,1	90,7
LP	72,6	77,0	83,4	81,8	87,9	90,4	92,0	94,0	92,7
SA	76,7	80,6	80,7	81,9	82,8	85,2	85,9	83,9	84,7

Source: Stats SA, 2019

Figure 2-1. Households with access to the mains electricity supply between 2002 and 2018 by provinces (Stats SA, 2019). WC- Western Cape; EC- Eastern Cape; NC- Northern Cape; FS- Free State; KZN- Kwa Zulu-Natal; NW- North West; GP- Gauteng Province, MP- Mpumalanga; LP- Limpopo; SA- South Africa.

The electricity service limitations have allowed several households to continue with their traditional and or primary energy sources. Various energy sources are used as alternatives to electricity, including wood, paraffin, and coal (Langerman et al., 2018). Stats SA (2019) reported that there was an increase in households making use of electricity for cooking, from 57.5% (2002) to 79.9% (2014). There was an almost twofold increase in LPG usage, from 2.2% (2002) to 4.2% (2017), but in 2018 this declined to 3.6% (Stats SA, 2019) (Figure 2-2).

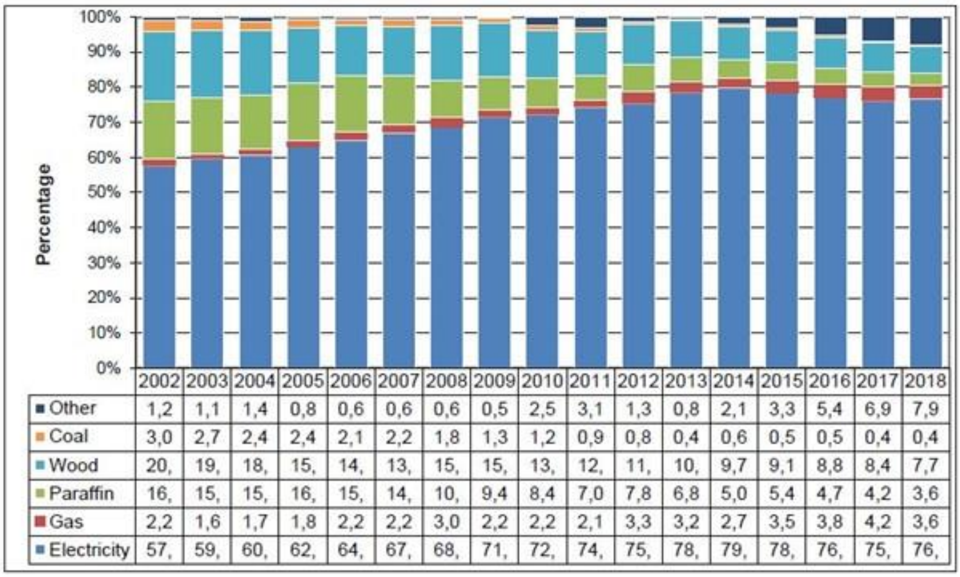


Figure 2-2. Primary energy sources used for cooking by households (Stats SA, 2019).

Mains electricity is the preferred energy for all domestic purposes: lighting 87.2%; cooking 81.3%; water heating 82.5%; and space heating 38% (Stats SA, 2019). Wood is the second energy preference with 14.4% for cooking, 12.9% for water heating and 13% for space heating. The frequency of use of other energy sources are listed in Table 2.1

Table 2.1. Percentage of households using different energy sources for basic domestic purposes such as lighting, cooking and heating (Stats SA, 2019).

	Lighting	Cooking	Heating water	Space heating
Electricity from mains	87.2	81.3	82.5	38.0
Other sources of electricity	8.2	7.9	7.9	4.2
Gas	0.8	6.9	3.2	3.4
Paraffin	3.4	7.7	7.1	7.3
Wood	n/a	14.4	12.9	13.0
Coal	n/a	1.2	1.0	1.6
Candles	16.3	n/a	n/a	n/a
Animal dung	46.3	0.8	0.8	0.7
Solar energy	0.7	0.1	0.5	0.1
Other	0.1	0.0	0.0	0.4
None	0.0	0.1	0.2	21.3

N = 20 208 households. It is important to note that the values in the table do not add up to 100%, as the participants were asked to indicate all the energy sources they use for different purposes.

2.2 The use of paraffin in South African low-income settlements

Approximately 3.5 million households in South Africa have been declared as energy-poor by the government (Lloyd, 2002). Most of these households prefer paraffin, and they are vulnerable to several energy-related risks or hazards such as fire incidents, significant pollutant concentrations, and poisonings (Lloyd, 2002; Kimemia, 2012). Paraffin is one of the significant energy carriers in low-income settlements in South Africa (Kimemia, 2012; Tait et al., 2013), evident in Figure 2-3.

It is widely distributed within the markets, making it easy and cheap compared to other energy carriers such as LPG and electricity. (Peck et al., 2000; Kimemia & Annegarn, 2014). This continued usage of paraffin contributes to the burden of diseases due to that there are several health impacts and safety risks associated with paraffin usage. The health impacts and safety risks include indoor air pollution, ingestions, burn injuries and fire risks. These health impacts and safety risks are caused by faulty and unsafe paraffin appliances and confusion of the fuel with consumable liquids, mainly water and sodas (Tait et al., 2013). Paraffin stoves were introduced with a pressurised system design and later modified and became non-pressurised (Tait et al., 2013). However, health and safety concerns continued to rise. The primary problems are inefficient paraffin appliances and poor fuel packaging (Tait et al., 2013). There is significant paraffin use, although there are other alternative fuels or energy sources (Table 2.2).

Several studies have investigated paraffin use in South African households in rural, peri-urban and urban areas. According to Roberts and Wentzel (2006), many houses use multiple fuels (a phenomenon referred to as fuel stacking), with paraffin as part of the fuel combinations (Figure 2.2). They reported that in Lady Grey,[1] ~91% of homes used paraffin; Benoni[2] ~73%, Gugulethu[3] ~73%, and Galeshwe[4] ~56% (Figure 2-3).

---

[1] A rural village in the north of the Eastern Cape Province, South Africa.
[2] A town located in the Ekurhuleni municipality in the Gauteng Province, South Africa.
[3] A township of Cape Town, Western Cape Province, South Africa.
[4] A township located in the Northern Cape Province, South Africa

Table 2.2. Fuel combinations amongst ten selected houses within the three settlements (Roberts & Wentzel, 2006).

Code	Fuel combinations
1	Paraffin, electricity, Coal, Candles, wood
2	Paraffin, coal, candles, wood
3	Paraffin, candles, wood
4	Paraffin, coal, wood
5	Paraffin, electricity
6	Paraffin, electricity, coal, coal
7	Paraffin, candles
8	Paraffin, electricity, coal
9	Paraffin, electricity, gas
10	Paraffin, electricity, wood, cow dung

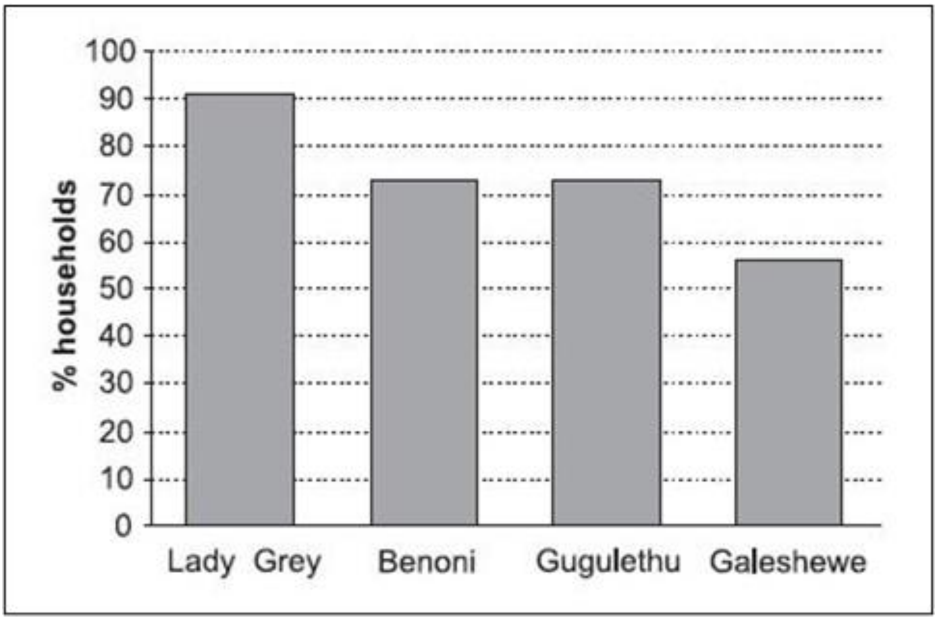


Figure 2-3. Percentage of households using paraffin within rural, peri-urban and urban areas selected from Benoni, Galeshwe, Lady Grey and Gugulethu (Roberts & Wentzel, 2006).

2.3 Risks and impacts of traditional biomass/coal stoves and poorly designed paraffin stoves.

2.3.1 Potential health risks and impacts of solid or biomass fuel stoves

Indoor air quality

Household air pollution (HAP) has been studied in South Africa, particularly within low-income settlements. South African low-income settlements are densely populated and characterised by high household air pollution concentrations. Serious HAP results from the use of solid fuels, biomass and paraffin for cooking and heating (Zhang et al., 2007; Language et al., 2016;

Chidhindi et al., 2019). Poor combustion practices and poor combusting appliances are aggravating factors. Most households use traditional coal or biomass stoves for cooking (Figure 2-4). The use of these conventional stoves results in poor combustion, whereas the stoves themselves may have poor combustion designs (Naidoo et al., 2015; Qhekwane et al., 2016; Shezi & Wright, 2018;). Major pollutants from the fuels and activities are carbon monoxide (CO), black carbon, nitrogen dioxide (NO_2), nitrogen oxides (NOx), sulphur (S), particulate matter (PM). Approximately 20% of South African households have health effects associated with HAP, with about 1 400 child deaths per year attributed to HAP (Barnes et al., 2009; Khopkar, 2011; Albeliotis & Pakula, 2013).

Figure 2-4. Traditional cast iron coal stove (Nkosi, 2017).

Language et al. (2016) investigated HAP within the South African Highveld in Mpumalanga. They found that indoor particulate matter varied seasonally. In winter, PM concentrations were high by a factor of seven compared to ambient concentrations. Indoor PM concentrations reached a high of 6 000 µg/m^3 in winter and 200 µg/m^3 in summer. Qhekwana et al. (2017) undertook a study in one of the townships (Ikageng) in the North-West Province, South Africa, where the relationship between thermal comfort and PM4 was evaluated. This included houses practising solid-fuel burning and houses not using solid fuels for domestic use. The study found that houses using solid fuels recorded high PM4 concentrations reaching approximately 226 µg/m^3 and 1 110 µg/m^3 in the morning and evening, respectively. The high concentrations found in both studies by Language et al. (2016) and Qhekwana et al. (2017) resulted from the increased usage of traditional solid fuel stoves and paraffin stoves for domestic purposes.

Other health risks associated with solid and biomass fuel stoves

Apart from contributing to poor health conditions through indoor air pollution, there are other health impacts of solid and biomass fuels. For example, firewood collection can result in injuries (Table 2.3). Several reports have shown that many household members get into risky conditions. People get cuts, skin irritations, broken bones, infected with diseases (malaria due to mosquito bite) and bitten by wild animals. In addition, when collecting the firewood, people carry the loads on their heads, leading to headaches, fatigue, chest and joint pains, waist pains, chronic back pains, and spinal injuries (Kimemia et al., 2014; Kimemia & Annegarn, 2014).

Table 2.3. Sources of energy and associated risk ratings (Kimemia et al., 2014; Kimemia & Annegarn, 2014)

Fuel type	Frequency of use (%)	Injury rating	Burn rating	Fire rating
Candles	49.8	0.08	0.31	0.81
Coal	3.0	0.40	0.91	0.14
Electricity	73.0	0.68	0.21	0.08
Gas	3.0	0.50	1.26	1.89
Paraffin	33.3	1.08	1.28	1.42
Wood	2.5	3.18	8.17	0.35

N = 6 379 reported incidents. The ratings were determined as the percentage of incidents caused by the particular fuel type by frequency of fuel use. A value greater than 1 indicates a dangerous fuel type, whilst a value less than 1 indicates a less dangerous fuel type.

2.3.2 Potential risks and impacts associated with paraffin stoves

Paraffin stoves and indoor air quality

Paraffin was introduced as a transitional fuel as it was rated as a cleaner fuel than traditional solid and biomass fuels. Since the introduction of paraffin stoves, there have been different modified designs to produce safe models to alleviate the risks associated with continued paraffin usage. Illegal models (paraffin stoves not in compliance with the compulsory paraffin stove safety standard of the SABS) are found to be widely distributed in the markets and play a significant role in poor indoor quality and fire incidents (Lloyd, 2002; Kimemia & Annegarn, 2014; Masekameni et al., 2015). However, paraffin combustion in poorly designed stoves (Figure 2-5) results in poor indoor air quality and fire incidents. Masekameni et al. (2015) undertook a study involving testing a paraffin stove, a certified model complying with SANS (1906), methanol and ethanol stoves. The paraffin stove had a $CO:CO_2$ ratio 2.3 times above the SABS emission limit of 2%. A peak of 18 000 ppm CO was observed from the first minutes after ignition due to the flame contacting the cold surface or parts of the stove and pot. Compared to other ‘clean’ fuel stoves (methanol and ethanol stove), the paraffin stove had the worst emission performance. Unburned paraffin escapes from the wick and flame zone into the surrounding space.

These emissions result in respiratory complications for the users and other inhabitants in the houses where paraffin is used. For example, dyspnoea is a lung problem caused by the inhalation of a high concentration of flue gases from paraffin stoves Chilcott (2006). Exposure to low paraffin concentrations for a longer duration may also cause appetite loss, nausea and nervousness Chilcott (2006). Skin exposure to paraffin is known to cause dermatitis. Chilcott (2006) reported that 65% of paraffin stove users had a coughing problem. Schwebel et al. (2009) reported a lack of knowledge among users about safe paraffin use, inadequate understanding of paraffin related risks and a high rate of unsafe paraffin usage.

Figure 2-5. Basic and poorly designed paraffin stove (Kimemia and van Niekerk, 2017).

Shack fires as a paraffin associated risk

According to the Paraffin Safety Association of Southern Africa (PASASA), approximately 59% of fire incidents within informal or low-income settlements are caused by faulty and unsafe paraffin fuel stoves (cited by Kimemia, 2012). Annually, more than 200 000 people lose their properties as a result of paraffin related fires. Amongst the four metropolitan centres of South Africa, Cape Town has been classified as the city with the most shack fire incidents (Francioli, 2011; Walls et al., 2017). There has been significant growth of informal settlement dwellings within the Cape Town Metropolitan, increasing from 28 000 to 104 000 between 1993 and 2006. Approximately 18 500 fire incidents were recorded between 1990 and 2004. About 47% of these fire incidents occurred within informal settlements. It is reported that from these incidents, about 500 deaths were recorded, and 15 000 people were hospitalised with fire/ burn injuries (Walls et al., 2017). Several causes of these fire incidents include open fires, faulty electrical connections or appliances, paraffin stove explosions, and burning candles left unattended. Shack fires are mostly happening at a large scale due to various reasons, including the nature of the building material (cardboards, wooden boards and timber woods as supporting frames) and the proximity of one shack to the other (Van Niekerk et al., 2009; Walls et al., 2017). There have been many large-scale accidental fires reported in the past ten years. Fires originating from household accidents have caused the conflagration of tens and sometimes hundreds of neighbouring dwellings. A 2013 fire in Khayelitsha left ~4 000 people homeless and five dead; in 2013 in Kayamandi[5], ~4 500 people were left homeless and two dead (2013); in 2015, in Imizamo Yethu[6] ~1 000 people were left homeless and one dead; and 2015 in Masiphumelele[7],~4 000 people were left homeless and two dead.

Community-based research reported by Swart and Bredenkamp (2012) outlines systematic challenges related to the supply and utilisation of paraffin fuelled stoves. The study reported that approximately 53% of fires were energy-related caused by the explosion of poorly designed stoves (Figure 2-6). The comparison of energy-related injuries is outlined in Table 2.4, as reported by Swart and Bredenkamp (2012). Paraffin was declared as the primary cause of flame burns, with about 663 people injured, followed by wood (309), electricity (229) and unknowns (215). Paraffin ingestion and chemical burns were found to be high compared to the other energy sources. Treating accidental fire injuries costs South Africa approximately USD 26.5 million per year, about fifty times the value of paraffin sales annually (Kimemia, 2012). This expenditure indicates that addressing household energy-related challenges associated with paraffin use will need comprehensive and trans sectoral approaches (Swart & Bredenkamp, 2012).

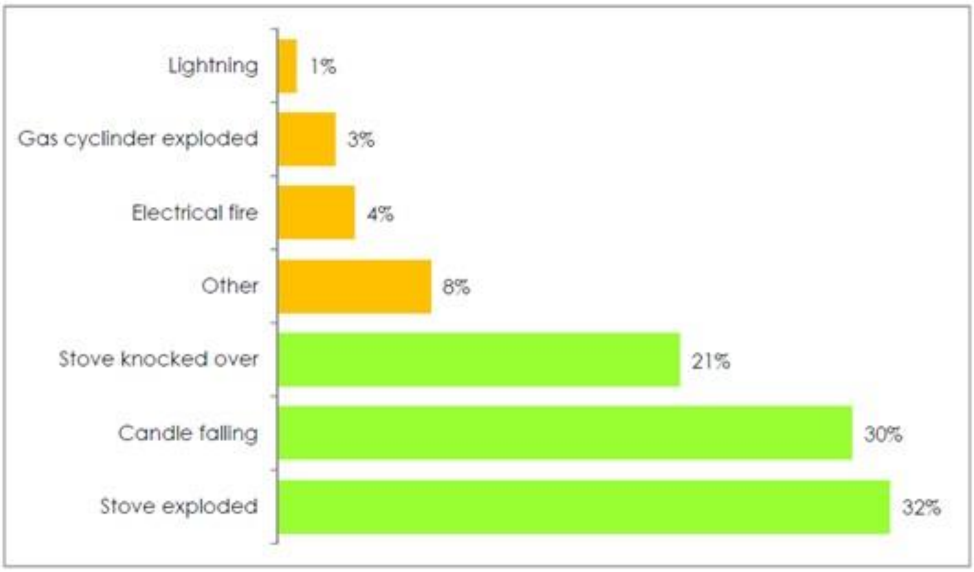


Figure 2-6. Characteristic causes of energy-related fire within settlements (Swart & Bredenkamp, 2012).

---

[5] A suburb in Stellenbosch, Western Cape province, South Africa.
[6] Low-income or informal settlement in the Western Cape Province, South Africa.
[7] A township located in Cape Peninsula, Western Cape province, South Africa.

Table 2.4. The cumulative number of injuries classified by injury type and energy source between 2008 and 2012 (according to PASASA, cited by Kimemia, 2012)

Energy source	Number of people injured by injury cause						
	Burn - Flame	Burn - Food	Burn - Liquid	Burn - Contact	Ingestion - Paraffin	Chemical burn - - Paraffin	Asphyxia
Candles	240	0	3	2	2	4	19
Coal	41	0	11	20	0	0	0
Electricity	229	238	2527	181	0	0	0
Ethanol Gel	7	0	3	0	0	0	0
LPG	56	5	21	6	0	1	3
Paraffin	663	105	698	35	937	463	39
Wood	309	22	142	30	0	3	13
Unknown	215	13	186	11	0	3	22

Paraffin ingestion

Paraffin poisoning is a severe public health issue, affecting mainly young children, due to paraffin packaging and storage, often in soft drink bottles in small amounts. Young children who have not yet developed a sense of tasting and smelling the difference of various products tend to mistakenly drink paraffin, confusing it with drinks such as water and sodas. Paraffin has surface tension and low viscosity; this allows the fuel to be drawn into the lungs after ingestion. In South Africa, between 40 000 and 60 000 incidents of accidental paraffin ingestions by children are reported annually (Matzopoulos & Carolissen, 2006; Schwebel et al., 2009)

2.4 Alternative fuels and cooking technologies

Clean fuels and improved cookstoves were introduced throughout the past decades to reduce health and environmental impacts (MacCarty et al., 2010). In addition, governments and non-governmental organisations (NGOs) have collaborated to reduce unsafe cooking practices and technologies by producing clean fuels and improved safer cookstoves (Kshirsagar & Kalamkar, 2014; Gallagher et al., 2016). However, these solutions focus primarily on optimising fuel efficiency, thermal performance and emission efficiency instead of having a significant focus on the safety of the appliance for the user (Gallagher et al., 2016).

Clean fuel cookstoves using LPG, methanol, and ethanol are currently introduced to reduce coal, biomass, and paraffin as primary energy sources, consequently attempting to alleviate negative environmental and human health impacts (Gallager et al., 2016; Okusanya et al., 2019). The basic parameters of the abovementioned alternative fuels, methanol, LPG and ethanol, are outlined in Table 2.5 (Engineering ToolBox, 2001). The fuels are also considered to be safe for users. About 40% of households use improved biomass cookstoves and clean fuels in the developing world, replacing traditional fuels and rudimentary cookstoves (Putti et al., 2015). Methanol stoves, ethanol gel stoves and LPG stoves are the most preferred clean fuel stoves intended to replace traditional and paraffin stoves within households in low-income settlements (Masekameni et al., 2015). The fuels used in these stoves are considered clean because they produce no smoke and are relatively odourless when burned, unlike the primarily used solid fuels, biofuels and paraffin. This implies a minimal release of pollutants such as black carbon and particulate matter in either fine or coarse fraction (Masekameni et al., 2015). However, these clean fuel stoves generate less firepower compared to solid fuel or paraffin stoves.

Table 2.5. Basic parameters of alternative fuels (Engineering ToolBox, 2001).

Fuel	Lower Heating Value (LHV) (MJ/kg)	Ignition temperature (Deg C)	Physical State
Methanol	19.8	481	Liquid
Ethanol	26.7	423	Liquid
LPG	45.5	470	Gas

Methanol fuel and stoves

Methanol fuel (CH_3OH) is a compound of four hydrogen atoms, one oxygen and one carbon atom. It is one of the organic compounds known as alcohols. Methanol fuel is a liquid at normal temperature and pressure, biodegradable, and water-soluble (Hagen, 1977; NIOSH, 2019). Methanol has been reported to be highly toxic through ingestion, inhalation or prolonged dermal contact (NIOSH, 2019).

Methanol fuel has the following advantages: clean-burning, low pollutant emissions; does not form soot while burning, can be combusted in non-pressurised appliances; is water-soluble, making it easier to extinguish; and is odourless (Stokes & Crocco, 2005; NIOSH, 2019). These advantages have played a significant role in adopting the fuel in several countries so far (Log & Moi, 2018). On the other hand, there are few disadvantages: it is highly toxic compared to other liquid fuels; it is relatively expensive compared to paraffin; fire may be invisible at a place with bright light; it has a heating value of only 60% compared to paraffin (NIOSH, 2019). Although there is an adequate supply of methanol from SASOL, produced as a by-product when coal is processed into gasoline, it has not yet gained much attention as a cooking fuel in South Africa (Stokes & Ebbeson, 2005; Makonese et al., 2020

There are cookstoves designed strictly for the use of methanol (Figure 2-7). Similar to the introduction of ethanol gel stoves, methanol stoves have been promoted as a replacement for paraffin fuelled cookstoves. The stoves have a rigid structure made of three steel limbs in a triangular design to enhance stability. The pot support is enhanced by having a raised rim to rest the pot and three upright steel limbs to prevent the pot from sliding. Refuelling can only be done through the combustion port to avoid refuelling while the stove is operating (Masekameni et al., 2015; Makonese et al., 2020). It is designed with a lever to regulate primary air intake into the combustion chamber, thereby controlling the firepower level. A removable lid for extinguishing the fire after an operation is fitted.

Figure 2-7. Methanol stove (Masekameni et al., 2015).

Ethanol gel fuel and stoves

The ethanol gel is a renewable energy fuel produced from sugar cane processing. Ethanol stoves are commonly made of refined stainless steel, has a cylindrical design shape, and is fitted with triangular pot support on top (Figure 2-8). It has a fuel holder that is cylindrical with holes around it for airflow. The stove is fitted with at least three feet to provide efficient stability to avoid easy tipping. Furthermore, concerning safety measures, the stove is designed so that refuelling is done through the combustion port to avoid refuelling while the stove is ignited or operating. It has a lever designed to adjust the power level by regulating airflow (Masekameni et al., 2015). Several studies have evaluated ethanol gel as fuel to alleviate energy poverty in third-world countries, specifically to replace paraffin. Ethanol gel has several advantages compared to paraffin: it burns almost cleanly; quickly extinguished compared to paraffin; it is viscous, which limits spillage quantity. Although it has such advantages over paraffin, adoption at a large scale is hindered by several factors. Like other renewable biofuels and modern fuel solutions, ethanol gel is more expensive per unit of energy content, rendering it unaffordable for low-income households (Utria, 2004; Lloyd & Visagie, 2007; Dioha et al., 2012).

Figure 2-8. Ethanol gel stove (Masekameni et al., 2015).

LPG

Liquefied petroleum gas (LPG) is a mixture of butane and propane. An LPG stove comprises a steel gas storage cylinder, a pressure regulator and a burner (Figure 2-9.). The pressure regulator acts as a power adjustment mechanism. LPG is a preferred cooking fuel for domestic and commercial purposes (Afrane & Ntiamoah 2011; Putti et al., 2015). LPG has the following advantages: clean combustion; fast and efficient; portable; safer compared to other fuels stored in pressurised tanks; appliances last longer when used according to manufacture instructions; and it is a precise off-set for deforestation (Basu et al., 2008; Mohlakoana & Annecke, 2009).

Figure 2-9. Liquefied petroleum gas (LPG) stove (Kimemia and Annegarn, 2016).

Improved biomass and solid fuel cookstoves

Solid fuels are, for example, firewood, animal waste (cow dung), coal, charcoal, and agricultural residuals. These fuels are usually burned in traditional stoves such as Mbaula, three-stone fire, Jiko stove, Tsotso stove, Pulumusa, and braziers. (Makonese & Bradnum, 2018). Several household air pollution impacts are associated with the use of these traditional biomass/solid fuel cookstoves. Improved biomass/solid fuel cookstoves have since been designed to improve fuel consumption, and thermal efficiency and combustion efficiency to reduce indoor air pollution. Makonese and Bradnum (2018) took the initiative to develop and test an improved biomass cookstove (energy-efficient and less emitting) (Figure 2-10) as a derivative of the internationally known 'rocket stove' idea. The stove was made of iron tubes and paint of galvanised iron. Several modifications were made to the fuel hopper shape and the size of the combustion chamber. Furthermore, other unique features were fitted, such as a removable ashtray and added metal sleeve over the combustion chamber. This added metal sleeve improves emission reduction and combustion efficiency by heating the air before entering the combustion chamber.

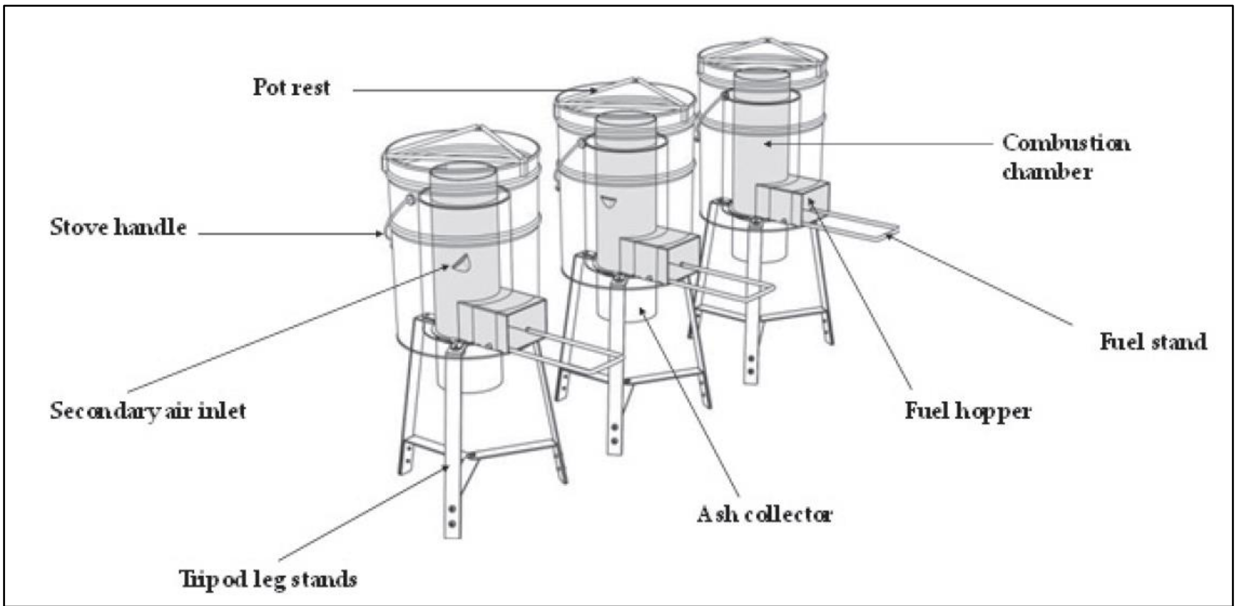


Figure 2-10. Drawing of the improved biomass cookstove (Makonese & Bradnum, 2018).

2.5 Standard testing protocols

2.5.1 The initial emergence of standard testing protocols

The primary goal of introducing clean fuels and improved cookstoves in developing countries was to reduce solid fuel use, protecting human health, and avoiding deforestation (Visser, 2005, Zhang et al., 2017). Assessments of improved cookstoves in the early 1980s were primarily done using the water boiling test (WBT) (Visser, 2005). Some later argued that the widely used water boiling efficiency was inadequate to characterise stoves in a scientifically rigorous manner (Visser, 2005). The argument was because several improved stoves identified as highly efficient with low fuel consumption in laboratory tests behaved differently in real-life situations (Visser, 2005). During the early stages, WBT involved using a cooking pan filled with a specific volume of water, then heated until the water boils and continues to boil for a few minutes. The efficiency was determined by the ratio of heat transferred to the cooking pan to the energy of the fuel consumed (Visser, 2005). The tests were done only at high power settings, with the efficiency being determined only in high power settings. The tests showed that newly improved cookstoves had different power settings with different heat transfer and fuel consumption at a specific power setting. The discovered changes in the stove performances brought the need to develop new standard testing protocols that considered all different aspects of new stoves and experimental conditions (Visser, 2005; Zhang et al., 2017). Standard testing protocols are incorporated primarily in a **standard** that is used to govern the testing of appliances.

A standard can be defined as *"…a document which is established by consensus and approved by a recognised institution, provides common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context"* (Zhang et al., 2017:3)

The most notable progression of international cookstove standards development occurred through the Lima Consensus in 2011. A provisional rating system was established to evaluate the different cookstoves models that show the different performance levels in terms of indoor air quality, fuel efficiency, safety (Ekouevi et al., 2014; Winrock International, 2017). Later, the Lima Consensus's primary principles were adopted and used as the foundation for the International Standards Organisation (ISO) and the International Workshop Agreement (IWA), specifically for cookstoves. It was then finalised and solidly declared by over 90 stakeholders during an ISO international workshop on cookstoves in 2012. Various laboratory protocols to evaluate cookstove safety and performance were put in place to allow testers to use numerous options within internationally recognised laboratory protocols. Evaluation tiers were developed based on the Water Boiling Test (WBT). It is a protocol with several tests to be performed (WBA, 2016; Winrock International, 2017).

A Technical Committee (TC) 285 then arose from the unanimous affirmation and rapid adoption and utilisation of the IWA. This led to the collaboration of numerous international experts within the sector for clean cooking to develop international voluntary standards for fuels and technologies intended to enhance the replacement of traditional cooking methods with clean(er) technologies (Winrock International, 2017). Consequently, creating international standards served as guidance to all countries that want to establish their independent national standards. When a country has its national standard, the international standard can facilitate international collaboration and trade (Rajabu et al., 2014; Winrock International, 2017). Currently, there are several existing standards such as the Adapted Water Boiling Test (AWBT) (AWBT, 2.0, 20010), Emissions and Performance Test Protocol (EPTP) (EPTP, 2009), Indian Standard on Solid Biomass Chulha-Specification - Test For Thermal Efficiency (Solid Biomass Chulha-Specification, 1991), and Indonesian Clean Stove Initiative Water Boiling Test (Indonesian Clean Stove Initiative Water Boiling Test, 2014).

2.5.2 Significance of standard testing protocols

Development of standards and performance testing of cookstoves and fuels plays a significant role in helping donors, investors, implementers, and consumers make an informed decision regarding the products' performance, quality, and safety. Furthermore, manufactures tend to identify errors and ways to better their new products compared to old products. When making modifications without testing the final product, the upgraded stoves are likely to have lower efficiencies and produce higher emissions than the traditional stoves intended to be replaced, therefore escalating the impacts. This will contrast with one of the critical objectives of cookstove standards: to ensure that programs achieve their intended goal (Gallagher et al., 2016).

International voluntary performance standards are currently being developed, enhancing policymaker and consumer abilities to distinguish between different cooking technology options and increasing manufacturers' motives to produce more efficient and cleaner-burning products (Gallagher et al., 2016). In addition, the performance standards have several benefits (Winrock International, 2017): (a) increase interest and confidence of consumers about the product quality; (b) give donors and investors an assurance that their funds are used to produce products that will achieve the intended goals; (c) drives innovation and ensures adequate competition in the market; (d) provides states with an international framework that may be used to develop national standards for labelling, collaboration and trading.

2.5.3 Standards in South Africa

South Africa's standard test protocols are governed by the South African Bureau of Standards (SABS). SABS has been operating for more than 60 years in developing national and internationalising standards. There are about 7 400 existing performance standards, with ~250 new performance standards being set annually (SABS, 2017). The SABS standards entail several subjects for all products according to their purpose: standardisation of various sizes or grades of products, or a product's technical specification, or services that are user friendly and enable interoperability. Furthermore, these standards substantiate legislative mandates and government policies by referencing and linking the related standards.

2.5.4 SABS standard test protocol development processes

National based process

Performance standards are either developed through a local approved process or by adopting International Standards Organisation (ISO) standards. The SABS standards development framework is shown in Figure 2-11. The development of a standard consists of the Technical

Committee (TC), Working Group (WG), Standard Approval Committee (SAC), and experts. The TC initiate or develop a new standard. It also reviews and amends existing national standards. These standards are developed through a consensus systematic process that involves a well-balanced TC. After the development of the standard, there is a 60-day period to allow for public comment. When the comments are addressed, the SAC reviews the standard to approve. When the SAC approves, the standard is published and named South African National Standard (SANS) with a specific numbering, for example, SANS 135:19xx. It is then for sale and available from the SABS web store (SABS, 2017).

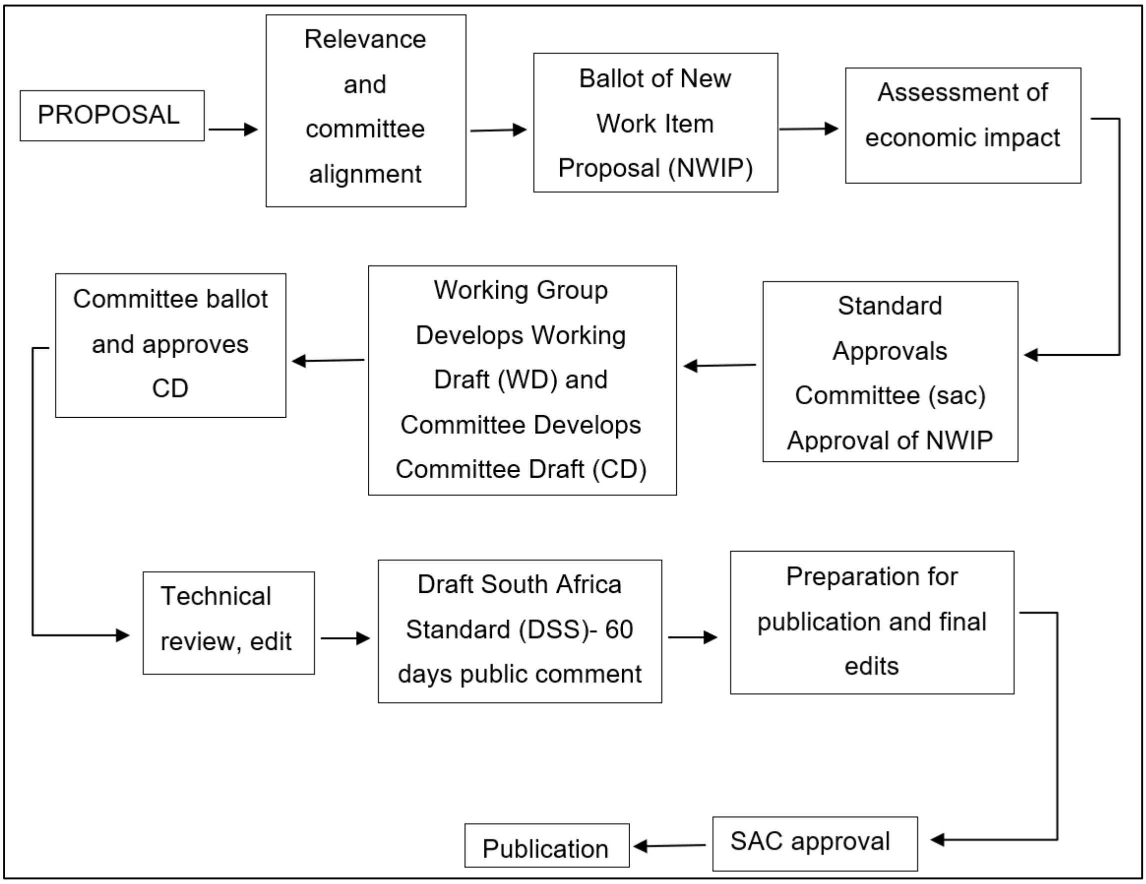


Figure 2-11. The SABS process for standards development (SABS, 2017).

Adoption based process

The adoption process is followed when a performance standard has to be developed with guidance from the international standard (SABS, 2017). The adopted performance standard contains foreign or international performance standard content acknowledged by relevant South African experts. When an international performance standard is adopted, it is given a dual number, for example, SANS 135:19xx ISO 135:19xx (SABS, 2017). The process is outlined in Figure 2-12.

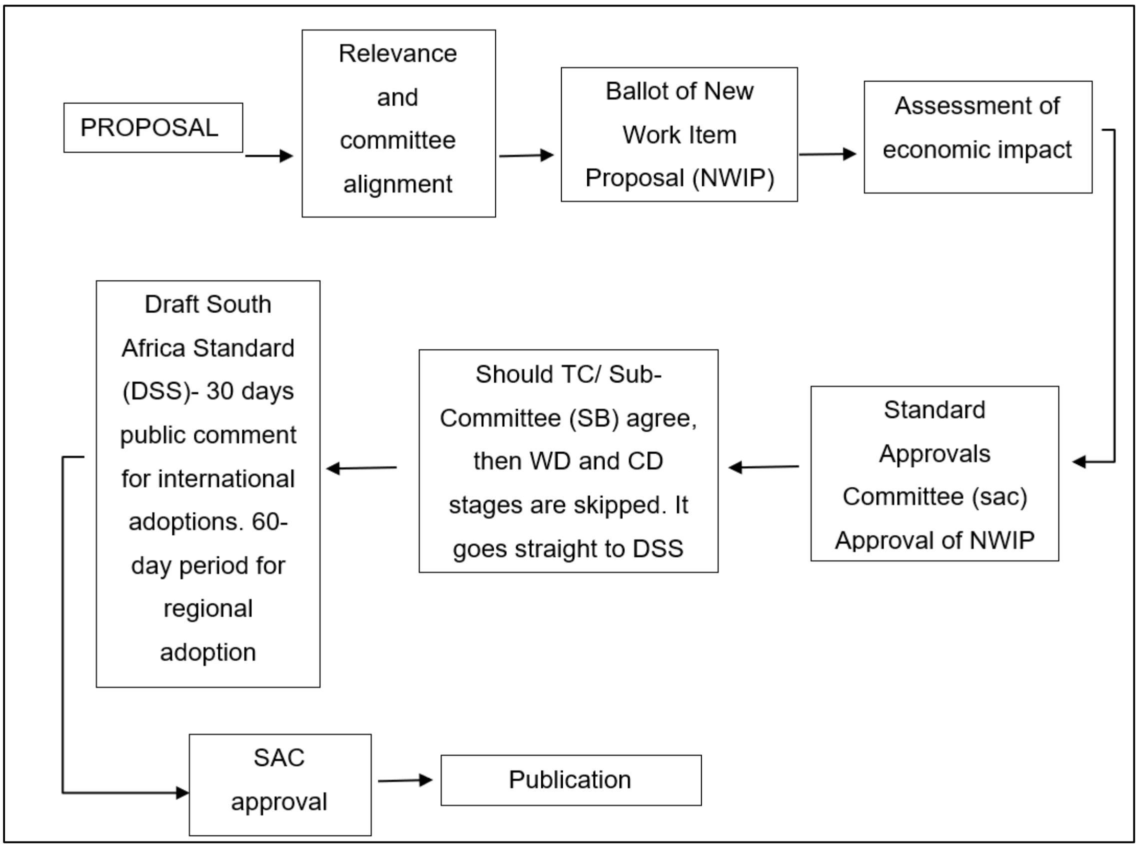


Figure 2-12. The adoption process of developing a standard test protocol by SABS (SABS, 2017).

2.6 Protocols for testing cookstoves performance

2.6.1 Laboratory-based test protocols

There are several well-known testing protocols used to test the efficiency of cooking technologies. The Water Boiling Test (WBT) and Heterogeneous Testing Protocol (HTP) are two widely used protocols worldwide.

The **WBT** was developed by VITA and later modified by the University of California-Berkeley, collaborating with Arts Research Centre (ARC) and several other stove researchers (Jetter & Kariher, 2009). It is the most common or well-known protocol (Makonese, 2018). The WBT is a laboratory-based replication of a household cooking process. It is used to determine the energy efficiency and the amount of the total amount of emissions produced through the combustion of the fuel used. The WBT can be conducted with the usage of simple instruments and equipment. However, the test becomes a little complex when one needs to monitor emissions. Key benefits of the WBT are that: it provides the initial primary evaluation of stove performance within controlled settings; assists in selection of eligible products for intended field testing; compares the efficiency of various cooking technology designs; assess the improvements or modifications of every cooking technology throughout its development phase; it ensures that all cooking technologies meet the performance requirements (Zhang et al., 2014). Since the tests are performed within controlled settings, the acquired results may differ from measurements done in the field when cooking food. Therefore, it is still necessary to conduct field trials to obtain measurements representing the desired effects (Zhang et al., 2014).

The Sustainable Energy Technology and Research (SeTAR) Centre at the University of Johannesburg, South Africa, formulated the **HTP.** The primary aim of the HTP is to evaluate the performance of stoves at different power settings (low, medium, and high) with an attempt of simulating the behaviour (Makonese, 2018; Makonese et al., 2010). The test involves the use of different pot sizes ranging between 2 and 5 Litres. Testing of the stoves at various power settings and using different pot sizes was initiated because stove emissions may vary with the power setting. In addition, the pot size influences the flow patterns of the flame and heated gas. The protocol requires the stove to be operated according to instructions provided by the manufacturer. The HTP test protocol should be to be conducted in a replicable, controlled laboratory setting. Combinations of the stove and fuel are needed to realistically represent real-world behaviour (Makonese et al., 2010; Masekameni et al., 2015; Makonese et al., 2020). Each test condition or combination for the definitive tests must be done a minimum of three times.

2.7 Radiative and conductive heat losses in determining cooking power

The performance behaviour of stoves is governed by thermodynamics within the physics discipline. Further explanation is derived from stove geometry and heat transfer (Zube, 2010; Motghare et al., 2015). The change in temperature of an object when it cools down depicts information about the thermodynamics of a material. The information involves the thermal properties and heat loss mechanism of the object's construction materials. According to principles of thermodynamics, heat transfer occurs through the processes of conduction, convection, radiation and evaporation (Rohsenow et al., 1998; Moran et al., 2010; OpensStax, 2015). Figure 2-13 illustrates these fundamental principles. **Convection** is defined as the transfer of heat from one point to another through fluid movement. **Evaporation** is when heat is lost from a system due to mass loss by converting liquids to the gas phase. This study focuses mainly on the two processes: conduction and radiation (Moran et al., 2010; OpensStax, 2015). They are discussed in the following subsections.

Conduction occurs when molecular collisions transfer heat from one object with a higher temperature to an object with a lower temperature (Rohsenow et al., 1998) (Figure 2-14). Objects at different temperatures have molecules with different kinetic energies. Collison of the molecules from the objects results in a transfer of energy from the object with a higher temperature to the object with a lower temperature (Figure 2-14) (Rohsenow et al., 1998). For flame heating, hot gases flow over the surface of an object's surface. Physical contact with the hot gases results in energy transfer through combined convection and conduction processes. In water heating, the heated metal of the pot conducts energy to the water. Convection distributes the heat throughout the contents (Zube, 2010).

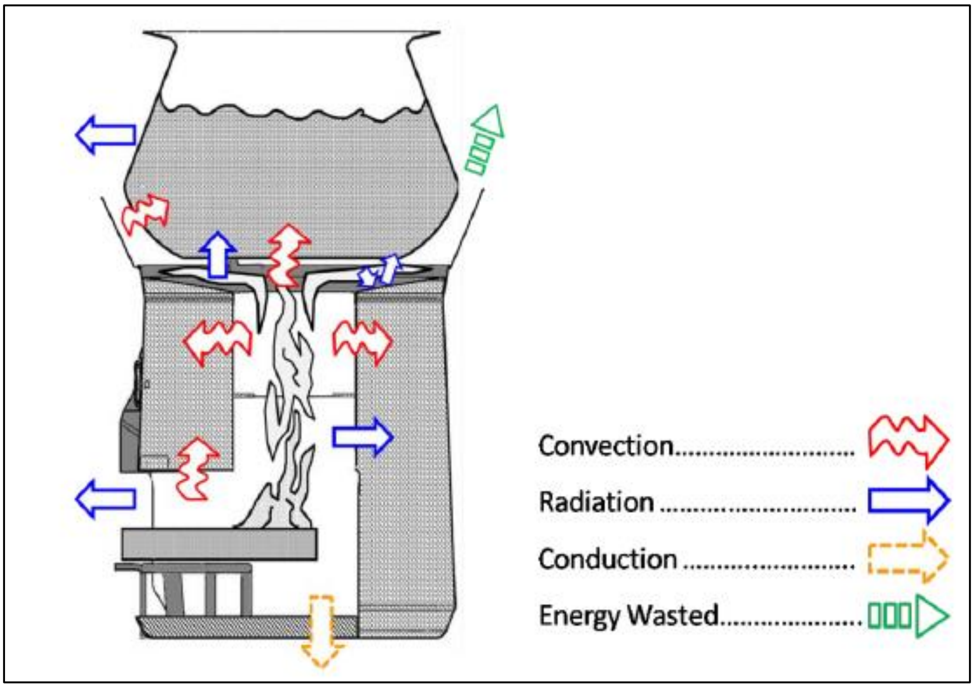


Figure 2-13. Illustration of the thermodynamic principles (Zube, 2010).

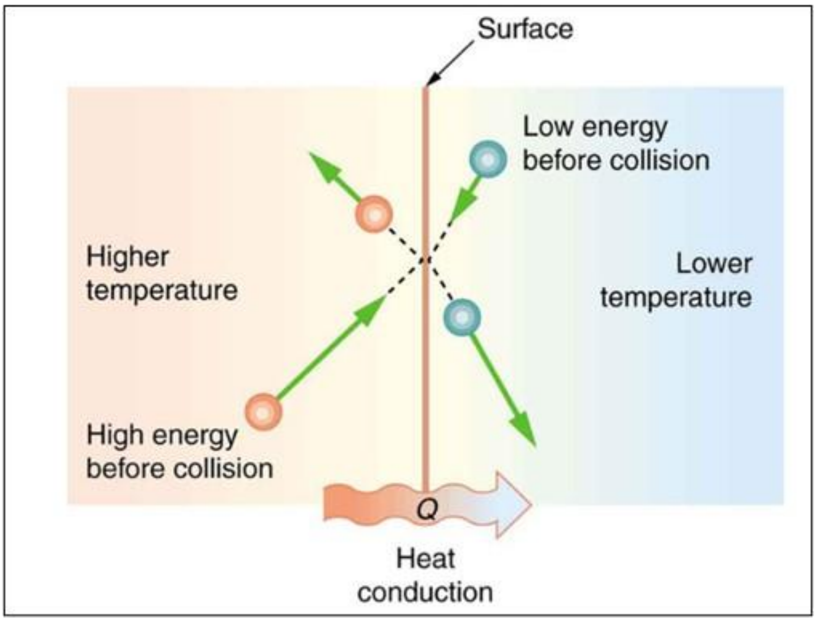


Figure 2-14. Schematic illustration of the microscopic processes of conduction across a solid surface separating two fluids (OpenStax, 2015).

Radiation is the release of energy by an object. The kinetic energy and potential energy of oscillating charged particles are converted to electromagnetic waves (Figure 2-15) (Rohsenow et al., 1998). Therefore, every object or system with a temperature higher than 0ºK will radiate energy to the surrounding (Rohsenow et al., 1998). All matter is capable of absorbing and emitting electromagnetic radiation. The radiation energy is dependent on the wavelength (colour) of the object. Black objects radiate the most while white radiates the least (OpenStax, 2015).

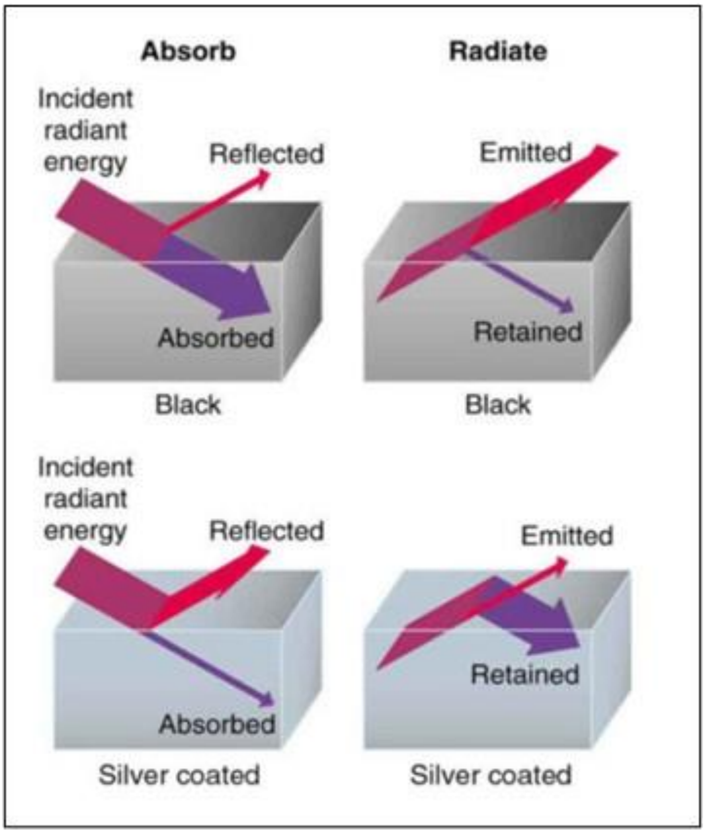


Figure 2-15. A comparison on the radiation rate of black coated objects vs white or shiny (silver) coated objects) (OpenStax, 2015).

The rate of energy released through radiation can be determined using the Stefan-Boltzmann law of radiation (Zube, 2010; OpenStax, 2015):

$$\frac{Q}{t} = \sigma e A T^4$$ **[kJ]**

Equation 2.1

"where σ=5.67×10^{-8} *is the Stefan-Boltzmann constant, A is the object's surface area, and T is its absolute temperature in Kelvin. The symbol* e *stands for the object's emissivity and is a measure of how well it radiates. An ideal jet-black (or blackbody) radiator has* e=1*, whereas a perfect reflector has* e=0*. Real objects fall between these two values. For example, tungsten light bulb filaments have an* e *of about 0.5, and carbon black (a material used in printer toner) has the (greatest known) emissivity of about 0.99"* (OpenStax, 2015).

The energy radiation rate of an object is proportional to the fourth power of the absolute temperature. Thus, the net radiation energy emitted is a function of the difference between the object's temperature and surroundings (OpenStax, 2015).

2.8 Testing cookstove safety

There has been a notable increase in demand for clean fuel cookstoves and safer cooking technologies across developing countries. This matter has shown the need and importance for developing cookstove testing protocols, certification procedures, capacity building across research and technical institutions (Rajabu et al., 2014; Still et al., 2015). The International Workshop Agreement (IWA) has developed a tier system that is widely used when testing all aspects of a stove (Table 2.6). When conducting tests, the IWA designates cookstoves into tier or criteria system which has four categories: thermal efficiency, total emissions, indoor emissions, and safety. Each category has various metrics that are determined explicitly during tests. The appliances are rated for all categories of indicators, respectively. The tiers range from good (Tier 4) to poor (Tier 0) for thermal efficiency and emissions (Johnson et al., 2005; Gallagher et al., 2016).

Table 2.6. Selection tiers and ranking of biomass stove performance (ISO, 2012; Masekameni, 2015).

Tier	Thermal efficiency (%)	CO emission factor (g/MJ)	$PM_{2.5}$ emission factor (mg/MJ)	Firepower (W)
Tier 0	< 15	>16	> 979	< 500
Tier 1	≥ 15	≤16	≤ 979	≥ 500
Tier 2	≥ 25	≤11	≤ 386	≥ 750
Tier 3	≥ 35	≤9	≤ 168	≥ 1 000
Tier 4	≥ 45	≤8	≤ 41	≥ 1 500

Regarding safety protocols for cookstoves, there have been few publications. Biomass Stove Safety Protocol (BSSP) is the only known publication that focuses mainly on safety measures (Gallagher et al., 2016). Tests performed through the BSSP were formulated to identify unsafe measures and features that may put the user at risk of scalds, burns, abrasions, lacerations, and house fires. With the BSSP, the materials and the stove operation are tested, which involves evaluation of sharp points/edges, stability (tipping angle), containment, removal of embers, protruding features causing obstruction, surface temperature, the transmission of heat to the surrounding, temperature of stove parts made for or prone to touching, dispersion of flames surrounding the pot, and flames coming from fuel tank (Johnson et al., 2005). These measures and features apply according to the type of stove that is being tested. This study is focused on features and measures that may apply to liquid fuel stoves, discussed below. Modifications were made on the procedures to become suitable for the liquid stoves

Sharp points/edges and protruding features causing obstruction

Sharp points/ edges are defined as exterior stove features that may catch or tear clothing or cut the user's hands when contacted. Testing for sharp points/edges is done using a piece of cloth. The cloth is rubbed over the stove's surface. Sharp points are identified when the fabric becomes torn or snagged. The rating for this test is either best (Tier 4) or poor (Tier 0) (Johnson et al., 2005).

Protruding features include handles or any part that extends outwards, especially at the top or near the cooking surface (Johnson et al., 2005). These features increase the risks of bumping when a pot is placed or removed, possibly resulting in spillage of hot contents onto the cook or any persons in the vicinity. The extent of the protrusion is done by determining the difference in cooking surface height to the height of any out-sticking features. A difference of less than 1 cm is rated best, 1 to 2.5 cm is rated good, 2.5 to 4 cm is rated fair, while more than 4 cm is considered poor (Johnson et al., 2005).

Cookstove stability

Cookstove stability may be defined as a stove's ability to sustain an upright position when tilted at a certain angle (Johnson et al., 2005; Johnson et al., 2015). The cookstoves need to maintain an upright position to avoid burnings and scalds caused by burning or spillage of boiling contents due to the easy tipping of a stove. The tests are done according to the number of supporting legs fitted on the stove. The stove should be filled with fuel to its maximum capacity. If the stove is circular, four tests are performed with equal distance between the four different tilting directions. The standard distance used is about a one-quarter turn from each point. When tilting a stove with supporting legs, the tilting direction is outwards and at an angle of 90° (perpendicular) to adjacent supporting legs. The tilting angles are dependent on the type of cooking stove and the protocol being used (Johnson et al., 2005; Johnson et al., 2015; Makonese et al., 2020).

The temperature of the operation surface and stove handles and prone to touching

It is essential to consider **the temperature of the surface** at which the stove is operated to allow easy usage of the stove and avoid the risk of burns. It is common for stoves to be fitted with **handles** to make it easy for users to move the stove around and be equipped with a **lever** as a **power regulator**. Depending on the stove design, there may be parts **prone to be touched during operation**. These features should not reach high temperatures (i.e. not exceed 40°C) to avoid risks of scalds and first or second-degree burns (Johnson et al., 2005; Makonese et al., 2020).

"Temperature measurements are taken at various points on the external surface of the cookstove. Horizontal cooking surfaces, such as burners or griddles, are excluded from the analysis because they need to be hot to cook food. Also, the chimney temperature is measured until Test 8. The

*first step in this test consists of using chalk to draw a horizontal and vertical grid composed of approximately 8 x 8 cm squares along the external surface of the cookstove. However, the cookstove configuration determines what method is easiest for creating a grid for easy location reference. Differentiating the lines with numbers or letters tends to be the most simple. Extra thick chalk lines marked at heights of 0.9 m and 1.5 m on the cookstove (if the cookstove is that tall) provide indicators of what areas are below and above the child line yet below the maximum testing height. In this test the cookstove is loaded with fuel and ignited. More fuel is added when necessary until the cookstove reaches its normal operating state (at least 30 minutes runtime). For solar stoves the unit should be in the sun for a similar duration of half an hour. First, the temperature of the ambient air is measured. Next, surface temperature measurements are taken using an infra-red thermocouple while recording the following information: data point reference, temperature, above or below the 0.9 m child-line, metallic or non-metallic material. Maximum surface temperatures are determined above and below the child-line and on both metallic and non-metallic materials, where applicable. The most deficient rating based on material, temperature, and location is used to determine the likelihood for a person to avoid burns when touching a cookstove. Differences between the ambient air and cookstove temperatures correspond to the safety ratings given in Table 7. For example, if the measured air temperature is 31.5 °C, then a Good rating for metallic components below the child-line would be 69.5 < T < 75.5" (*Johnson et al., 2005:57)

Transmission of heat to the surrounding

Transmission of heat to the surroundings may lead to the ignition or explosion of heat-sensitive materials within the vicinity. To avoid such hazards and incidents, cookstoves should not transmit excessive amounts of heat to the surroundings (Johnson et al., 2005). The ambient air temperature needs to be taken into account when determining heat transferred to the surrounding. When doing the test, *"…the cookstove is placed in its normal operating location and orientation (if the test is not performed in the field with the usual location of the stove, find a suitable location for a supplement). Chalk is used to sketch a silhouette of the cookstove on the ground when looking from above and a silhouette on the wall when looking towards the wall. The stove is then pulled away, and approximately 8 x 8 cm squares are chalked inside the silhouettes on the floor and wall, with additional squares chalked two high (16 cm) above the silhouette on the wall. Intersections of lines are again given a form of reference chosen by the user. The cookstove is returned to its normal operating location and orientation, and the fuel ignited. Fuel should be added until the cookstove reaches a stable and regular working state. Then, the temperature is measured using a hand-held thermocouple at each intersection of lines, while recording the following: data point, temperature, floor or wall." (*Johnson, 2005:58*)*

Flames coming from the fuel tank and dispersion of flames surrounding the pot

Liquid fuelled stoves may be prone to **flames coming from the fuel tank** due to pressure or leakage. These flames may lead to a stove exploding or ignition of clothes or any readily flammable nearby material, resulting in a conflagration. The user or any person nearby may be at risk of getting burned from these flames (Johnson et al., 2005). In addition, poorly designed stoves tend to have **flames dispersing around a pot**. The dispersion of flames increases the risk of burning clothes or the user during operation. Therefore, a stove should be designed to conceal flames coming from the burner (Johnson et al., 2005). Testing these parameters can be done by filling the stove to its maximum capacity per the manufacturer's instruction. The stove is then ignited to observe any flames coming from the fuel tank. The tests involve observation of the extinguishing mechanism of the stove. The mechanism should be able to extinguish the stove within a given time frame. The most appropriate time frame should be approximately 30 seconds (Johnson et al., 2005).

2.9 Determining thermal efficiency

Thermal efficiency is the primary metric that was adopted from the WBT. Testing protocols are developed to guide stove designers to understand how energy is generated from the fuel and transferred to the pot (Bailis et al., 2007; Johnson et al., 2010; Makonese, 2011). Efficiency can be defined as the amount of energy transferred and entered the pot as per consumed fuel (Ballard-Tremeer & Jawurek, 1996). The energy transferred to heat the water is the totality of the sensible heat, latent heat, convection, radiation, and conduction (Prinsloo, 2018). Therefore, the thermal efficiency of a device can be defined as "***the ratio of energy retained by water (in the pot) to the energy released by the fuel combustion."*** (Makonese, 2011: xv). Fuel consumption can be defined as fuel burned per litre of water boiled or kg of cooked food averaged over a cooking sequence, such as bringing to the boil 5 L or 2 L of water (Makonese, 2011: xv). The thermal efficiency of cookstoves depends on the energy generated by the fuel and transferred to the pot (Labhsetwar et al., 2015). The performance of a stove is determined by its Specific Consumption (SC) or by its Percent Heat Utilised (PHU) (Baldwin, 1987; Makonese, 2011). The SC can be defined as the total amount of fuel used to replicate a cooking process divided by the amount of water boiled (Makonese, 2011). PHU of a cookstove is defined as '***the percentage of heat released by the fire that is absorbed by the water in the pot***' (Rani et al., 1992:922). For example, PHU for biomass cookstoves is determined using the equation:

$$PHU = \frac{C_p M(\Delta T) + hfg\overline{M}}{M_f\left(LHV_f\right) - M_c(LHV_c)}$$

Equation 2.2

where C_p is the specific thermal capacity of water. (kJ/kg/ C), M is the initial water mass in the pot (g), ΔT is the change in water temperature in the pot (min), hfg is the vaporisation enthalpy (kJ/kg), $\bar{M}$ evaporated water mass (g), M_f is the mass of used fuel (g), LHV_f is the lower heating value of the fuel (kJ/kg), M_c is the mass of residual charcoal (g), and LHV_c is the lower heating value of the residual charcoal (kJ/kg) (Rani et al., 1992; Makonese, 2011).

The thermal efficiency (H_c) of a fuel or stove combination may be calculated using the following formula, taken from the University of California Berkley WBT 4.2.3:

$$H_c = \frac{[4.186^{*}(P_{ci} - P)^{*}\left(T_{cf} - T_{ci}\right)] + 2260(W_{cv})}{f_{cd} * (LHV)}$$

Equation 2.3

where 4.186 is the specific water heat (kJ/kg/ C), T_{cf} is final water temperature(C), T_{ci} is initial water temperature (C), P_{ci} is initial water mass (g), Pj mass of the pot when empty (g), 2260 is the specific enthalpy of vaporisation (kJ/kg), W_{cv} is the vaporised water (g), f_{cd} is the equivalent consumed dry wood (g), and LHV is the lower heating value (kJ/kg) (Berrueta et al., 2008; Makonese, 2011).

2.10 Determining emission efficiency

2.10.1 Emission monitoring methodologies

Emission performance is evaluated through the hood or chamber method concurrently with the WBT, commonly referred to as a baseline protocol (Makonese, 2011).

The chamber method was developed to minimise complexities and costs and evade specific flaws that were presumed to be inherent in the hood method. The hood method requires ductwork and efficient airflow circulations, whereas the chamber method does not require any. The chamber method is a versatile method that can be done within a remote village dwelling with restricted airflow circulations due to a lack of ventilation. However, there are limitations when making use of the chamber method. Due to the stratification of smoke inside the dwelling, a constant mix of the air is required to make assumptions that there is a steady-state condition because the exchange rate substantially affects the observed outcome (Ahuja et al., 1987; Makonese, 2011).

The hood method measures pollutants emitted by unvented cookstoves (Figure 2-16). It is also referred to as a direct measuring system. This method was designed to measure flue gases and total suspended particulates (Makonese et al., 2015). The method involves a hood placed above a stove and the emissions drawn upward due to thermal draught. Drawing of the emissions can be achieved with or without producing an external draught using a ventilator (Ahuja et al., 1987; Makonese, 2011). A duct is used when drawing the emissions. The chimney is connected to an instrument that measures the pollutant concentration and the flow rate. A steady, constant flue rate is required when monitoring the flue gases throughout the experiment (Ahuja et al., 1987; Makonese, 2011). According to Ballard-Tremeer and Jawurek (1996), the hood method has fewer confounding factors that might limit the emission measurements' precision and accuracy. This method has proven to be efficient. It has been used to assess and design improved cooking technologies by one of the well-known research centres, Aprovecho Research Centre, Oregon, USA.

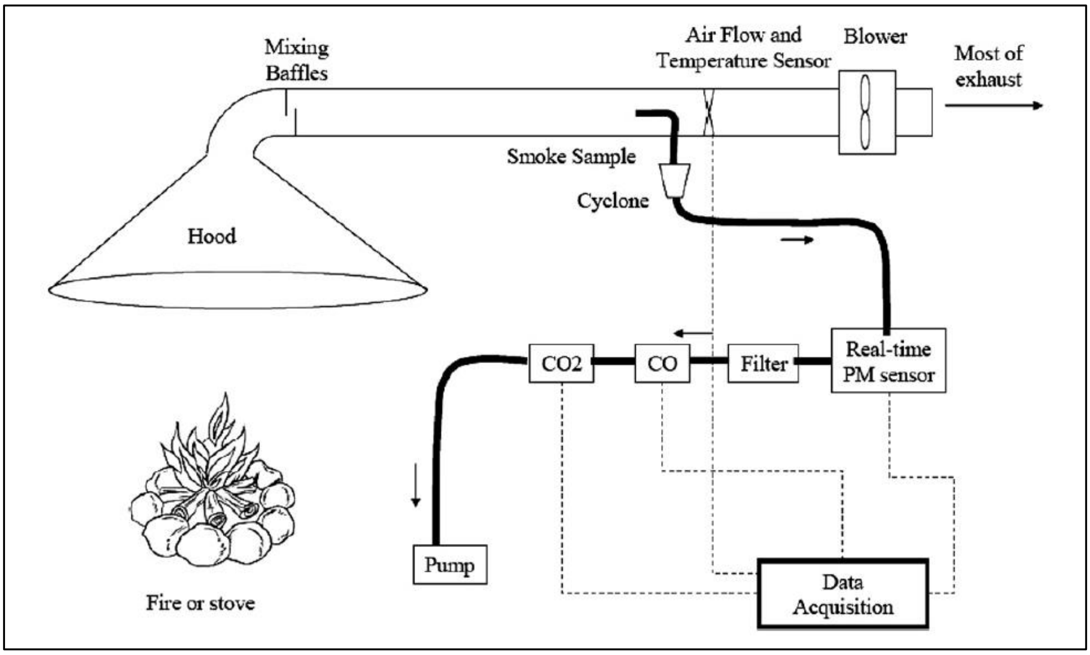


Figure 2-16. Schematic diagram of the hood method (MacCarty et al., 2010).

There are several **limitations** noted with the hood method (Makonese et al., 2011). First, the airflow rate must be determined to account for the dilution by entrained ambient air into the captured air stream. Determining the airflow rate is an essential condition that increases the cost and complexity of the method. Second, the mechanically drawn airflow ability to alter the stove combustion characteristics may also hinder the final results. Third, the hood may impose physical interference when operating the stoves. Finally, measurement errors may occur due to not all emissions being captured by the hood. (Ahuja et al., 1987; Makonese, 2011).

2.10.2 Determining emission performance

Pollution sources can be evaluated using various quantification methods and emission factors. The emission factor is the mass of a pollutant emitted per unit mass of the substance burned or per activity. Emission estimates are essential to derive emission control strategies, emission inventories and the appropriateness regulations (Ahuja et al., 1987; Ballard-Tremeer & Jawurek, 1996; Makonese, 2011). In the concept of analysing stove performance, the term *emission factor* represents a normalised gas concentration, normalised to compensate for variable dilution by bypass air. It is the mass of a pollutant emitted per unit mass of the fuel burned. Emission factors of activities (task-based) are referred to as emission rates. (Ahuja et al., 1987; Makonese, 2011). The best way of making emission comparisons of different stoves is by using the emission factor per given energy amount instead of per cooking activity as used traditionally is the best way to make emission comparisons of various stoves. The correlation amongst task-based emission rates and emission factors in domestic stoves may be mathematically described where emissions per kg of fuel consumed to emission per MJ can be converted by using the equation (Ahuja et al., 1987; Ballard-Tremeer & Jawurek, 1996; Makonese, 2011):

$$E_e = \frac{E_m}{H.\eta} \qquad \text{[MJ]}$$

Equation 2.4

E_e- task-based emission; *E_m*- mass-based emission; H- fuel energy (MJ/kg); and H- thermal efficiency (%). Emission mass per task related to direct human exposure is determined using the equation:

$$M_E = \left[\int_{t=0}^{T} C_M v_{flue}\, dt\right] \qquad \text{[g]}$$

Equation 2.5

where M_E is the pollutant mass (g), T is the duration of the test (s), C_M is the concentration of the pollutant (g/m^3) at a given time t, and v_{flue} is the extraction rate of the flue (m^3/s) (Ballard-Tremeer & Jawurek, 1996; Hildemann et al. 1991; Zhang et al., 2000; Makonese, 2011).

When using the Water Boiling Test (WBT), emission factors are calculated per task performed. The problem of estimating carbon balance may occur due to an unknown realistic precision of maximum CO_2 emission from a fuel. This is due to the reaction of carbon with oxygen forming CO and CO_2 during combustion. (Ahuja et al., 1987; Makonese, 2011; Roden et al., 2006).

3 Methods

3.1 Developing a standard testing protocol for methanol cookstoves

Drafting of the standard testing protocol was incorporated during the development of the SABS standard for methanol appliances for cooking and illuminating. Figure 3-1 shows the SABS workflow process, which was followed to develop the standard for methanol stoves. The development of a standard for methanol stoves involved the SABS/TC 1054 Technical Committee (TC), which deals with domestic combustion stoves. A Working Group (WG) was set up under TC 1045, comprising domestic fuel experts, academics and representatives from methanol stove manufacturing companies. The standard test protocol draft was based on the existing standards for ethanol gel stoves and paraffin stoves. These normative reference standards were used as guidance for headings, formatting, and contents. The WG agreed to use these existing standard test protocols as templates and make necessary methanol-fuelled appliances. The procedures were made based on experiments performed as part of this thesis to assess the draft standard methods. The final detailed standard testing protocol is yet to be finalised by the SABS Technical Committee (March 2021).

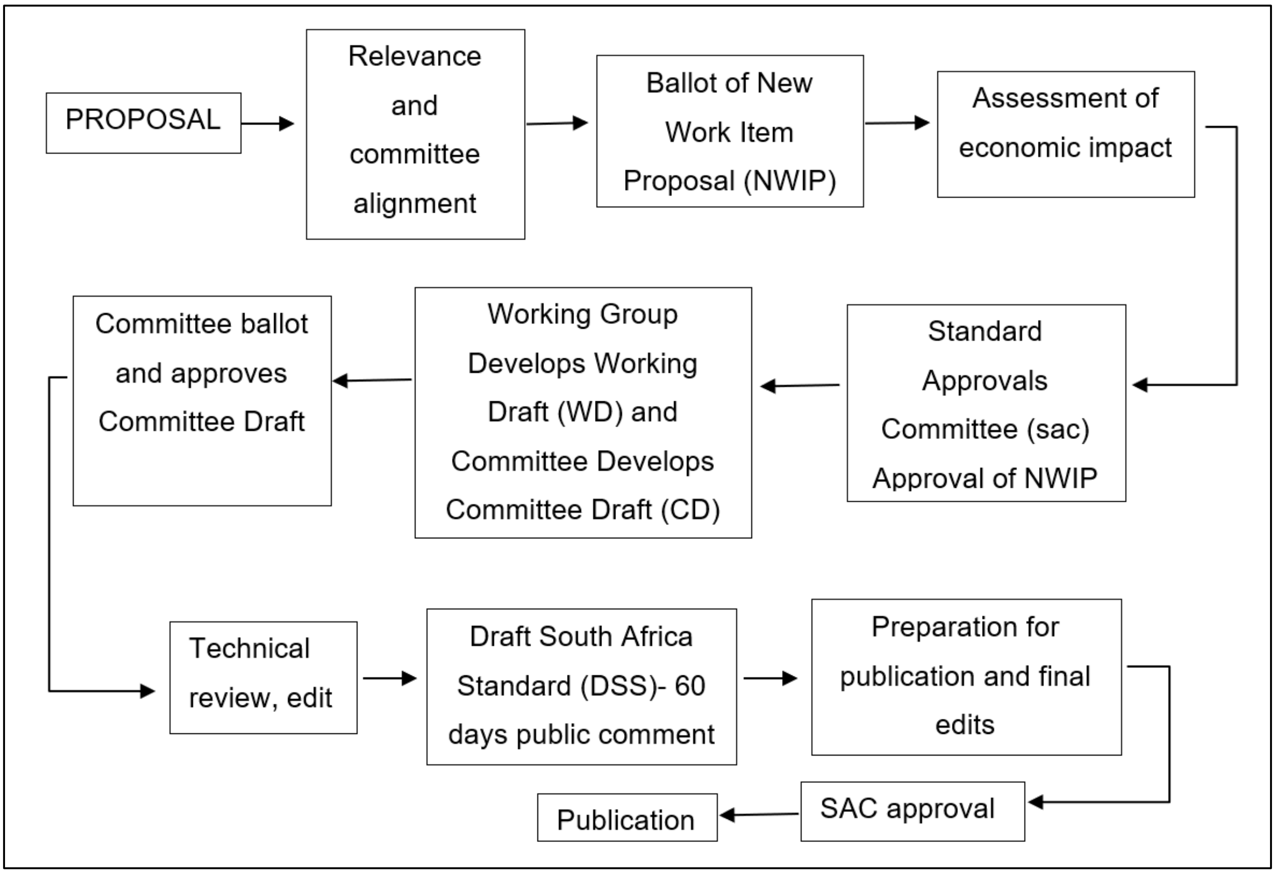


Figure 3-1. The process of developing a standard testing protocol by SABS (SABS, 2017).

3.2 Evaluating the safety of three differently designed methanol cookstoves

3.2.1 Fire extinguishing test and evaporation loss

An easy and quick way to extinguish a stove is a vital operational requirement to minimise fire accidents. Accordingly, the stoves' **flame extinguishing** processes were assessed according to the draft standard test method derived in Section 3.1. The stove was ignited, and the flame adjusted to the high power setting. A pot filled with ~3 L of water was placed on the stove and left to heat for 30 min and then removed. The flame regulator was adjusted to the low power setting for about 30 s, and the shut-off cap is inserted. After ~30 s after the flame regulator was adjusted to the high power setting and the shut-off cap removed. It was recorded whether the flame remains extinguished. Categorical criteria were used to certify whether the stove complies with the regulatory measures in the draft standard.

Immediately after the stove has been extinguished, the mass is recorded as $StoveMass_{Initial}$. After ~60 minutes, the mass is recorded as $StoveMass_{Final}$. **Evaporation loss** is determined mathematically using the following equation:

$$Evaporation\ loss = \frac{StoveMass_{intial} - StoveMass_{fnal}}{\Delta t/_{60}} \quad \text{[g/h]}$$

Equation 3.1

where $StoveMass_{Initial}$ is the mass recorded immediately after the flame is extinguished; $StoveMass_{Final}$ is the final mass of the stove plus fuel recorded after ~60 min; Δt [min] is the elapsed time during cooling or storage; 60 [min/h] converts the elapsed time from minutes to hours.

3.2.2 The surface temperature of the touchable parts during operation

The power setting regulator and handles are considered touchable parts of an appliance during operation. The draft standard specifies that the **surface temperature of touchable parts** should not exceed 42°C, to minimise contact burn risks and injuries (Kimemia & van Niekerk, 2017). The stoves used in this study have no handles; a thermocouple was attached to the power setting lever to determine compliance with this criterion.

3.2.3 Safe handling of methanol fuel

Safe handling of methanol fuel involves avoiding **fuel spillage**. To determine the possible spillage of fuel if the stove is knocked over, the following procedure was followed: refuelling the appliance to maximum capacity following manufacturer's instructions; determining the mass of the appliance and fuel combined; positioning the control lever to the high power setting; **rotating the appliance through approximately 90°** over the drip tray, placing it on the tray surface and allowing it to come to rest on its side for 60 seconds; after that, the appliance is returned to its upright position and wiped off any fuel remaining on the outside surfaces; it is then allowed to stand for 5 minutes to enable the evaporation of any remaining external fuel droplets; lastly the combined mass of the appliance and the remaining fuel is determined. **The same procedure is performed for the 180° inversion** for the spillage or leak test. A criterion with different categories was used to assess the adherence of the stoves to the limits set in the draft standard.

3.3 Effect of radiative and conductive losses in determining cooking power

Evaluation of radiative and conductive losses is performed for two sequences, namely heating at high and low power settings. The test sequence involves measuring the temperatures while heating to the specified maximum temperature at the selected power setting and then extinguishing the flame and allowing the pot and contents to cool to laboratory temperature. The apparatus comprised either the large shiny aluminium pot or the matt black stainless steel pot filled with ~3 L of water; a thermocouple immersed in the water ~50 mm above the bottom and one-third of the pot diameter from the edge. The pot is placed on the stove, both being on a mass balance. The burner is ignited and adjusted to the high or low power setting as required. When the water reaches ~80°C, the flame is extinguished, and the water left to cool with the pot remaining on the stove. The 80°C endpoint of temperature rise is chosen per the HTP standard operating procedures to avoid uncertainties due to evaporation losses (Prinsloo, 2018). Temperatures and mass are logged at 10-s intervals for the duration, starting from when the burner is ignited until the pot cools down to the laboratory temperature.

3.3.1 Data processing and analysis

The data obtained from the tests are stored in spreadsheet format and used to determine the heating and cooling curves. Heating and cooling curves were derived separately and combined to determine the total heat transferred into the water after considering all possible radiation and convection losses. Considering that the lab conditions were kept constant, there was less noise on the data captured. The heating curve was used to calculate the heat generated by the stove, while the cooling was used to determine the heat loss by radiation.

3.4 Determining thermal efficiency

3.4.1 Experiment apparatus

Methanol cookstoves

Three commercially available methanol stoves from three manufacturers were evaluated for thermal and emissions performance (Figure 3-2). The stoves are made of either galvanised or stainless steel and are fitted with triangular pot support. They have a cylindrical fuel reservoir and a burner, also known as a combustion chamber, with holes around it for airflow. The stoves are fitted with three feet to provide stability. The stoves have a power control regulator, a lever that adjusts the power by regulating airflow into the burner (Makonese, 2011; Masekameni et al., 2015). Concerning safety measures, the stoves are designed so that refuelling is done through the burner, preventing refuelling while the stove is operating. Each stove is provided with its proprietary methanol fuel packaging (Figure 3-2). The stove models are designated as STV01, STV02 and STV03.

Figure 3-2. Three commercially available methanol cookstoves from different manufactures.

Panda paraffin wick stove

A Panda paraffin wick type stove was used in this study as a reference. The stove has a cylindrical shape (Figure 3-3). It is fitted with one wick going outward from the combustion pot for adjusting the power setting. The stove has three pot stand-offs fitted at the top to enhance pot stability. In addition, it has a self-extinguishing mechanism such that it is self-extinguished when knocked off or tilted (Masekameni et al., 2015).

Figure 3-3. Reference paraffin wick stove

Pots

Three shiny aluminium pots of different sizes and three black stainless steel pots of various sizes were used (Figure 3-4). Each lid had a hole drilled at one-third of the diameter from the edge to allow the insertion of a thermocouple or thermometer such that the tip could be located ~50 mm above the bottom of the pot.

Figure 3-4. Aluminium (shiny) pots and stainless-steel (black) pots of different sizes.

Thermocouples and mass balance

The thermocouples had a range of up to 1 000°C and precision of ±0.5°C. The mass balance had a maximum capacity of 35 kg with ±1 g r precision. In addition, the mass balance had an option to connect to a data logger (Figure 3-5).

Electronic CR 1000 data logger and Vaisala

Figure 3-6 shows the Vaisala and the electronic CR 1000 data logger. The Vaisala is an instrument that measures ambient temperature and humidity. An electronic data logger was used to continuously log data from the thermocouple, mass balance, and Vaisala.

Figure 3-5. Mass balance, Avery Weigh Tronix.

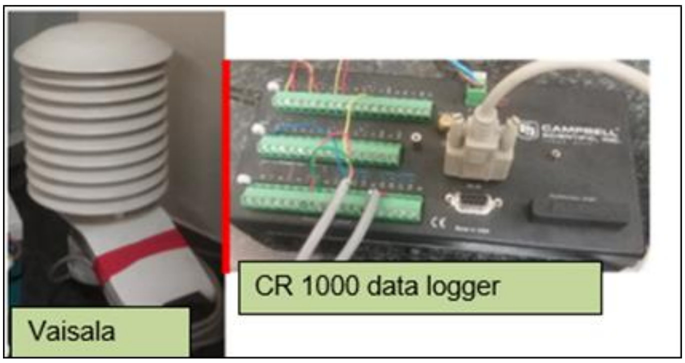


Figure 3-6. Vaisala and the electronic CR 1000 data logger

3.4.2 *Incorporated procedure*

The standard test protocol derived in Section 3.1 was applied to evaluate the thermal performance of the three methanol cookstoves and the reference paraffin stove. Evaluation of thermal performance was done at two different tasks at high and low power settings. The following metrics were determined: thermal power, cooking power, thermal efficiency, turn down ratio (TDR), and specific-time-to-boil. The derived standard test methods involved the following primary steps: pot filled with water two-thirds of its capacity; thermocouple immersed in the water ~50 mm above the bottom of the pot and one-third of the pot diameter from the edge; The pot placed on the stove, both being on a mass balance; heating the water until it reaches ~80°C. The thermocouple was positioned in that manner to avoid direct heating from the bottom of the heat. The water was heated until ~80°C to avoid evaporation losses. After that, the burner is ignited, and the stove is adjusted to a high-power setting or low power. Six pots of different sizes and exterior finishes were used - three shiny aluminium pots and three black stainless steel pots (Figure 3-4). The test of each stove/fuel/pot size/pot-type combination was repeated three times. The three thermocouples were placed one below the pot in the flame zone, one-third of a diameter from the edge and one centred in the pot (Figure 3-7).

Figure 3-7. The orientation of the pot, stove, mass balance and thermocouples.

The CR 1000 electronic data logger was used for logging and storing the data from the thermocouples and the weight scale. The data were logged at 10-s intervals starting when the burner was ignited until the water temperature reaches 80°C. This 80°C is chosen per HTP standard operating procedures to avoid uncertainties due to evaporation losses when the water approaches boiling point (Prinsloo, 2018). When the temperature reached ~80°C, the pot was removed, and the flame extinguished.

3.4.3 Data processing and analysis

The test data were used to determine the thermal performance metrics of the stoves. Equations were used to determine the thermal power, thermal efficiency, cooking power, equivalent time-to-boil and the turn-down ratio for each of the three test sequences. For each metric, the average and standard deviation were determined. The following equations were used.

Thermal power at high power (H) and low power setting (L)

The same equation is used to determine thermal power over high and low power settings.

$$\text{Thermal power} = \frac{\triangle \text{F x LHV}}{\triangle \text{t x 60}}$$ [Watts]

Equation 3.2

where ΔF is the mass of the fuel burned, LHV is the methanol fuel energy density. In the absence of a SANS standard for methanol as a domestic fuel, the default value of pure methanol, 19.780 kJ/kg, is used; which is the value of pure methanol; Δt is the test duration time [min], and the 60 [sec/min] is the factor to convert duration time from minutes to seconds.

$$\triangle \text{F} = \text{StoveMass}_{\text{initial}} - \text{StoveMass}_{\text{final}}$$ [g]

Equation 3.3

where $\text{StoveMass}_{\text{Initial}}$ is the mass of the pot and water before the commencement of the test; $\text{StoveMass}_{\text{Final}}$ is the final mass of the pot and water at the end of the test.

$$\triangle \text{t} = \text{time}_{\text{pot\_off}} - \text{time}_{\text{pot\_on}}$$ [seconds]

Equation 3.4

where $\text{time}_{\text{pot-off}}$ is the time the pot was removed and the stove extinguished; $\text{time}_{\text{pot-on}}$ is when the pot is placed on the stove, and the stove ignited.

Cooking power

The equation below was used to determine cooking power over high and low power settings.

$$Cooking\ power = \frac{WaterMass \text{ x } C_{Pwater} \text{ x } \triangle T}{\triangle t \text{ x } 60}$$ [Watts]

Equation 3.5

$$WaterMass = PotWaterMass_{initial} + PotWaterMassEquivalent$$ [g]

Equation 3.6

$$PotWaterMass_{initial} = PotMass_{full} - PotMass_{empty} \qquad [g]$$

Equation 3.7

where $PotMass_{full}$ is the mass of the pot with the lid on and water content of two-thirds of its capacity at the beginning of the test sequence; Pot $Mass_{Empty}$ is the mass of the empty pot with the lid on.

$$PotMassWaterEquivalent = \frac{\boldsymbol{PotMass_{empty}} \text{ x } \boldsymbol{C_{P\_Al}}}{\boldsymbol{C_{P\_water}}} \qquad [g]$$

Equation 3.8

where $C_{P\text{-}water}$ is the isobaric specific heat of water at 50°C = 4.182 [kJ/kg/°C], Pot $Mass_{Empty}$ is the mass of the empty pot with the lid on, $C_{P\text{-}Al}$ is the specific heat of aluminium = 0.91 kJ/kg/°C; ∆t is the test duration time [min], and 60 [sec/min] is a factor to convert duration time from minutes to seconds.

$$\triangle T = Temperature_{pot_{off}} - Temperature_{pot\_on} \qquad [°C]$$

Equation 3.9

where $Temperature_{Pot\text{-}off}$ is the recorded water temperature at ~80°C inside the pot; $Temperature_{Pot\text{-}on}$ is the water temperature (test room temperature) at the beginning of the test time (water at test room temperature. △t is calculated as in Equation 3.4.

Turn-down ratio

The controllability of the stoves was determined using the following formula:

$$TDR = \frac{cooking\ power\ (high\ power)}{cooking\ power\ (low\ power)}$$

Equation 3.10

where cooking power at high and low power settings are calculated as in Equation 3.5.

Specific time-to-boil

$$Specific\ time\ to\ boil = \frac{\triangle t \text{ x } 80 / \triangle T}{WaterMass / p} \qquad [minutes]$$

Equation 3.11

where △t is calculated as in Equation 3.9; 80°C is considered as a standard temperature rise from a nominal starting point of 20°C to boiling point presumed to be at standard atmospheric pressure = 100°C; $PotWaterMass_{Initial}$ is initial water mass inside the pot two-thirds of the pot capacity) and is determined as in Equation 3.7; PotWaterMassEquivalent is determined as Equation 3.8; ρ is water density = 1.00 kg/L; △T is determined as in Equation 3.9.

Thermal efficiency

$$Thermal\ efficiency = \frac{PotMass_{full} \times Cp_{water} + PotMass_{empty} \times Cp_{al}}{(\Delta F \times LHV)} \times 100 \qquad [\%]$$

Equation 3.12

where $PotMass_{full}$ is the mass of the pot with the lid on and water content of ~⅔[d] of capacity at the beginning of the test sequence; $C_{P\text{-water}}$ is the isobaric specific heat of water at 50°C = 4.182 [kJ/kg/°C)]; Pot $Mass_{Empty}$ is the mass of the empty pot with the lid on; $C_{P\text{-Al}}$ is the specific heat of aluminium = 0.91 kJ/kg/°C); ∆F is the mass of the fuel burned; LHV is the methanol fuel energy density. In the absence of a SANS standard for methanol as a domestic fuel, the default value of pure methanol, 19.780 kJ/kg, is used, which is the value for pure methanol.

3.5 Determining emission performance

3.5.1 Apparatus

The hood

The emission capture hood is made of stainless steel with three adjustable steel legs (Figure 3-8). Figure 3-9 shows the schematic drawing. It has a cone shape with a chimney at the stop where a probe is inserted to extract the flue samples.

Figure 3-8. The emission capture hood.

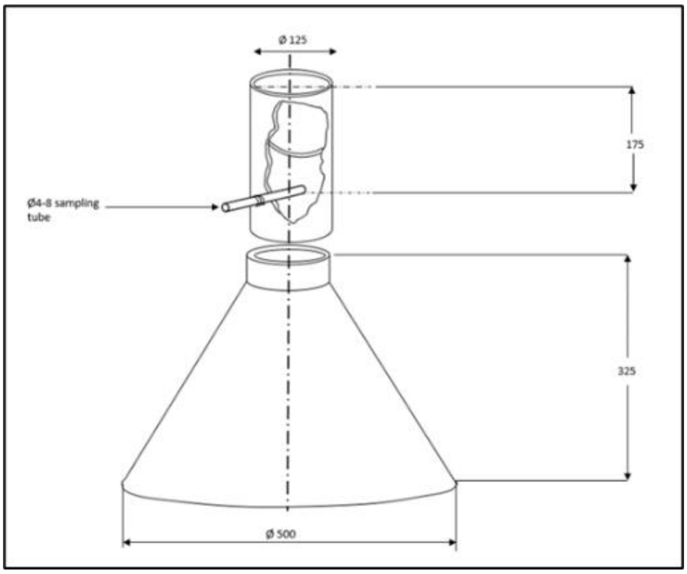


Figure 3-9. A schematic drawing of the emission capture hood.

Moisture remover and gas analyser

A PG-350 Horiba gas analyser that can simultaneously measure CO (range 0 to 5 000 ppm) and CO_2 (range 0 to 25%, precision 0.01%) (Figure 3-10).

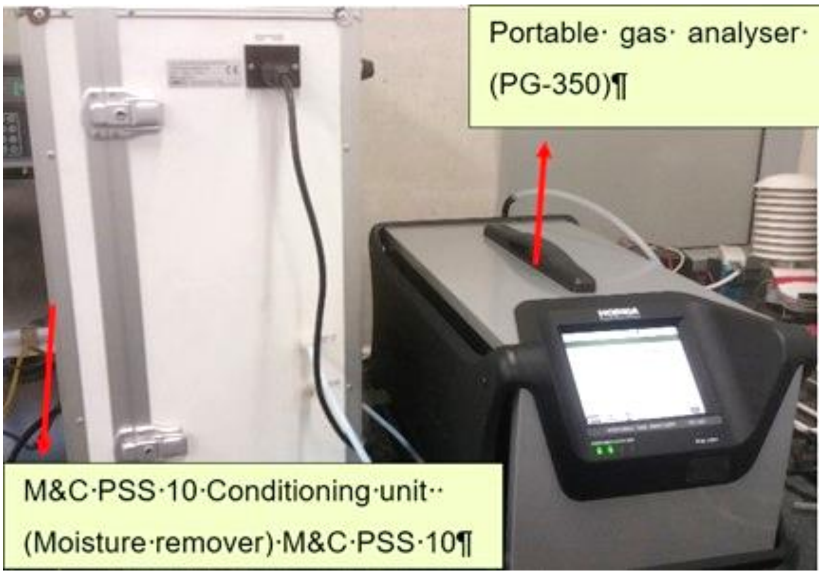


Figure 3-10. Moisture remover and gas analyser.

3.5.2 Incorporated procedure

Figure 3-11 shows the diagram of the system that was used to measure the emissions. The hood method was employed to capture emissions from the three methanol stoves and baseline paraffin. Flue samples, CO, and CO_2 concentrations were drawn from the chimney directly using a probe connected to a duct from a conditioning unit (an instrument that removes moisture in the system) then fed into a portable gas analyser (Horiba PG350). The emission performance tests were done simultaneously with thermal performance tests. Samples CO, and $CO_{2,}$ were drawn by the analyser at a flow rate of 0.4-0.5 L/min with limits of 5 000 ppm, 20 vol%, and 25 vol%, respectively. The data are stored on a memory card and were retrieved after each experiment. In addition, the data were uploaded to a computer for analysis and archiving.

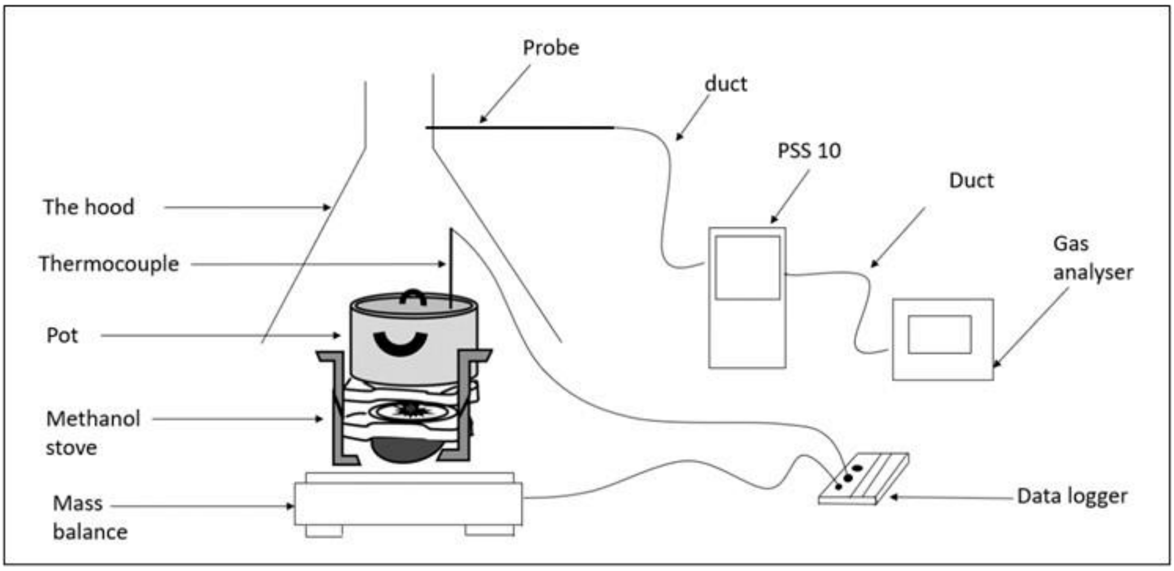


Figure 3-11. Diagram of the emission monitoring system.

3.5.3 Data processing and analysis

The concentrations of the flue were used to determine the Relative Carbon Monoxide Emission (RCE) (new term defined in the glossary) ratio using the following formula:

$$\text{RCE ratio} = \frac{CO_v}{(\text{CO}_{2\_\text{v}} \times 10\ 000) + CO_v} \times 100\% \qquad [\%]$$

Equation 3.13

where CO_V [ppm] and CO_{2_V} [%] are the respective volumetric concentrations of CO and CO_2, averaged over a measurement interval of 50°C, commencing from the start of ignition with water at test room temperature. The calculation is performed for the high and low power settings to derive the RCE at both power settings. If the temperature does not reach 50°C above the starting temperature during the low power test, the RCE is determined from the average gas concentrations over 30 minutes. The value 10 000 [ppm/%] converts the CO_2 concentration from [%] to [ppm].

3.6 Quality control

Several test runs were performed following the precise documented Standard Operating Procedure (SOP) before the commencement of actual tests for the study. These test runs were used as an exercise to familiarise the testing personnel with the SOP. Each definitive test was repeated a minimum of three times to ensure that the acquired data is reproducible. Daily calibrations were done on the gas analyser before the commencement of the tests. With the mass balance having high precision, movement in the testing laboratory was limited during test cycles.

4 Results and Discussion

4.1 Development of a standard testing protocol

4.1.1 The motivation for Objective 1

The development of the standard testing protocol was incorporated to develop a standard for methanol appliances by the South African Bureau of Standards (SABS). The process involved consensus between SABS officers and several South African experts in the field of study, including manufacturing industries, academic institutions and research centres. For the past decade, new technologies have been introduced as better appliances for domestic use. As a result, several projects have been formed to produce domestic stoves with advanced safety mechanisms, thermal performance and emission performance as alternatives for poor combusting traditional coal braziers and hazardous paraffin stoves. This study serves as part of these projects. A standard testing protocol is developed to evaluate the safety, thermal and emissions performance of methanol-fuelled cookstoves.

The objective of the test protocol is to test the full range of the stoves design qualities relevant to domestic usage, particularly in low-income settlements. The stoves are evaluated over a range of power settings (high and low) using a suite of pot sizes made from different materials and surface finishes (colour) - shiny aluminium and black stainless steel. The essence of the proposition is that pollutant emissions vary with power settings or altered flow patterns due to different pot sizes or types (Makonese, 2011). In addition, the energy transfer from the stove to the water may differ due to the material or surface finish/colour of the vessel.

Safety tests such as fuel loss during storage or upset and safety against conflagration after accidental upset are incorporated in the protocol. It is required that triplicate tests are performed for each condition (power setting, pot size, pot type, fuel loss, accidental upset) to ensure data quality and assurance and to determine standard deviations. CO is used as the only indicator pollutant for the fuel/stove combination being evaluated regarding emissions. It is worth noting that methanol combustion cannot produce black carbon particulate matter and is superior to paraffin in this respect. Therefore, particulate emission measurements were not included in this study. Other aspects of methanol safety, such as packaging and rigidity that are important to counteract associated risks, were outside the scope of this thesis.

The testing protocol is laboratory-based; it is termed the Water Heating Test (WHT). Like the WBT, the WHT does not attempt to emulate the real-world use of the appliances but tries to determine the appliance's overall thermal and emission performance. WHT requires laboratory conditions that are controlled and replicable. Considering that the stoves are designed for domestic use, the proposed test methods cover user scenarios of anticipated use and possible accidental situations in a real-world setup.

4.1.2 Standard testing protocol

The developed and documented draft standard testing protocol provides a detailed standard operating procedure (SOP). However, it is not permitted to attach a copy of the complete draft standard testing protocol to this thesis because the standard is under a SABS embargo while in the committee stage. For illustrative purposes, only parts or sections of the draft are captured and provided so far as they relate to the evaluation and trial of these procedures carried out by the candidate as his contribution to the SABS WG. The standard operating procedures are differentiated into (a) Water Heating Test (determining thermal and emission performance) and (b) safety test for methanol cookstoves. The procedures are formatted in such a way that they meet the basic requirements of SABS. Existing standard testing protocols for ethanol (SANS 666) and paraffin (SANS 1906) appliances were used as reference standards. Every procedure has a section that lists and outlines the required apparatus (Figure 4-1) and laboratory conditions (Figure 4-2) for that particular test. A well-written SOP is required to be concise, have instructions arranged step-by-step, written with sentences in command form, and easily comprehended (Makonese, 2011). Such requirements for good written SOP were adhered to when compiling the testing procedures for methanol appliances.

Inspection and methods of test

6.1 Apparatus

(a) **Appliance** designed to operate on methanol as defined in Section **Error! Reference source not found.**: Scope.

(b) **Stopwatch or clock with seconds indicator, or data logger** set to record at ten-second intervals.

(c) **Thermocouple or thermometer** able to measure water temperature range up to 100°C with a precision of 0.5°C.

(d) **Thermocouple or contact thermometer** to measure the metal surfaces and operating controls of the appliance, with temperature range up to 100°C and precision of 0.5°C.

(e) **Mass balance** with a precision of 1 g and a load rating of 5 kg or higher with an optional connection to a data logger.

(f) **Log sheets,** electronic or manual

(g) **Capture hood and gas sample probe,** as illustrated in Figure 1 in the case of a stove, or as illustrated in Figure 2 in the case of a heater.

(h) **A gas analyser to simultaneously measure CO** (range 0 to 5 000 ppm) and **CO_2** (range 0 to 5%, precision 0.01% at full range)

Figure 4-1. A section (example) from the standard testing protocol showing the required apparatus and test room/laboratory conditions.

6.4 Combined procedure applicable to cookstoves for thermal power, cooking power, emissions and turn-down ratio performance

This set of integrated procedures is used to determine within a combined burn sequence the ***thermal power***, ***cooking power***, ***emissions at full*** and ***low power settings,*** and ***turndown ratio.***

The ***specific time-to-boil*** metric is not measured directly but is calculated from the high-power setting ***cooking power*** determination.

Before commencing the tests described in this sub-section, ensure that the all the apparatus required has been assembled, that the test room conditions are prepared and the inspection and preparation of the appliance has been carried out.

6.4.1 **Integrated procedure to determine thermal and emissions metrics**

(a) If using an electronic data logger, connect and check that it is operating properly, recording the temperature, mass and gases at ten-second intervals

Figure 4-2. A section (an example) from the standard testing protocol showing the procedures.

4.2 Radiative and conductive heat losses in determining cooking power.

This section report results from measurements of the rate of energy loss as a function of temperature, a method based on Newton's Law of Cooling. The measurements determine the combined radiative and convective heat losses of a system as a function of temperature. Tests were conducted using shiny aluminium and matt black pots. Combining these heat loss processes with the sensible heat gain of the pot and its contents allows the determination of the total heat gain from the flame across the pot's bottom surface.

Figure 4-3 and Figure 4-4 show the combined heat loss rate, heating curve and the total heat input from heating and cooling test sequences. The aim of combining the derived *heat in* rate and the *heat loss* rate curve was to deduce the *corrected total cooking power* of the fuel/stove combination and demonstrate that it is, as expected, constant, irrespective of the temperature of the pot content. However, the result shows otherwise, where the total *heat in* is not constant. It is low at the beginning of the test (ignition time) and steadily rises as the experiment continue. At ~840 s, the heat into the pot becomes constant as the water reaches ~75°C. This phenomenon was observed for both black and shiny pots at high power. Non-uniform total heat into the pot was attributed to water condensation outside the pot, commencing ~120 s after ignition until ~750 s (Figure 4.5). The temperature increase rate (heat in) was 0.049°C/10-sec during the ignition phase and 0.053°C/10-sec towards the end of the experiment for the black pot. The temperature rise was 0.046°C/10-sec during the ignition phase and 0.049°C/10-sec towards the end for the shiny pot. The *heat loss* rate started low at the beginning of the test, as expected due to the slight temperature difference between the pot and surroundings (Zube, 2010). A steady increase in heat loss rate was reported from ignition until the end of the experiment, indicating that *heat in* is directly proportional to *heat loss.* These observations demonstrate an insignificant influence of pot colour on the cooking power metric. It is important to note that the condensation occurring during the initial stages of the tests may have influenced the results.

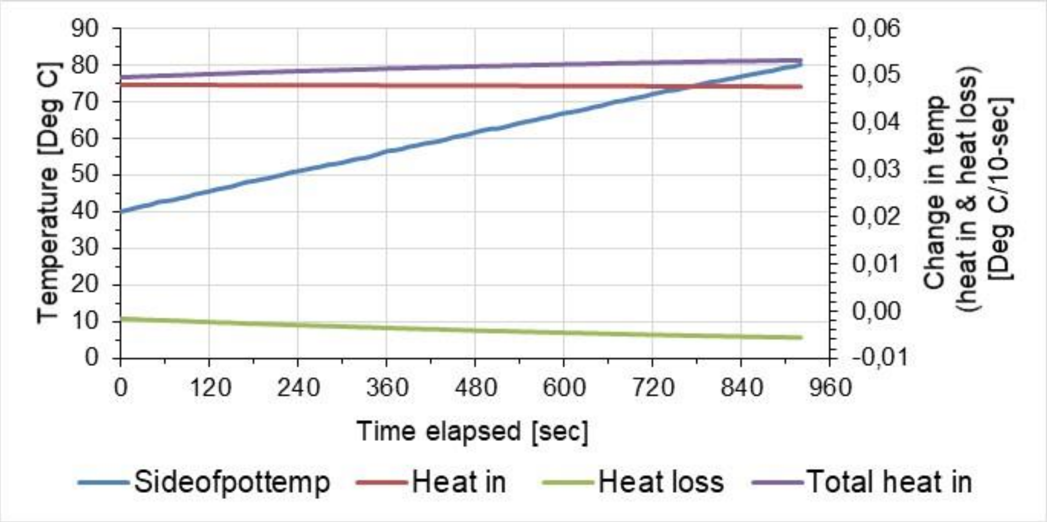


Figure 4-3. The combined heat loss rate, heating curve and the total heat input for the black pot at high power.

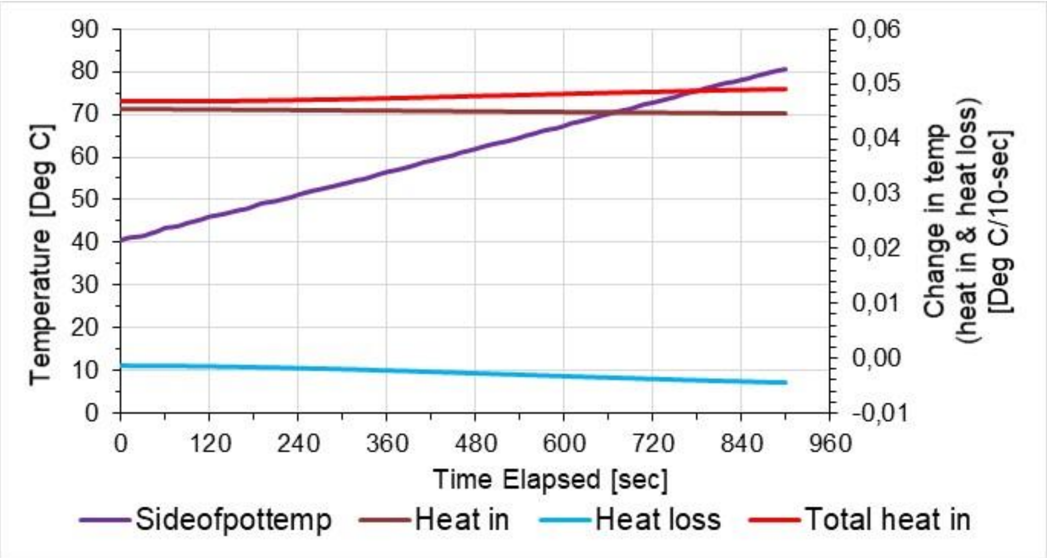


Figure 4-4. The combined heat loss rate, heating curve and the total heat input for the shiny pot at high power.

Figure 4-5. Water condensation on the outside of the pot.

4.3 Safety, thermal performance and emission performance

4.3.1 Safety and use of cookstoves

The safety or use of methanol stoves and the baseline paraffin wick stove was evaluated and ranked according to the draft standard protocol. A provisional check sheet to certify whether the stove pass or fail to comply with the safety requirements was used.

Table 4.1 presents the results of the safety metrics tests performed on various stoves. The power setting lever of each stove was measured to evaluate its surface temperature. They all reported high **surface temperatures** exceeding the limit of 42°C as specified in the SABS draft standard. This resulted from the short length of the lever and its proximity to the burner. The levers of all the stoves are short and located directly beneath the flame, approximately 2 cm, allowing them to heat up during operation. STV01 and the paraffin stove recorded surface temperatures of 45°C on their respective levers, relatively close to the 42°C limit. STV02 reported the highest temperatures at 74°C, followed by STV03 at ~52°C.

The evaporative losses from all the stoves, including the reference paraffin stove, were within the limit of 10 g/h. During the upset of the stoves at 90° angle, STV01 and STV03 passed the test with spillages of less than 10 g/min, averaged over measurements in three orientations. STV02 spilled 108 g/min of fuel. This was because the stove is designed with an air inlet located underneath the fuel tank, which allowed leakage in specific orientations. Most leakages were observed when the air inlet was located at the lowest position, while slight or no fuel leaked when the air inlet was orientated at the highest position (Figure 4-6). At 180° upset angle, only STV03 failed this test, leaking 16.8 g/min of fuel.

All the stoves evaluated extinguished within 30 seconds of being shut off. In terms of design, all the stoves had no **sharp edges and points**.

Table 4.1. Assessment of safety aspects of the methanol stoves and baseline paraffin stove.

			STV01		STV02		STV03		Paraffin	
Metric	**Standard requirement**	**Unit**	**Mean ± STDV**	**Pass/ Fail**	**Mean ± STDV**	**Pass/ Fail**	**Mean ± STDV**	**Pass/ Fail**	**Mean ± STDV**	**Pass/ Fail**
Surface temperature	42.0	°C	45.3 ± 2.1	Fail	74 ± 14	Fail	51.7 ± 6.0	Fail	44.3 ± 0.5	Fail
Evaporation loss	10.0	g/h	2.0 ± 0.2	Pass	1.3 ± 0.3	Pass	1.67 ± 0.64	Pass	1.4 ± 0.2	Pass
Fuel spillage (90° upset)	10.0	g/min	9.6 ± 3.5	Pass	108 ± 13	Fail	5.1 ± 3.08	Pass	6.3 ± 0.8	Pass
Fuel spillage (180° upset)	10.0	g/min	2.3 ± 0.7	Pass	1.3 ± 0.8	Pass	16.5 ± 9.8	Fail	0.3 ± 0.2	Pass
Extinguishing the flame	30	sec	30	Pass	30	Pass	30	Pass	30	Pass
Sharp edges and points	n/a	n/a	n/a	Pass	n/a	Pass	n/a	Pass	n/a	Pass

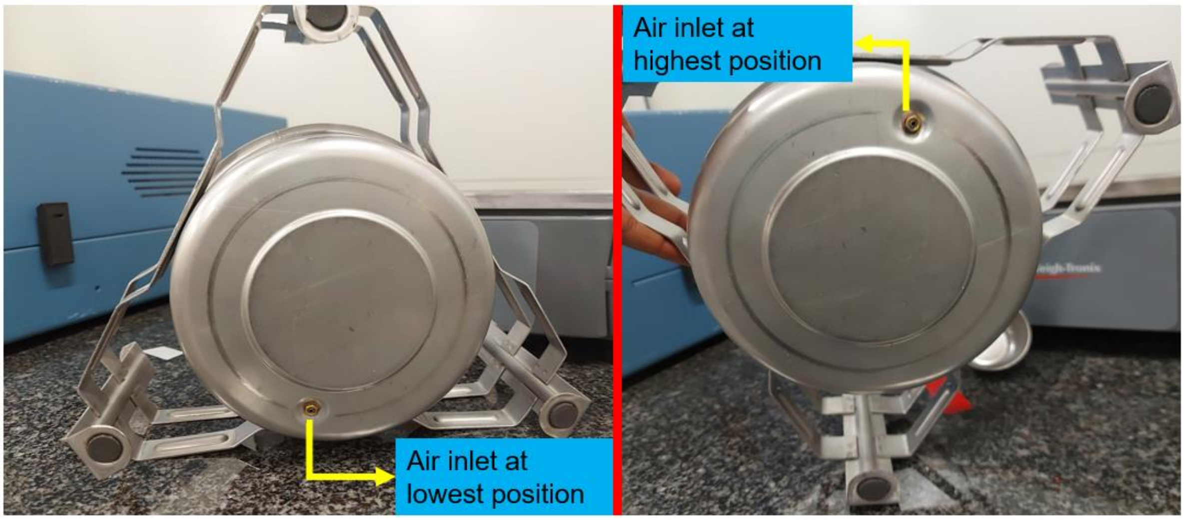


Figure 4-6. The orientation of the air inlet on a methanol stove.

4.3.2 Thermal performance

A comparison of thermal performance between three differently designed methanol cookstoves and a wick-type paraffin stove was conducted. The tests were performed using three aluminium pots of different sizes (large, medium and small) and three stainless steel (black) pots of various sizes (large, medium and small). Each pot was filled with water to two-thirds of its capacity. Tests were performed at both high and low power settings. Each test condition was replicated three times, averages and standard deviations were calculated.

High power

Table 4.2 presents the thermal performance metrics obtained from the tests performed on the reference paraffin stove and the methanol stoves at the high power setting with the **shiny aluminium pot**.

Cookstoves are required to produce a minimum **thermal power** of at least 1 kW, according to SANS 1906. Two methanol fuel stoves (STV01 and STV02) and the paraffin wick stove generated thermal power of more than 1 kW irrespective of pot size. With the small pot, STV03 could not reach the required 1 kW, producing about 0.97 kW. Overall, the paraffin stove produced the highest thermal power with all pot types, followed by STV02, STV01 and STV03. This was expected as the energy density of methanol is only ~60% of that of paraffin.

According to the draft standard, the stoves must produce at least 580 W of **cooking power**. Two methanol fuel stoves (STV01 and STV02) and the paraffin wick stove generated more than 580 W irrespective of pot size. STV03 was unable to reach the 580 W requirement producing ~528 W with the small pot. The paraffin stove generated the highest cooking power of 752 W with the large pot, followed by STV02 (659 W) with the small pot. Among the methanol fuel stoves, STV02 ranked first, producing more than 600 W cooking power irrespective of pot size.

The maximum **specific time to boil** *(equivalent time to boil)* prescribed in the draft SABS standard is 10 minutes. The SABS Working Group considered this to be the maximum acceptable performance criterion for the targeted South African domestic market. As the specific time to boil is inversely proportional to cooking power, overall, STV02 yielded the shortest specific time to boil, followed by Paraffin stove, STV01 and STV03. Thus, the equivalent time to boil is less than 10 minutes for all three methanol stoves.

Table 4.2. Thermal power, cooking power and specific time to boil at high power for the three methanol and reference stoves for the shiny pots.

Stove type	Pot size	Thermal power (kW) (Mean ± STDV)	Cooking power (W) (Mean ± STDV)	Specific time to boil (min) (Mean ± STDV)
	Large	1.16 ± 0.16	640 ± 48	8.7 ± 0.32
STV01	Medium	1.01 ± 0.04	589 ± 33	9.5 ± 0.53
	Small	1.07 ± 0.19	595 ± 120	9.7 ± 2.22
	Large	1.23 ± 0.10	635 ± 71	8.8 ± 0.93
STV02	Medium	1.14 ± 0.01	644 ± 14	8.7 ± 0.18
	Small	1.22 ± 0.07	659 ± 10	8.5 ± 0.12
	Large	1.03 ± 0.10	630 ± 31	8.9 ± 0.43
STV03	Medium	1.03 ± 0.18	584 ± 68	9.6 ± 1.11
	Small	0.97 ± 0.08	528 ± 30	10.3 ± 0.60
	Large	1.43 ± 0.10	752 ± 15	7.4 ± 0.14
Par	Medium	1.27 ± 0.11	605 ± 49	9.3± 0.73
	Small	1.39 ± 0.19	608 ± 64	9.2 ± 0.97

Table 4.3 presents the thermal performance metrics using the **black stainless steel pots** at the high power setting. The paraffin stove produced the highest **thermal power** irrespective of the pot size. STV03 was unable to deliver a thermal power above 1 kW with any pot size. STV01 generated a thermal power of 1.10 kW with the medium pot, while STV02 generated 1.12 and 1.17 kW with large and small pots, respectively.

STV01 failed to generate the required minimum **cooking power** of 580 W with the large and small pots. STV03 showed to be underpowered as the stove generated a cooking power that is relatively lower than the required cooking power. STV02 and the paraffin stove had satisfactory cooking powers, Failing to perform as per the standard requirement when using the medium and small pots.

STV01 reported the longest **specific time to boil**, ~12 minutes with large and small pots. On the other hand, the paraffin stove recorded the shortest specific time to boil, of 7.4 minutes with a large pot. The long specific time to boil observed for STV01 indicates the typical user experience that hinders wider adoption of these particular stoves intended to replace paraffin stoves.

Table 4.3. Thermal power, cooking power and specific time to boil at high power for the three methanol and reference stoves, for the black pots.

Stove type	Pot size	Thermal power (kW) (Mean ± STDV)	Cooking power (W) (Mean ± STDV)	Specific time to boil (min) (Mean ± STDV)
STV01	Large	0.81 ± 0.23	489 ± 132	12.1 ± 3.86
	Medium	1.10 ± 0.04	608 ± 30	9.2 ± 0.43
	Small	0.95 ± 0.19	472 ± 69	12.0 ± 1.80
STV02	Large	1.12 ± 0.07	668 ± 42	8.4 ± 0.54
	Medium	0.97 ± 0.22	570 ± 127	10.1 ± 2.20
	small	1.17 ± 0.15	605 ± 72	9.3 ± 1.09
STV03	Large	0.89 ± 0.08	578 ± 55	9.7 ± 0.97
	Medium	0.93 ± 0.03	581 ± 24	9.6 ± 0.41
	Small	0.99 ± 0.21	514 ± 32	10.8 ± 0.71
Par	Large	1.54 ± 0.19	760 ± 4	7.4 ± 0.06
	Medium	1.48 ± 0.06	643 ± 2	8.7 ± 0.03
	Small	1.41 ± 0.11	555 ± 43	10.1 ± 0.76

Low power setting

Table 4.4 and Table 4.5 present the thermal performance metrics obtained from the tests performed on the reference paraffin stove and the methanol stoves at low power, with the shiny and black pots. For this parameter, lower values are favourable, enabling the cook to simmer the pot contents. The stoves are expected to generate thermal and cooking power that is adequate for simmering.

Low power results were incorporated in calculating the derived ***Turn-Down Ratio (TDR)*** metric, an indication of stove controllability (the higher, the better) – an indicator of the stove's capability to operate at low power for simmering. The required TDR is 2.0. With the shiny pots, STV01 reported the largest turn-down ratio (best controllability) with large (TDR = 3.7) and medium pots (TDR = 3.1), followed by STV02 and the paraffin stove, both producing TDR values of ~2, irrespective of pot size (Table 4.4). STV03 produced the poorest TDR, producing TDR of 2 with the medium pot only

STV01 and STV02 reported the largest TDRs with all three black pot sizes (Table 4.5). The paraffin stove was able to produce the minimum required TDR with the large pot. STV03 produced the poorest TDR - it was unable to produce a TDR of at least 2 with any pot size, indicating poor controllability.

Table 4.4. Thermal power, cooking power and turn-down-ratio at low power for the three methanol and reference stoves, for the shiny pots.

		Aluminium pot		
Stove type	**Pot size**	**Thermal power (kW) (Mean ± STDV)**	**Cooking power (W) (Mean ± STDV)**	**Turn down ratio (Mean ± STDV)**
STV01	Large	0.31 ± 0.04	182 ± 49	3.7 ± 1.4
	Medium	0.29 ± 0.10	202 ± 68	3.1 ± 1.2
	Small	0.42 ± 0.10	251 ± 5	2.3 ± 0.5
STV02	Large	0.43 ± 0.01	293 ± 12	2.2 ± 0.2
	Medium	0.43 ± 0.01	313 ± 7	2.1 ± 0.1
	small	0.41 ± 0.04	285 ± 37	2.3 ± 0.3
STV03	Large	0.89 ± 0.01	556 ± 112	1.1 ± 0.04
	Medium	0.65 ± 0.30	369 ± 147	1.8 ± 0.9
	Small	0.80 ± 0.11	444 ± 53	1.2 ± 0.2
Par	Large	0.94 ± 0.09	452 ± 63	1.7 ± 0.2
	Medium	0.92 ± 0.10	332 ± 92	1.9 ± 0.7
	Small	0.86 ± 0.10	428 ± 217	1.6 ± 0.5

Table 4.5. Thermal power, cooking power and turn-down-ratio at low power for the three methanol and the reference stoves, for the black pots.

		Black pot		
Stove type	**Pot size**	**Thermal power (W) (Mean ± STDV)**	**Cooking power (W) (Mean ± STDV)**	**Turn down ratio (Mean ± STDV)**
STV01	Large	0.32 ± 0.20	222 ± 1	2.1 ± 0.6
	Medium	0.36 ± 0.01	228 ± 7	2.6 ± 0.06
	Small	0.36 ± 0.04	207 ± 20	2.3 ± 0.4
STV02	Large	0.48 ± 0.09	321 ± 56	2.1 ± 0.5
	Medium	0.37 ± 0.04	239 ± 33	2.4 ± 0.5
	small	0.40 ± 0.04	260 ± 35	2.3 ± 0.04
STV03	Large	0.78 ± 0.12	477 ± 70	1.3 ± 0.2
	Medium	0.83 ± 0.07	511 ± 70	1.1 ± 0.1
	Small	0.77 ± 0.09	413 ± 35	1.3 ± 0.2
Par	Large	0.89 ± 0.03	390 ± 36	2.0 ± 0.2
	Medium	1.22 ± 0.38	501 ± 125	1.3 ± 0.3
	Small	1.00 ± 0.06	380 ± 31	1.5 ± 0.2

Table 4.6 presents the **thermal efficiency** at both high and low power settings, with the shiny and black pots. There is an observed trend from STV03 and the paraffin stove where the thermal efficiency increases with pot size; the bigger the pot, the higher the efficiency. STV02 produced

the highest efficiency of ~77% with the medium shiny pot at low power. The lowest efficiency of ~39% was observed for the paraffin stove with the shiny small pot.

The results are further illustrated in Figure 4-7 and Figure 4-8. The trend mentioned above can be observed where the stoves' efficiency increased with increasing pot size. However, this was not the case with the methanol stoves at low power when using the shiny pots. The observed trend is due to the reduced bottom surface area of the small pots, which allows the flame to be dispersed around the pot sides. Especially at the high power, a large fraction of heat was lost to the surroundings. With the larger pots, the bottom surface area is wide enough for the flame to transfer most of its energy, with only a small part of the flame dispersing to the sides, resulting in improved energy transfer into the pot. The methanol stoves were more efficient when operated at low power, while the paraffin stove efficiency increased from low to high. The methanol stove behaviour is because, at high power, flames occur in a circular doughnut shape as the flame burns only at the edges, leaving the middle section hollow (with less flame occurring). Lack of oxygen diffusion to the middle of the burner and flame may cause the observed flame behaviour, resulting in heat being distributed only towards the pot edge with little heat in the middle.

Consequently, a significant fraction of the heat is dispersed and lost to the ambient. The flame is produced in a solid circular shape at low power, heating the pot directly in the centre. The observed reduced efficiency at low power for all the stoves is because it takes longer to heat the water, allowing for an extended period for heat loss through convection and radiation from the top and sides (Makonese, 2011). Overall, the methanol stoves had higher thermal efficiency compared to the paraffin stove.

Table 4.6. Thermal efficiency at high and low power for the three methanol and reference stoves for the shiny and black pots.

Stove type	Pot size	Aluminium pot		Stainless steel pot	
		Thermal efficiency high power (%) (Mean ± STDV)	Thermal efficiency low power (%) (Mean ± STDV)	Thermal efficiency high power (%) (Mean ± STDV)	Thermal efficiency low power (%) (Mean ± STDV)
STV01	Large	59.9 ± 10.0	60.4 ± 4.3	65.5 ± 5.8	71.6 ± 6.0
	Medium	60.5 ± 1.4	72.8 ± 1.9	56.3 ± 3.5	67.4 ± 1.1
	Small	57.3 ± 1.7	71.2 ± 1.8	51.8 ± 2.6	61.9 ± 4.6
STV02	Large	70.9 ± 3.1	72.1 ± 1.5	61.5 ± 0.4	70.4 ± 3.2
	Medium	54.0 ± 8.3	76.9 ± 3.3	62.2 ± 1.5	69.4 ± 2.4
	small	56.3 ± 3.9	64.8 ± 8.6	54.1 ± 0.3	68.1 ± 2.7
STV03	Large	70.9 ± 3.1	65.8 ± 2.4	65.4 ± 1.2	69.5 ± 4.7
	Medium	60.1 ± 3.0	64.2 ± 6.5	63.6 ± 3.0	64.6 ± 2.4
	Small	56.7 ± 2.2	58.4 ± 1.0	55.6 ± 6.1	56.0 ± 1.8
Par	Large	56.7 ± 1.3	51.3 ± 2.8	56.0 ± 1.2	46.1 ± 2.7
	Medium	51.1 ± 3.8	40.7 ± 8.2	48.4 ± 1.8	45.2 ± 2.9
	Small	45.9 ± 0.4	39.6 ± 1.1	43.3 ± 0.2	40.6 ± 1.5

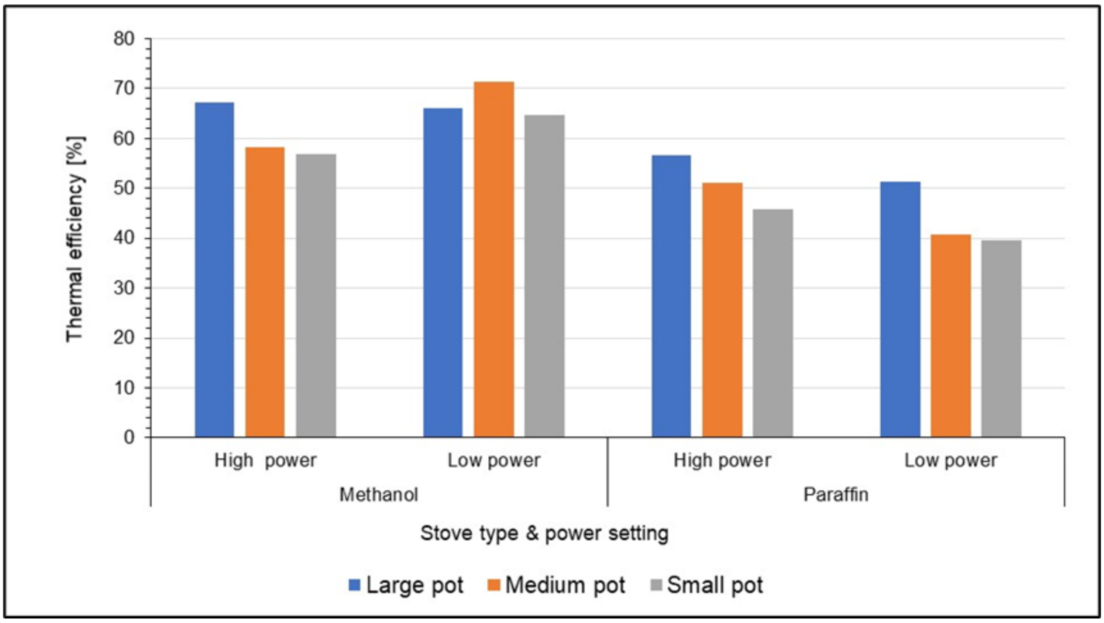


Figure 4-7. Performance of methanol fuel stoves compared to paraffin stoves at both high and low power setting with the shiny pot.

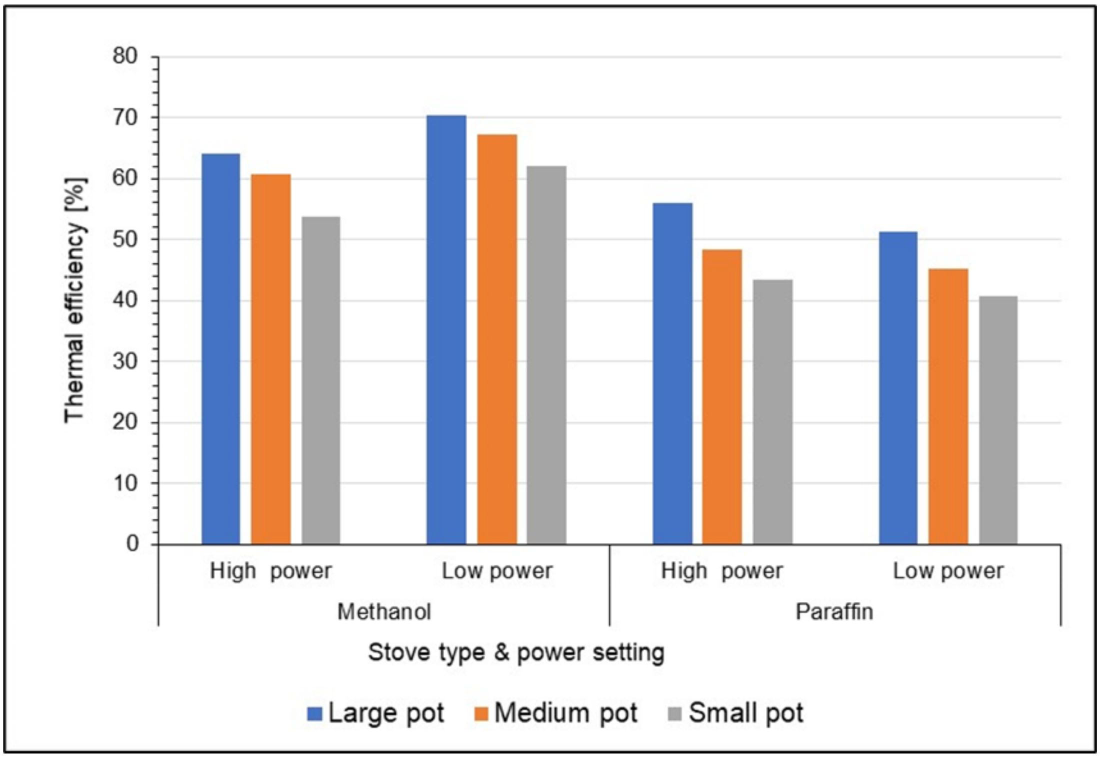


Figure 4-8. Performance of methanol fuel stoves compared to paraffin using different shiny pot sizes at both high and low power setting with the black pot.

4.3.3 Emission performance

The emission performance of methanol fuel cookstoves and baseline paraffin wick stove were investigated, including any influences due to pot type and size. The relative Carbon monoxide Emission (RCE) ratios are presented in Figure 4-9 and Figure 4-10 at high power, starting at ignition with the water at test room temperature (~20°C) until the water reached ~80°C. When using the large shiny pot, the RCE ratio rises steeply during the first 120 s. A similar phenomenon was observed with the black pot; however, only with the paraffin and STV03. The high emissions result from the flame quenching (hot gases dropping below the ignition temperature for combustion of CO) when coming into contact with the cold surface of the pot. The peak RCE values of 7% and 18% were recorded for the paraffin stove using the shiny and black pots. From ~150 to ~750 s, high CO emissions were recorded from STV01 and STV02, after which the RCE stabilised (Figure 4-9). This increase in CO emissions may have been due to the observed water condensation outside the pot (Figure 4-5), commencing ~120 s after ignition. When the water droplets interact with the flame from the burner, higher emissions of CO are recorded. This phenomenon was notable when using both shiny and black pots. However, this phenomenon was not reported for the STV03 and the paraffin stove for either pot type. There is no explanation for the secondary peaks in RCE at the end of the paraffin stove sequences at this stage.

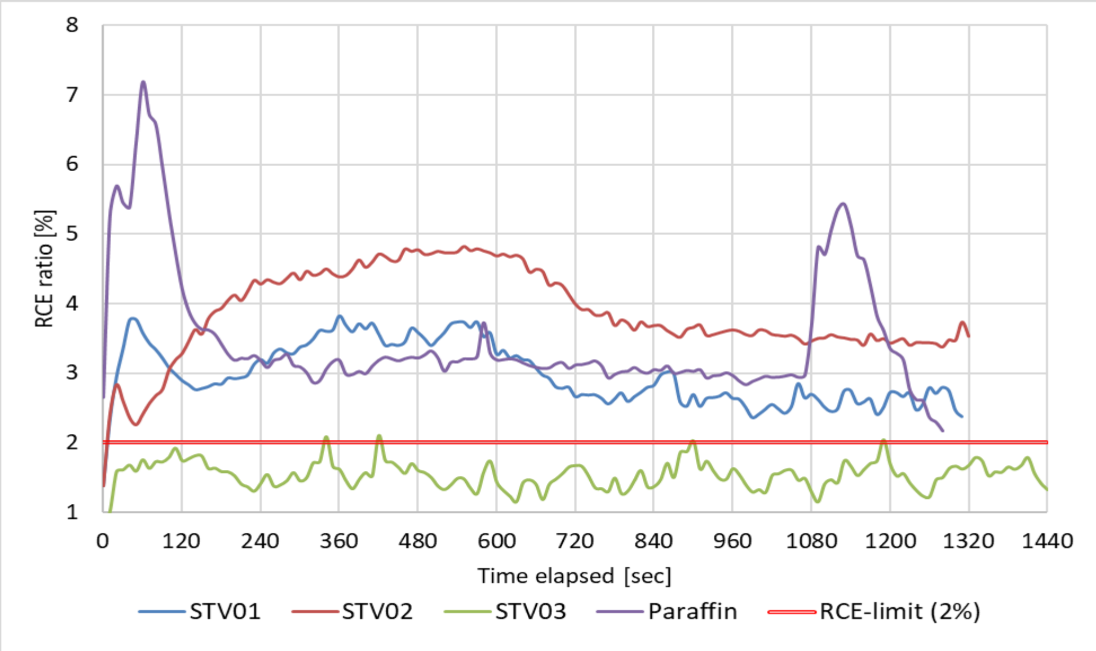


Figure 4-9. RCE of the methanol stoves and a baseline paraffin stove at high power using an aluminium (shiny) pot.

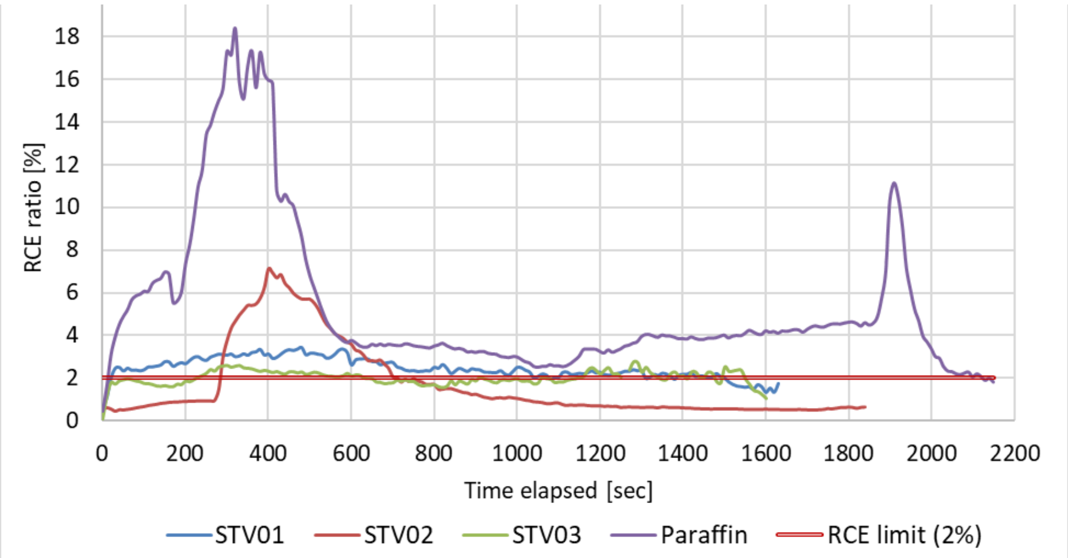


Figure 4-10. RCE of the methanol stoves and a baseline paraffin stove at high power. Stainless steel (black) pot.

Table 4.7 presents the integrated RCE of the stoves at high and low power settings for both pots. **At high power**, only STV03 has an RCE that complies with the 2% CO/CO_2 emission limit set in SABS 1906 (a paraffin stove standard for the safety and emission limits). Overall, the paraffin stove recorded the lowest combustion efficiency, with RCE reaching ~5% with the small shiny pot and 8% with the medium black pot. The observed RCE from the paraffin stove is a phenomenon that has been evident in a study by Makonese et al. (2012).

The results are further depicted in Figure 4-11 and Figure 4-12 for the shiny and black pots. A notable difference is observed with the black pot, where STV03 recorded RCE of 2.73%, 2.33%, and 2.77% for the large, medium, and small pot, respectively. In comparison, the paraffin stove had RCE of 3.7%, 4.9%, and 4.9% for the large, medium, and small pot, respectively. Although the methanol stoves emissions exceed the emission limit, their emissions are significantly lower than those of the paraffin stove. The paraffin stove emissions are higher than those of methanol stoves for all combinations of stove/pot size and pot types.

STV01 and STV02 recorded reduced emissions at low power compared to high power and were within the 2% limit with either pot. In contrast, STV03 exceeded the 2% limit with the black pot. The paraffin stove had the highest emissions, 8.0% and 7.3%, with the medium and small black pots. Figure 4.11 and Figure 4.12 show that even at low power, the methanol stoves have notably lower emissions than those of the paraffin stove. With the black pots (Figure 4-12), the methanol stoves have an RCE of ~1.3% with the medium-sized pot and ~1.7% with the small pot. In comparison, the paraffin stove produced significantly high emissions, having an RCE of ~8% with the medium pot size and 7.3% with the small pot. Similar results were observed with the shiny pots; however, the paraffin emissions decreased to 4.85% and 4.92%, with the medium and small pots, respectively.

The differences in RCE for the different pot type and sizes are not consistent. There is no explanation for this phenomenon, other than noting that at high power and during the initial heating, condensation occurred on either black or shiny pot exterior, sometimes with water dripping off the pot surface. This condensation and partial re-evaporation of water might have influenced chemical reactions within the flame zone. The more so if the flame was in extensive contact with the pot bottom. Overall, at high power when using the shiny pots, the methanol stoves recorded slightly higher RCE than when using black pots.

Table 4.7. Relative Carbon monoxide Emission (RCE) at high and low power for the three methanol and reference stoves for the shiny and black pots.

		Aluminium pot		Stainless steel pot	
Stove type	**Pot size**	**RCE high power (%) (Mean ± STDV)**	**RCE low power (%) (Mean ± STDV)**	**RCE high power (%) (Mean ± STDV)**	**RCE low power (%) (Mean ± STDV)**
	Large	3.2 ± 0.1	1.00 ± 0.1	2.6 ± 0.4	1.3 ± 0.1
STV01	Medium	2.9 ± 0.1	1.08 ± 0.8	2.6 ± 0.1	1.7 ± 0.1
	Small	2.7 ± 0.02	1.78 ± 0.1	2.6 ± 0.1	2.3 ± 0.7
	Large	4.9 ± 1.3	0.3 ± 0.2	4.2 ± 0.1	2.4 ± 1.9
STV02	Medium	4.0 ± 0.6	0.2 ± 0.02	3.1 ± 1.1	0.1 ± 0.02
	small	4.5 ± 0.2	0.2 ± 0.04	4.5 ± 0.7	0.4 ± 0.3
	Large	1.6 ± 0.1	1.4 ± 0.3	1.4 ± 0.3	2.3 ± 0.5
STV03	Medium	1.5 ± 0.2	1.3 ± 0.1	1.3 ± 0.1	2.2 ± 0.6
	Small	1.8 ± 0.6	1.3 ± 0.1	1.2 ± 0.1	2.4 ± 0.1
	Large	3.7 ± 0.1	3.7 ± 0.1	3.7 ± 0.1	6.3 ± 3.3
Par	Medium	3.6 ± 1.9	4.9 ± 0.3	4.9 ± 0.3	8.0 ± 1.7
	Small	5.4 ± 0.2	4.9 ± 0.3	4.9 ± 0.2	7.3 ± 0.2

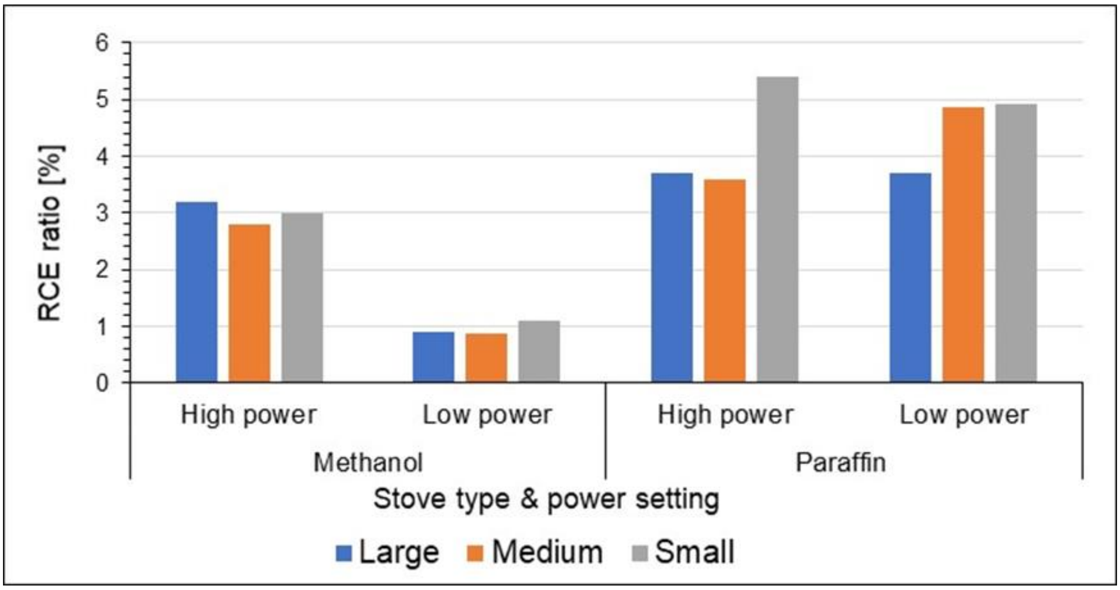


Figure 4-11. Emission performance at high and low power for the three methanol and reference paraffin stove for the shiny pots.

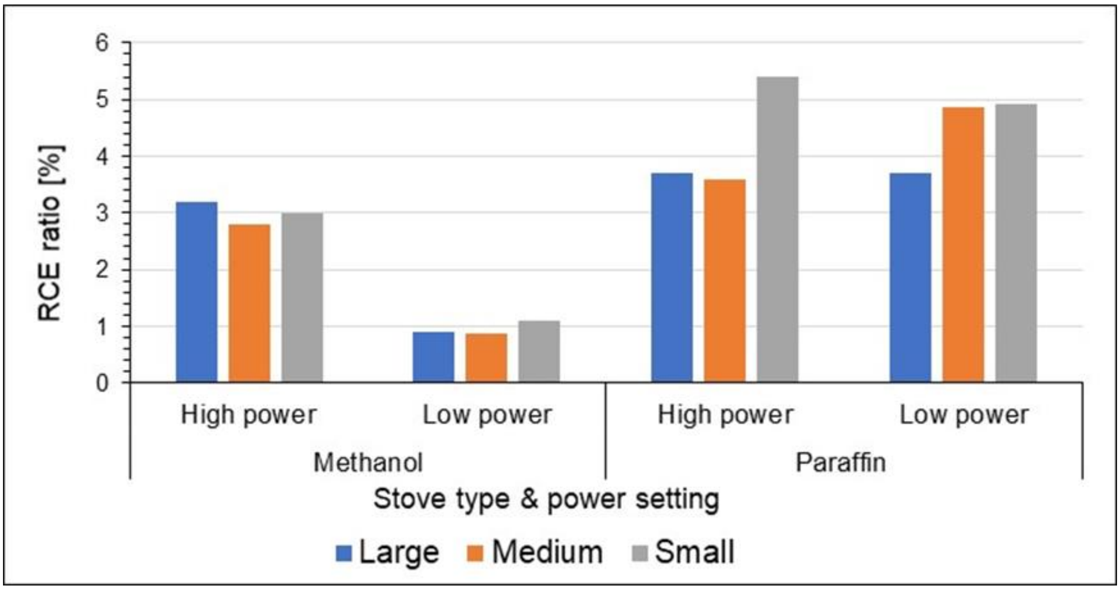


Figure 4-12. Emission performance at high and low power for the three methanol and reference paraffin stove for the black pots.

4.3.4 Influence of pot size and external finish (shiny Al or matt black) on the thermal and emission performance of the stove/fuel/pot combination.

Influence on thermal performance

The results are illustrated in Figure 4-13 and Figure 4-14. The baseline paraffin stove had good performance with the large shiny and black pots at **high power (**Figure 4-13**)**. It can be noted that there is a possible trend for STV03 and the Paraffin stove where the thermal performances of the stoves increase with an increase in pot size.

At **low power,** there is also no notable trend of the pot size or type influence on the stoves' performance (Figure 4-14). There were insignificant variations in cooking power between STV01 and STV02. STV03. With the large shiny pot and medium black pot, the paraffin stove had moderate cooking power, higher than desirable for simmering, a weakness in the stove's controllability.

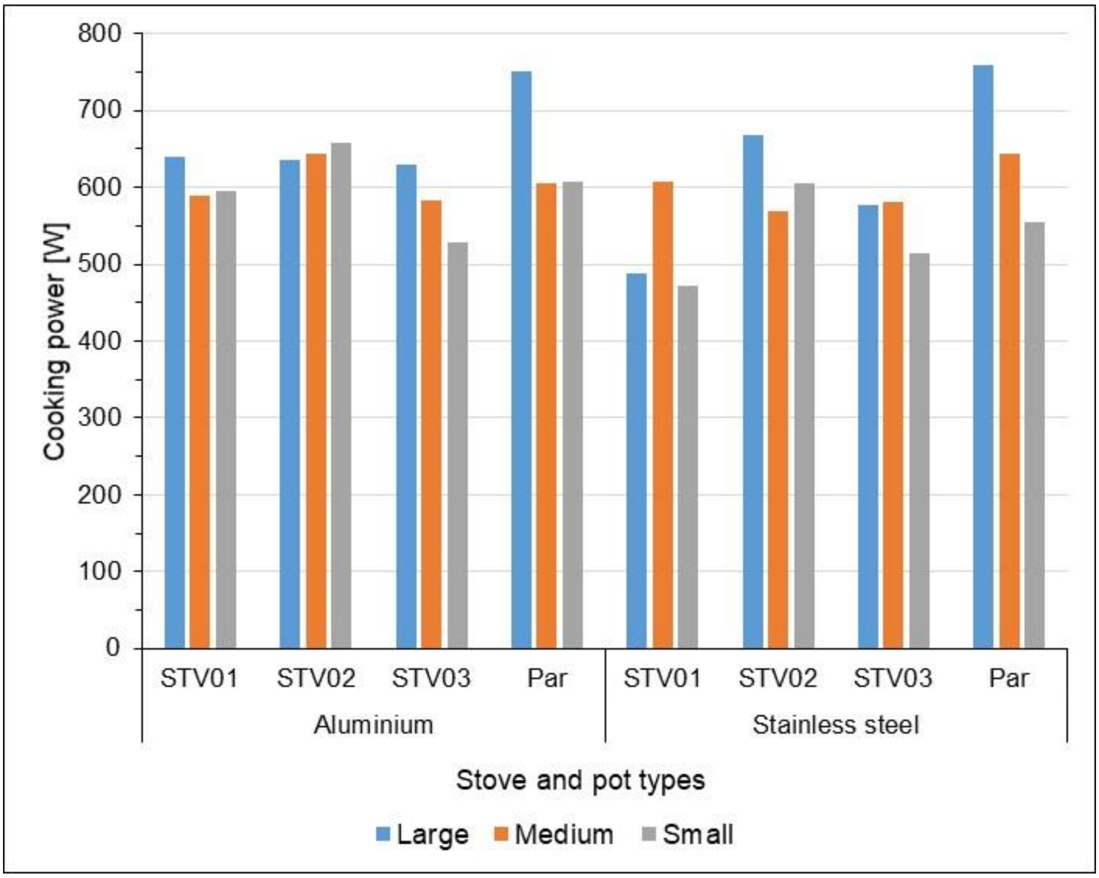


Figure 4-13. Influence of pot type and size on cooking power of the stoves at high power.

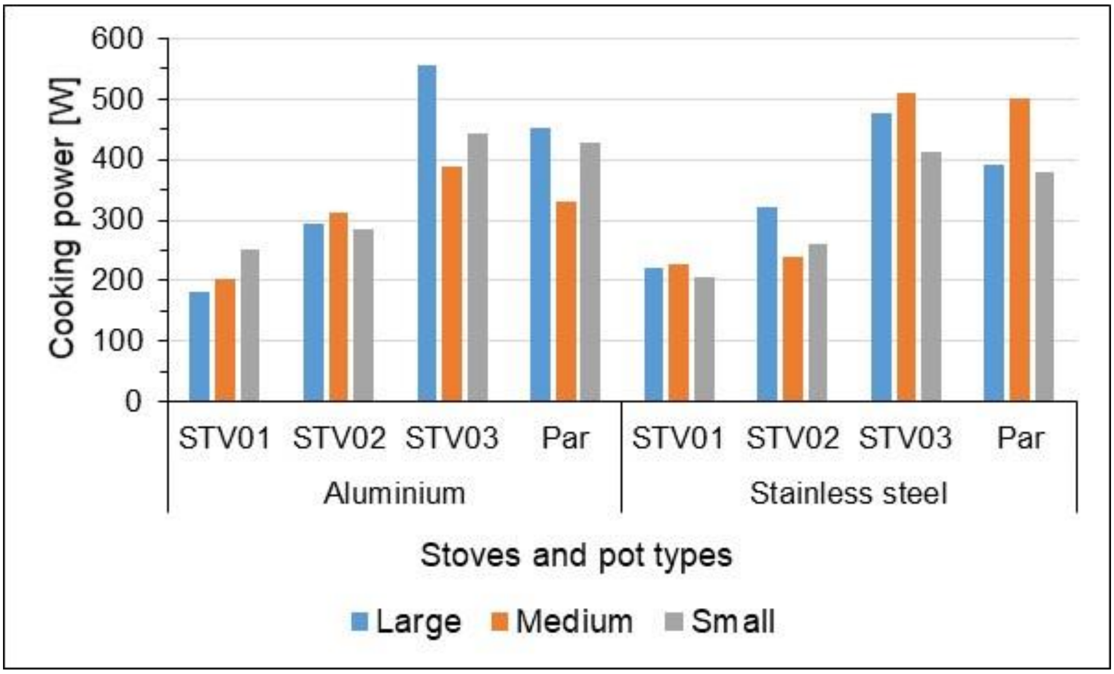


Figure 4-14. Influence of pot type and size on cooking power of the stoves at low power.

Influence on emission performance

The results are illustrated in Figure 4-15 and Figure 4-16. There was no significant influence on the methanol stoves' emission performance at high power with either pot size or type (Figure 4-15). High emissions were observed with the paraffin stove using either a small shiny or a small black pot.

At **low power**, the pot size had slightly the same influence on the emission performance of the STV02 and STV03. The small pot showed to have a slight influence on the emission performance of STV01. The medium and small pot showed a notable influence on the paraffin stove's emission performance.

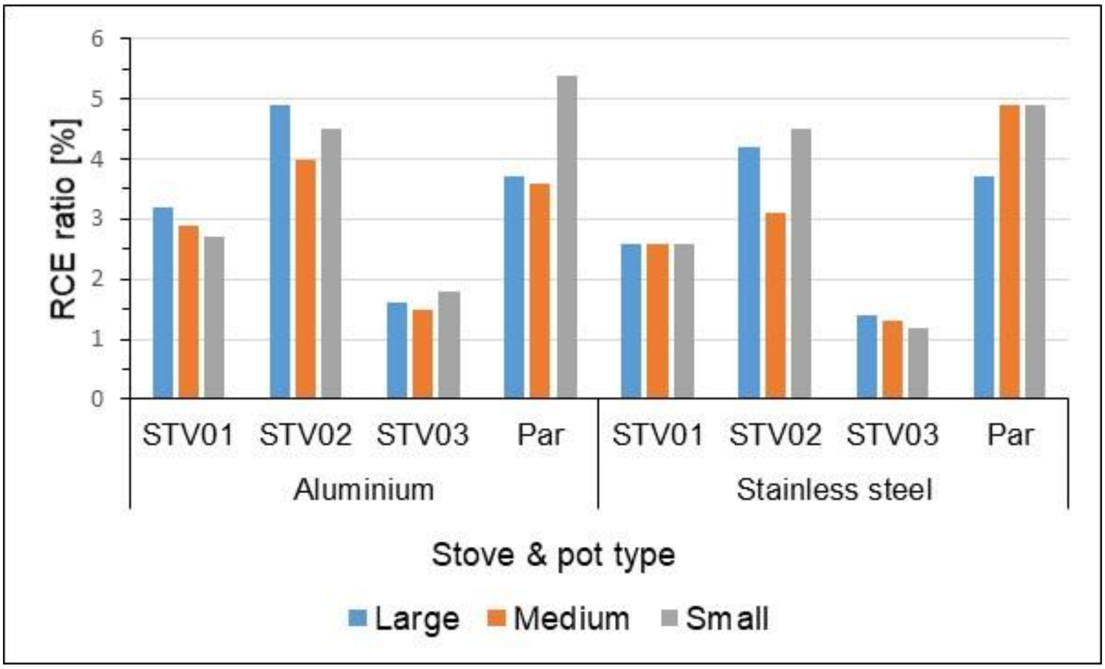


Figure 4-15. Influence of pot type and size on emission performance of the stoves at high power.

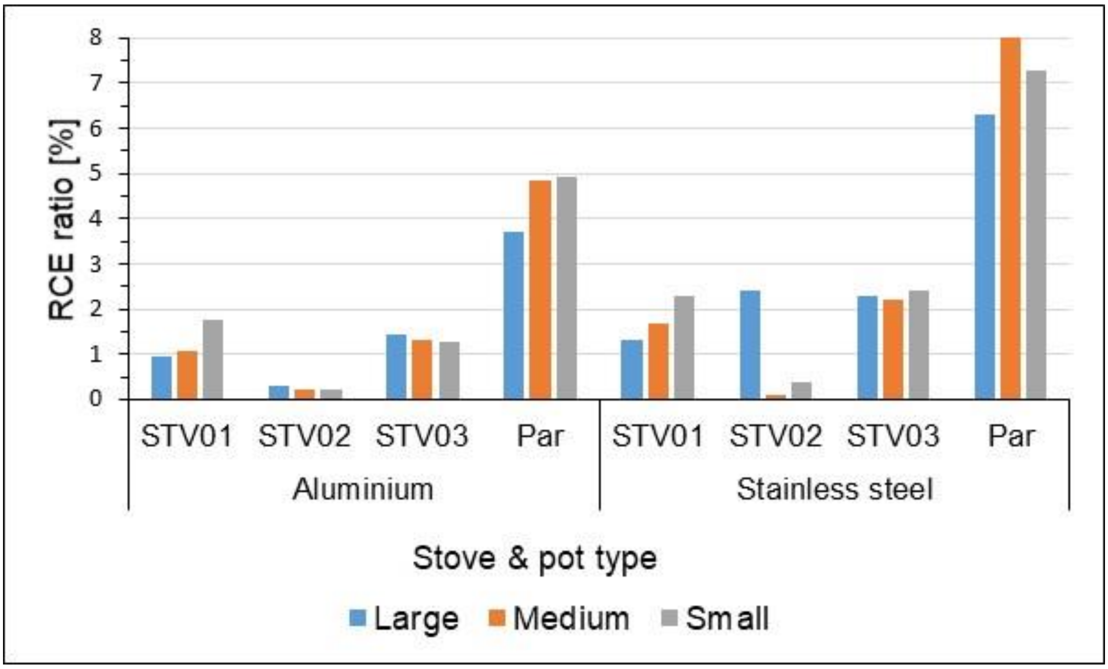


Figure 4-16. Influence of pot type and size on emission performance of the stoves at low power.

5 Conclusions and Recommendations

5.1 Summary

The study had the following objectives: (i) developing a standard testing protocol for methanol fuel stoves; (ii) investigating the radiative and conductive heat losses in determining cooking power; and (iii) evaluating safety and use, testing thermal and emission performance of three different methanol fuel stoves.

5.1.1 Developing a standard testing protocol for methanol fuel stoves

The standard was developed in collaboration with the South African Bureau of Standards. The author was mainly involved with the development of the testing protocols. The author's involvement included attending SABS TC Working Group meetings and assuming responsibility for performing all the preliminary tests required by the TC Working Group throughout the standard development. This was the first objective that was undertaken because the other objectives were dependant on it. The test method contains protocols for thermal and emission performance and safety of methanol fuelled stoves. Developing these testing protocols was done to create a standard way and guidance for designing and testing methanol fuel stoves in the South African context.

The testing protocols were developed to address questions related to the stove testing industries regarding the performance of stoves with different combinations, stove/fuel/pot. The developed standard testing protocol is termed the Water Heating Test (WHT) protocol. Furthermore, it is termed a WHT rather than a Water Boiling protocol as it does not involve heating the water to boiling water. With modifications derived from tests conducted as part of this thesis, the protocols have been adopted in the SABS draft standard, later published as a SABS standard.

5.1.2 Investigate the radiative and conductive heat losses in determining cooking power.

Many studies and experiments have been conducted to determine the cooking power of stoves. However, most of the studies have neglected the effect of thermodynamics on the performance of the stoves. This section investigated the influence of the radiative and convective heat losses on the stove performance. The heating and cooling curves were derived and combined to deduce the corrected *total cooking power* of the fuel/stove combination and demonstrate that it is constant, irrespective of the pot temperature. However, the expected *corrected total cooking power* deviated from the expected constant value due to perturbations from condensation forming during the initial warming. The water from the condensation resulted in an interruption of heat transfer within the system. Consequently, there was inconsistency in the heating rate, resulting in reduced heat transfer. The heat transfer was observed stabilising as the temperature rose above 60ºC. This phenomenon was a notable limitation for this part of the study. Therefore, it is difficult to conclude the extent to which radiative and conductive losses impact the performance of the stoves as the condensation, and radiative losses are of a similar magnitude.

5.1.3 Testing the safety and use, thermal performance, emission performance of three differently designed methanol fuel stoves using the developed standard

i. Safety

Several safety aspects of the methanol stoves and the reference paraffin wick stove were assessed. The procedures were adopted from the developed SABS draft standard for methanol fuelled appliances. This required evaluating surface temperatures, evaporation losses during operational and storage periods, fuel losses from a stove upset at 90º and 180 º, sharp points, and portability.

The touchable parts of the power adjustment levers were found to have temperatures exceeding the limit of 42°C, therefore failing the test. The fuel evaporation losses of all the stoves were within the limit set in the draft standard, indicating reduced risks relating to inhalation.

For the fuel spillage test, with the stoves tipped through 90º, the methanol stoves had high fuel losses when the air inlet tube was orientated at the lowest point, where the fuel level was above the outlet. The paraffin stove had immediate spillage when the fuel tank opening positioned at the lowest position, even though the tank closure was in position and tightened; the leak from the fuel inlet cap shows design or manufacturing defect. At a 180º upset angle, the stoves had minimal fuel loss, except for one of the methanol stoves.

Regarding snagging, the methanol stoves proved safe as they had no sharp points or edges that could catch on clothes or lead to cut-related injuries. The same was observed with the paraffin stove.

ii. Thermal performance and controllability

An assessment was performed on three methanol fuel stoves that are within the South African market. A paraffin wick type stove was used as a baseline. The Water Heating Test adopted from the SABS draft standard for methanol fuel appliances was used. The results showed that the paraffin stove had superior thermal power with all stove/fuel/pot combinations. However, the methanol stoves were superior to the paraffin stove with all stove/fuel/pot type and size combinations in terms of efficiency. All three methanol stoves had an equivalent time to boil less than 10 minutes, an acceptable performance range for the targeted South African domestic market.

Low power results were incorporated in determining the Turn-Down Ratio (TDR) metric used to evaluate the stove's ability to operate at low power for simmering. The methanol stoves had better controllability compared to the paraffin stove. With all stove/fuel/pot combinations, the paraffin stove failed to produce the required TDR per the draft standard.

iii. Emission performance

Relative Carbon monoxide Emissions from methanol fuel stoves and baseline paraffin wick stove were investigated. The tests were conducted using the WHT, performed simultaneously with the thermal performance tests. During the ignition stage, a rise in emissions was observed from two methanol stoves (STV01 and STV02) and the paraffin stove. However, the emissions were stabilising at about the middle of the 0.5 hr test. Moisture forming around the sides and at the bottom of the pot during the initial combustion phase was responsible for the observed high emissions. As the water formed from the moisture completely evaporated, the emissions reduced before stabilising.

Comparing the methanol fuel stoves and paraffin stove showed that methanol stoves have lower emissions than the paraffin stove. One of the methanol stoves was able to adhere to the CO/CO_2 emission limit, as stated in the SABS 1906 (a standard for the safety and emission limits for paraffin stoves). While other methanol fuel stoves (STV01 and STV02) were sometimes able to adhere to particular stove/pot combinations, the paraffin stove failed with all stove/pot combinations.

iv. Influence of pot size and external finish (shiny Al or matt black) on the thermal and emission performance of the stove/fuel/pot combination.

The pot size and type influences on the thermal and emission performance was investigated on methanol stoves and a baseline paraffin stove. The **pot size** had a slight influence on the thermal performance of the methanol stoves at high power. Higher cooking powers were observed for the paraffin stove at high and low power, respectively, using either the large shiny pot or the medium black pot. In contrast, the **pot type** (shiny or black) had no significant influence on thermal power or cooking power for the methanol stoves and the baseline paraffin stove.

Similarly, the pot size significantly influenced the methanol stoves' emission performance at high power. The type of pot had no significant influence on emissions - emissions above the 2% $CO/(CO_2 + CO)$ limit were observed with shiny and black small pots. Emissions varied slightly with the large and medium size of both pot types. With either the large shiny or black pot, low emissions were reported at low and high power for all stoves. Overall, pot size has shown to influence emissions.

5.2 Conclusion

The study involved the development of a standard test protocol for methanol fuel stoves. The standard was further used to conduct performance tests on methanol stoves and a paraffin wick stove as a baseline. Conducting these performance tests was a way to assess the test methods' applicability in the draft SABS standard for methanol fuelled stoves. According to the successful tests conducted, it was evident that the tests methods are applicable and can be replicable in an appropriately equipped laboratory. The compiled test protocols involve assessing the safety and use, thermal performance and emission performance. The test protocol is termed the *Water Heating Test (WHT)*.

Using the derived WHT, initial tests were conducted to assess the influence of radiative and conductive heat losses on the stove performance. This involved assessing whether the different external finish of the pots influences the cooking power. It is well known that dark colours better absorb and radiate heat, while light colours or shiny metal surfaces radiate less. The results have shown that the external finish (matt black or shiny aluminium) had minor influences on the stove performance. However, condensation on the outside of the pots was observed during the ignition phases of the tests. This phenomenon had a significant perturbing influence on the heat transfer over a test sequence.

The safety and use of the stoves were evaluated. The methanol stoves were assessed as user-friendly, posing few safety-related issues. Fuel spillage and evaporation from the stoves were low, and most of the stoves passed these tests, except one methanol stove. The methanol stoves had low fuel spillage, indicating that methanol fuelled stoves would be a safe technology. Therefore, methanol fuel and methanol fuel stoves are considered viable alternatives to mitigate the fire hazards associated with paraffin stoves.

The WHT was used to assess the methanol cookstoves thermal and emission performance and compare them to a baseline paraffin stove. The results have demonstrated that all three methanol stoves have slightly lower thermal power and a longer time to boil than the paraffin stove. This was expected as the energy density of methanol is only ~60% of that of paraffin. Nevertheless, the specific time to boil for two of the methanol stoves are within ten minutes which market surveys determine is the maximum limit expected by consumers. The thermal power differs between the methanol stoves, indicating an opportunity for design optimisation by manufacturers.

Although the paraffin stove had higher thermal and cooking power than methanol stoves, it had lower thermal efficiency and higher CO emissions. The methanol stove and pot combinations had significantly lower CO emissions than the paraffin stove, indicating that the methanol stoves are an inherently improved technology on this criterion. Although not measured in this project, it is worth noting that methanol combustion cannot produce black carbon particulate matter and is superior to paraffin also in this respect.

There was a notable influence on the thermal performance due to pot size rather than the external finish. The bigger the pot, the higher the thermal efficiency depending on the power setting. The observation in this study indicates that conducting the performance test at different power settings with different pot types and size combinations provides comprehensive analysis and assessment. Consequently, thorough knowledge and understanding are gained about the parameters that influence the stove's performance (Makonese et al., 2020). The influence on the thermal and emission performance was observed on the stoves depending on the power setting.

The study has shown that methanol stove performance is highly dependent on stove/fuel/pot size combinations. Nevertheless, the overall assessment is that methanol fuel and methanol stoves are a suitable alternative to replace paraffin stove use, having adequate performance to satisfy user requirements while presenting inherently lower accidental fire hazards.

5.3 Recommendations

Several recommendations can be made to improve the safety and overall performance of the methanol stoves. Further investigations of methanol stove designs and safety aspects are needed, including corrosion resistance, durability, conflagration and stability. The South African Bureau of Standards is engaged in developing a safety and performance standard for methanol appliances that will address all these issues comprehensively, facilitating the manufacture and marketing of methanol stoves as a viable substitute for paraffin wick stoves. Further design improvements are needed to bring the carbon monoxide emissions within the health safety limits. "*Nevertheless, if these challenges can be appropriately addressed, a case can be made for developing methanol stoves and a marketing distribution chain for the fuel, based on social, utility, safety and economic criteria"* (Makonese et al., 2020:14).

Considering that Water Heating Test is a laboratory-based method, it does not attempt to replicate real-world use. Field-based testing will be required to determine contextual use of methanol stove/fuel performance and user acceptance of the new technology.

References

Abeliotis, K. and Pakula, C., 2013. 'Reducing health impacts of biomass burning for cooking—The need for cookstove performance testing.' *Energy Efficiency*, **6(3)**: 585-594.

Afrane, G. and Ntiamoah, A., 2011. 'Comparative life cycle assessment of charcoal, biogas, and liquefied petroleum gas as cooking fuels in Ghana.' *Journal of Industrial Ecology*, **15(4):** 539-549.

Ahuja, D.R., Joshi, V., Smith, K.R. and Venkataraman, C., 1987. 'Thermal performance and emission characteristics of unvented biomass-burning cookstoves: a proposed standard method for evaluation.' *Biomass*, **12(4)**:247-270.

Albers, P.N., Wright, C.Y., Voyi, K.V. and Mathee, A., 2015. 'Household fuel use and child respiratory ill health in two towns in Mpumalanga, South Africa.' *South African Medical Journal*, **105(7)**: 573-577.

Alberts, H., Moreira, C. and Pérez, R.M., 1997. 'Firewood substitution by kerosene stoves in rural and urban areas of Nicaragua, social acceptance, energy policies, greenhouse effect and financial implications.' *Energy for Sustainable Development*, **3(5)**: 26-39.

Amegah, A.K. and Jaakkola, J.J., 2016. 'Household air pollution and the sustainable development goals.' *Bulletin of the World Health Organisation*: **94(3)**: 215-221.

AWBT, 2.0, 2010. Adapted water boiling test. https://www.cleancookingalliance.org/binary-data/DOCUMENT/file/000/000/75-1.pdf Accessed 05 June 2021

Ballard-Tremeer, G. and Jawurek, H.H., 1996. 'Comparison of five rural, wood-burning cooking devices: efficiencies and emissions.' *Biomass and Bioenergy*, **11(5)**: 419-430.

Balmer, M., 2007. 'Household coal use in an urban township in South Africa.' *Journal of Energy in Southern Africa*, **18(3)**: 27-32.

Barnes, B., Mathee, A., Thomas, E. and Bruce, N., 2009. 'Household energy, indoor air pollution and child respiratory health in South Africa.' *Journal of Energy in Southern Africa*, **20(1)**: 4-13.

Barnes, D.F. and Floor, W.M., 1996. 'Rural energy in developing countries: a challenge for economic development.' *Annual Review of Energy and the Environment*, **21**: 497-530.

Barnes, D.F. and Qian, L., 1992. 'Urban Interfuel Substitution, Energy Use, and Equity in Developing Countries.' Report No. 11336, Industry and Energy Department Working Paper, Energy Series Paper No. 53, The World Bank, Washington D.C., March 1992. 38 https://www.researchgate.net/publication/5077912_Urban_Interfuel_Substitution_Energy_Use_and_Equity_in_Developing_Countries. Accessed 04 Jun 2021.

Basu, D., Saha, R., Ganguly, R. and Datta, A., 2008. 'Performance improvement of LPG cook stoves through burner and nozzle modifications.' *Journal of the Energy Institute*, **81(4)**: 218-225.

Berrueta, V.M., Edwards, R.D. and Masera, O.R., 2008. 'Energy performance of wood-burning cookstoves in Michoacan, Mexico.' *Renewable Energy*, **33(5)**: 859-870.

Chidhindi, P., Belelie, M.D., Burger, R.P., Mkhatshwa, G. and Piketh, S.J., 2019. 'Assessing the impact of Eskom power plant emissions on ambient air quality over KwaZamokuhle.' *Clean Air Journal*, **29(1)**: 29-37.

Chilcott, R.P., 2006. 'Compendium of chemical hazards: kerosene (fuel oil).' Chilton, Oxfordshire, UK: Chemical Hazards and Poisons Division (HQ), Health Protection Agency. 31 pp. Available from https://www.who.int/ipcs/emergencies/kerosene.pdf. Accessed 02 March 2020.

Dasgupta, S., Martin, P. and Samad, H.A., 2013. 'Addressing household air pollution: a case study in rural Madagascar.' Policy Research Working Paper WPS6627, Washington D.C.: The World Bank, Africa Region, 20 pp.

Davis, M., 1998. 'Rural household energy consumption: the effects of access to electricity—evidence from South Africa.' *Energy Policy*, ***26*(3)**: 207-217.

DEA, 2016, 'Draft strategy for addressing air pollution in dense low- income communities. Government Gazette No. 40088, 24 June 2016', https://www.environment.gov.za/sites/default/files/gazetted_notices/airpollution_strategy_g40088_gen356_0.pdf Access 04 June 2021.

Dioha, I.J., Ikeme, C.H., Tijjam, N. and Dioha, E.C., 2012. 'Comparative studies of ethanol and kerosene fuels and cook stove performance.' *Journal of Natural Sciences Research*, **2(6)**: 34-39.

Engineering ToolBox, 2001. 'Tools and basic information for design, engineering and construction of technical applications.' https://www.engineeringtoolbox.com/combustion-boiler-fuels-t_9.html 06 November 2019.

EPA, 2021. 'From Air Quality to Zero Emissions.' Environmental Protection Agency. https://www.epa.ie/footer/a-zglossaryofenvironmentalterms/ Accessed 18 February 2021.

EPTP, 2009. 'A protocol for testing stove fuel efficiency and emissions and a standard for improved stoves.' Emissions & Performance Test Protocol. https://www.cleancookingalliance.org/binary-data/DOCUMENT/file/000/000/73-1.pdf Accessed 05 June 2021

Francioli, A.P., 2011, 'Investigating energy usage among low income households and implications for fire risk.' MSc Thesis, Stellenbosch University, South Africa.

Gallagher, M., Beard, M., Clifford, M.J. and Watson, M.C., 2016. 'An evaluation of a biomass stove safety protocol used for testing household cookstoves, in low and middle-income countries.' *Energy for Sustainable Development*, **33**: 14-25.

Gevaart-Durkin, A., Swart, D. and Chowdhury, Z., 2014. 'A study of energy-related injuries from hospital admissions among children and adults in *South Africa.' Burns*, **40(6)**: 1209-1218.

Hagen, D.L., 1977. 'Methanol as a fuel: a review with bibliography.' *SAE Transactions*, **86(4)**: 2764-2796. http://www.jstor.org/stable/44644586. Accessed 11 March 2021

Heltberg, R., 2004. 'Fuel switching: evidence from eight developing countries.' Energy Economics, 26(5): 869-887.

Hernández, D., 2016. Understanding 'energy insecurity' and why it matters to health. *Social Science and Medicine*, 167, 1-10.

Hildemann, L.M., Markowski, G.R., Jones, M.C. and Cass, G.R., 1991. 'Submicrometer aerosol mass distributions of emissions from boilers, fireplaces, automobiles, diesel trucks, and meat-cooking operations.' *Aerosol Science and Technology*, **14(1)**: 138-152.

HTP 1.05, 2012. 'The Heterogeneous Testing Procedure For Thermal Performance and Trace Gas Emissions.' Heterogeneous Testing Procedure. https://www.cleancookingalliance.org/binary-data/DOCUMENT/file/000/000/74-1.pdf Accessed 05 June 2021

IEA and World Bank, 2014. 'Sustainable Energy for All 2013-2014: Global Tracking Framework Report.' Washington D.C.: International Energy Agency and The World Bank. 292 pp. https://openknowledge.worldbank.org/handle/10986/16537. Accessed 11 March 2021.

Indonesian Clean Stove Initiative Water Boiling Test, 2014. 'Indonesian Clean Stove Initiative Pilot Programme Water Boiling Test Methods and Product Evaluation Criteria.' https://www.cleancookingalliance.org/binary-data/DOCUMENT/file/000/000/87-1.pdf Accessed 05 June 2021

Ismail, Z. and Khembo, P., 2015. 'Determinants of energy poverty in South Africa.' *Journal of Energy in Southern Africa*, **26(3)**: 66-78.

ISO, 2012. 'Guidelines for evaluating cookstove performance.' Guideline Document IWA 11:2012. Geneva: International Organisation for Standardisation https://www.iso.org/obp/ui/#iso:std:iso:iwa:11:ed-1:v1:en. Accessed 18 February 2021.

ISO, 2018. 'Clean cookstoves and clean cooking solutions — Harmonized laboratory test protocols — Part 1: Standard test sequence for emissions and performance, safety and durability.' Standard Document ISO 19867-1:2018. Geneva: International Organisation for Standardisation https://www.iso.org/obp/ui/#iso:std:iso:19867:-1:ed-1:v1:en Accessed 18 February 2021.

Jetter, J.J. and Kariher, P., 2009. 'Solid-fuel household cook stoves: Characterization of performance and emissions.' *Biomass and Bioenergy*, **33(2)**: 294-305.

Johnson, M., Edwards, R., Berrueta, V. and Masera, O., 2010. 'New approaches to performance testing of improved cookstoves.' *Environmental Science and Technology*, **44(1)**: 368-374.

Johnson, N.G. and Bryden, K.M., 2015. 'Field-based safety guidelines for solid fuel household cookstoves in developing countries.' *Energy for Sustainable Development*, ***25***: 56-66.

Johnson, N.G., Bryden, K.M. and Xiao, A., 2005. 'Reconsidering the stove design process: some proposed safety guidelines.' Paper presented to the ETHOS Conference, Kirkland, WA, January 2005. 23 pp. http://ethoscon.com/pdf/ETHOS/ETHOS2005/pdf/bryden1.pdf Accessed 05 Jun 2020.

Khopkar, A., 2011. 'The past, present, and future of improved cookstoves initiatives.' Website developed by Akhilesh Khopkar, Master of Natural Resources Student, North Carolina State University. https://sites.google.com/a/ncsu.edu/khopkarworldforestry. Accessed 06 November 2019.

Kimemia, D. and Annegarn, H., 2016. 'Domestic LPG interventions in South Africa. Challenges and lessons.' *Energy Policy*, **93**: 150-156.

Kimemia, D. and Van Niekerk, A., 2017. 'Cookstove options for safety and health: Comparative analysis of technological and usability attributes.' *Energy Policy*, ***105***: 451-457.

Kimemia, D., 2012. 'Energy poverty: Reconciling safety and health dimensions in South Africa.' Final report, IIASA South African – Young Scientist Summer Program, Bloemfontein. 20 pp. https://www.researchgate.net/publication/236902326_Energy_Poverty_Reconciling_Safety_and_Health_Dimensions_in_South_Africa. Accessed 11 March 2021.

Kimemia, D., Vermaak, C., Pachauri, S. and Rhodes, B., 2014, 'Burns, scalds and poisonings from household energy use in South Africa: Are the energy poor at greater risk?' *Energy for Sustainable Development*, **18**: 1-8.

Kimemia, D.K. and Annegarn, H.J., 2014, 'Energy access and household risk transitions in South Africa.' Twenty-Second International Conference on the Domestic Use of Energy, Cape Town, *IEEE Xplore:* doi: 10.1109/DUE.2014.6827757, 7 pp.

Kimemia, D.K. and Van Niekerk, A., 2017. 'Energy poverty, shack fires and childhood burns.' *South African Medical Journal*, **107(4)**: 289-291.

Kruger, G., 2006, 'Firebomb kerosene stoves without social bounds – addressing energy poverty in South Africa.' Fourteenth Conference on the Domestic Use of Energy, 2006. Cape Peninsula University of Technology, Cape Town.

Kshirsagar, M.P. and Kalamkar, V.R., 2014. 'A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design.' *Renewable and Sustainable Energy Reviews*, **30**: 580-603.

KTP 4.0, 2018. 'Kitchen Performance Test.' https://www.cleancookingalliance.org/binary-data/DOCUMENT/file/000/000/604-1.pdf Accessed 05 June 2021

Labhsetwar, N.K., Motghare, K.A., Rathod, A.P., Waghmare., S.S. and Wasewar., KL., 2015. 'Performance evaluation and heat transfer studies on biomass gasifier cook-stove.' *International Journal of Application or Innovation in Engineering & Management (IJAIEM),* **4(5)**: 352-361.

Lam, N.L., Smith, K.R., Gauthier, A. and Bates, M.N., 2012. 'Kerosene: a review of household uses and their hazards in low-and middle-income countries.' *Journal of Toxicology and Environmental Health, Part B*, **15(6)**: 396-432.

Langerman, K.E., Pauw, C.J., Smith, H.J. and Piketh, S.J., 2018. 'Moving households to cleaner energy through air quality offsets.' 2018 International Conference on the Domestic Use of Energy (DUE), Cape Town, South Africa, *IEEE Xplore:* doi: 10.23919/DUE.2018.8384405, 8 pp.

Language, B., Piketh, S.J., Wernecke, B. and Burger, R., 2016. ‘Household air pollution in South African low-income settlements: a case study.’ *WIT Transactions on Ecology and the Environment*, **207:** 227-236.

Lloyd, P., 2014, ‘A pilot test of ethanol gel as a paraffin replacement in a low-income urban environment.’ *Journal of Energy in Southern Africa,* **18(4)**:26–31. DOI: 10.17159/2413-3051/2007/v18i4a3392

Lloyd, P., 2014. ‘The energy profile of a low-income urban community.’ Twenty-second Conference on the Domestic Use of Energy, Cape Town, South Africa, 2014, *IEEE Xplore:* doi: 10.1109/DUE.2014.6827762, 6 pp.

Lloyd, P.J. and Truran, G., 2008. ‘Safe paraffin appliances and their contribution to demand side management.’ Sixteenth Conference on the Domestic Use of Energy, Cape Peninsula University of Technology, Cape Town. 4 pp.

Lloyd, P.J., 2002. ‘The safety of paraffin and LPG appliances for domestic use.’ Tenth Conference on the Domestic Use of Energy, Cape Peninsula University of Technology, Cape Town, pp. 79-84.

Lloyd, P.J.D. and Visagie, E.F., 2007. ‘The testing of gel fuels, and their comparison to alternative cooking fuels.’ *Journal of Energy in Southern Africa,* **18(4)**: 26–31. DOI: http://dx.doi.org/10.17159/2413-3051/2007/v18i4a3392.

Log, T. and Moi, A.L., 2018. ‘Ethanol and methanol burn risks in the home environment.’ *International Journal of Environmental Research and Public Health*, **15(11)**: 2379. https://doi.org/10.3390/ijerph15112379.

Ludwig, J., Marufu, L.T., Huber, B., Andreae, M.O. and Helas, G., 2003. ‘Domestic combustion of biomass fuels in developing countries: A major source of atmospheric pollutants.’ *Journal of Atmospheric Chemistry*, **44(1)**: 23-37.

MacCarty, N., Still, D. and Ogle, D., 2010, ‘Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance.’ *Energy for Sustainable Development*, **14(3)**:161-171.

Makonese, T. and Bradnum, C.M., 2018. ‘Design and performance evaluation of wood-burning cookstoves for low-income households in South Africa.’ *Journal of Energy in Southern Africa*, **29(4)**: 1-12.

Makonese, T., 2011, ‘Protocols for thermal and emissions performance testing of domestic fuels and stoves.’ MSc Thesis, University of Johannesburg, South Africa.

Makonese, T., Annegarn, H.J. and Meyer, J., 2020. ‘Performance evaluation of three methanol stoves using a contextual testing approach.’ *Energy for Sustainable Development*, **55**: 13-23.

Makonese, T., Pemberton-Pigott, C., Robinson, J., Kimemia, D. and Annegarn, H., 2012. ‘Performance evaluation and emission characterisation of three kerosene stoves using a Heterogeneous Stove Testing Protocol (HTP).’ *Energy for Sustainable Development*, **16(3)**: 344-351.

Masekameni, M.D., Makonese, T. and Annegarn, H.J., 2015. 'A comparison of emissions and thermal efficiency of three improved liquid fuel stoves.' 2015 International Conference on the Domestic Use of Energy (DUE), 71-76**.** *IEEE Xplore,* DOI: 10.1109/DUE.2015.7102965.

Matzopoulos, R. and Carolissen, G., 2006. Estimating the incidence of paraffin ingestion: original contribution. *African Safety Promotion*, **4(3)**, 4-14.

Methanol Institute., 2021. 'About methanol.' https://www.methanol.org/about-methanol/ Accessed 09 March 2021.

Mohlakoana, N. and Annecke, W., 2009. 'The use of liquefied petroleum gas by South African low-income urban households: A case study.' *Journal of Energy in Southern Africa*, **20(4)**: 3-10.

Moran, M.J., Shapiro, H.N., Boettner, D.D. and Bailey, M.B., 2010. '*Fundamentals of Engineering Thermodynamics*.' Hoboken, NJ: John Wiley & Sons.

Motghare, K.A., Rathod, A.P., Waghmare, S.S., Wasewar, K.L., Labhsetwar, N.K., 2015. 'Performance evaluation and heat transfer studies on biomass gasifier cook-stove.' *International Journal of Application or Innovation in Engineering and Management (IJAIEM)*, **4(5)**: 352-361.

Muller, E., Diab, R.D., Binedell, M. and Hounsome, R., 2003. 'Health risk assessment of kerosene usage in an informal settlement in Durban, South Africa.' *Atmospheric Environment*, **37(15)**: 2015-2022.

Naidoo, S., Piketh, S. and Curtis, C., 2015. 'Domestic fuel combustion in un-electrified low-income settlements in South Africa.' International Emission Inventory Conference 2015, San Diego, CA. 21 pp. https://19january2017snapshot.epa.gov/sites/production/files/2015-09/documents/naidoo.pdf.

NIOSH, 2019. 'Methyl Alcohol (Methanol).' National Institute for Occupational Safety and Health. https://www.cdc.gov/niosh/topics/methyl-alcohol/default.html Accessed 12 March 2021

Nkosi, N.C., 2017. 'Quantifying particulate emissions from domestic burning in the kwaDela township, Mpumalanga. MSc thesis, North-West University, South Africa.

Nkosi, N.C., Piketh, S.J. and Burger, R.P., 2018. 'Fine PM emission factors from residential burning of solid fuels using traditional cast-iron coal stoves.' *Clean Air Journal*, 28(1): 35-41.

Okusanya, M.A., Ibrahim, G.W. and Ogunlade, C.B., 2019. 'The Use of Ethanol Gel Cook-Stove as a more Accessible Alternative Cooking Energy.' *International Journal of Engineering Science Invention (IJESI)*, **8(10)**: 15-22.

OpenStax, 2015. 'Mechanism of Heat Transfer.' https://opentextbc.ca/universityphysicsv2openstax/chapter/mechanisms-of-heat-transfer/ Accessed 20 July 2020

Pailman, W., De Groot, J., Clifford, M., Jewitt, S. and Ray, C., 2018. 'Experiences with improved cookstoves in Southern Africa.' *Journal of Energy in Southern Africa*, **29(4)**: 13-26.

Peck, M.D., Kruger, G.E., van der Merwe, A.E., Godakumbura, W., Oen, I.M., Swart, D. and Ahuja, R.B., 2008, 'Burns and injuries from non-electric-appliance fires in low-and middle-income countries: Part II. A strategy for intervention using the Haddon Matrix.' *Burns*, **34(3)**:312-319.

Prinsloo, T., 2018. 'The effect of particle size on performance of low-smoke fuels in coal stoves.' MSc Thesis, North-West University, South Africa.

Putti, V.R., Tsan, M., Mehta, S., Kammila, S., 2015. 'The State of the Global Clean and Improved Cooking Sector.' ESMAP Technical Paper No. 007/15. Washington, D.C.: World Bank. https://openknowledge.worldbank.org/handle/10986/21878. Accessed 02 November 2019.

Qhekwana, M., Letsholo, T., Burger, R.P. and Piketh, S.J., 2017. 'The relationship between thermal comfort and indoor PM 4 mass concentration within low-cost houses in Ikageng.' 2017 International Conference on the Domestic Use of Energy (DUE), Cape Town, *IEEE Xplore*: doi: 10.23919/DUE.2017.7931821, pp. 30-37.

Quinn, A.K., Bruce, N., Puzzolo, E., Dickinson, K., Sturke, R., Jack, D.W., Mehta, S., Shankar, A., Sherr, K. and Rosenthal, J.P., 2018. 'An analysis of efforts to scale up clean household energy for cooking around the world.' *Energy for Sustainable Development*, **46**: 1-10.

Rajabu, H., Rweyemamu, L., Sago, S., Sawe, E., Laswai, E., Matimbwi, M., Lelievre, M., Magessa, F., 2014. 'Country action plan for clean cookstoves and fuels.' https://www.tarea-tz.org/storage/app/media/Blog/ICS%20Country%20Action%20Plan.pdf Accessed 06 November 2019.

Rani, C.S., Kandpal, T.C., Mullick. S.C., 1992. 'Preliminary study of water boiling test procedures used for performance evaluation of fuelwood cookstoves', *Energy Conversion and Management*, **33(10)**: 919-929.

Reddy, A.K.N., Reddy, S.B., 1994. 'Substitution of energy carriers for cooking in Bangalore.' *The International Journal of Energy,* **19(5)**: 561–572.

Roberts, E. and Wentzel, M., 2006. 'Household paraffin consumption in four areas: Benoni, Galeshewe, Gugulethu and Lady Grey.' *Journal of Energy in Southern Africa*, **17(2)**: 23-26.

Robinson J., Ibraimo M., Pemberton-Pigott C., 2011. 'The uncontrolled cooking test: Measuring three-stone fire performance in northern Mozambique.' Proceedings of the 19th International Conference Domestic Use of Energy, 12-13 April, Cape Town. ISBN 978-0-9814311-4-7, pp. 71-78.

Roden, C.A., Bond, T.C., Conway, S. and Pinel, A.B.O., 2006. 'Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves.' *Environmental Science and Technology*, **40(21)**: 6750-6757.

Rohsenow, W.M., Hartnett, J.P. and Cho, Y.I., 1998. '*Handbook of Heat Transfer (Vol. 3)*.' New York: McGraw-Hill.

Runsten, S., 2015. 'Energy provision and informality in South African informal urban settlements: A multi-criteria sustainability assessment of energy access alternatives.' BSc Thesis, KTH Royal Institute of Technology, Sweden.

SABS, 2017. 'Standard development process.' *South African Bureau of Standards* http://sabs.westeurope.cloudapp.azure.com/services/standards/standards-development-process Accessed 26 November 2020

SANS 1906:2009. 'Non-pressure paraffin stoves and heaters.' *South African Bureau of Standards,* Pretoria, South Africa

Schwebel, D.C., Swart, D., Hui, S.K.A., Simpson, J. and Hobe, P., 2009. 'Paraffin-related injury in low-income South African communities: Knowledge, practice and perceived risk.' *Bulletin of the World Health Organization*, **87**: 700-706.

Shezi, B. and Wright, C.Y., 2018. 'Household air pollution exposure and respiratory health outcomes: a narrative review update of the South African epidemiological evidence.' *Clean Air Journal*, **28(1)**: 43-56.

Solid Biomass Chulha-Specification, 1991. Indian Standard on Solid Biomass Chulha-Specification. https://www.cleancookingalliance.org/binary-data/DOCUMENT/file/000/000/78-1.pdf Accessed 05 June 2021

Stats SA, 2019. 'General Household Survey 2018.' Statistical Release P0318. Pretoria: Statistics South Africa, 191 pp. http://www.statssa.gov.za/publications/P0318/P03182018.pdf. Accessed 18 February 2020.

Stats SA, 2020. '2020 Mid-year population estimates.' Statistical Release P0302. Pretoria: Statistics South Africa, http://www.statssa.gov.za/?p=13453 Accessed 02 February 2021.

Still, D., Bentson, S. and Li, H., 2015. 'Results of laboratory testing of 15 cookstove designs in accordance with the ISO/IWA tiers of performance.' *EcoHealth*, **12(1)**:12-24.

Stokes, H. and Ebbeson, B., 2005. 'Project Gaia: Commercialising a new stove and new fuel in Africa.' *Boiling Point*, **50**: 31-33.

Stokes, H.C. and Crocco, J.R., 2005, 'The reality of methanol fuel use as a cooking fuel in developing countries.' https://projectgaia.com/wp-content/uploads/2013/10/The-Reality-of-Methanol-Use-as-a-Cooking-Fuel-in-Developing-Countries-2005.pdf. Accessed 26 October 2020

Swart, D. and Bredenkamp, B., 2012. 'The challenge of addressing household energy poverty.' Conference *Strategies to Overcome Poverty and Inequality Conference -Towards Carnegie III,* Cape Town, 2-3 September 2012,http://www.mandelainitiative.org.za/images/docs/2012/papers/258%20THE%20CHALLENGE%20OF%20ADDRESSING%20HOUSEHOLD%20ENERGY%20POVERTY%20(FINAL).pdf, 11 pp.

Tait, L., Merven, B. and Senatla, M., 2013. 'Investigating the current and future roles of paraffin in South Africa.' Contract final report, Cape Town: Energy Research Centre, University of Cape Town, 56 pp. https://open.uct.ac.za/bitstream/handle/11427/16879/Tait_Investigating_current_2013.pdf?sequence=1 Accessed 14 January 2020

Tibbutt, D., 2011. "How to treat kerosene (paraffin) poisoning." *South Sudan Medical Journal*, 2011 November, 1 p. Online at http://www.southsudanmedicaljournal.com/archive/november-2011/how-to-treat-kerosene-paraffin-poisoning.html. Retrieved 11 March 2021.

Utria, B.E., 2004. 'Ethanol and gel fuel: clean renewable cooking fuels for poverty alleviation in Africa.' *Energy for Sustainable Development*, **8(3)**: 107-114.

Van der Kroon, B., Brouwer, R. and van Beukering, P.J., 2013. 'The energy ladder: Theoretical myth or empirical truth? Results from a meta-analysis.' *Renewable and Sustainable Energy Reviews*, **20**: 504-513.

Van Niekerk, A., Laubscher, R. and Laflamme, L., 2009. 'Demographic and circumstantial accounts of burn mortality in Cape Town, South Africa, 2001-2004: An observational register based study.' *BMC Public Health*, **9(1)**: 1-10.

Visagie, E., 2008. 'The supply of clean energy services to the urban and peri-urban poor in South Africa.' *Energy for Sustainable Development*, **12(4)**:14-21.

Visser, P., 2005. 'The testing of cookstoves: data of water-boiling tests as a basis to calculate fuel consumption.' *Energy for Sustainable Development*, **9(1)**: 16-24.

Walls, R.S., Eksteen, R., Kahanji, C. and Cicione, A., 2019. 'Appraisal of fire safety interventions and strategies for informal settlements in South Africa.' *Disaster Prevention and Management,* **28(3)**: 343-358.

WBA, 2016. 'Clean and efficient bioenergy cookstoves.' Factsheet. Stockholm: World Bioenergy Association. https://worldbioenergy.org/uploads/Factsheet%20-%20Cookstoves.pdf, 6 pp. Accessed 06 November 2019.

WBT 4.2.3, 2014. 'Cookstove Emissions and Efficiency in a Controlled Laboratory Setting.' Water Boiling Test. https://www.cleancookingalliance.org/binary-data/DOCUMENT/file/000/000/399-1.pdf. Accessed 19 March 2021

WHO, 2014. 'WHO guidelines for indoor air quality: household fuel combustion.' Word Health Organisation https://www.who.int/airpollution/guidelines/household-fuel-combustion/IAQ_HHFC_guidelines.pdf Accessed 10 October 2020

WHO, 2018. 'Household air pollution.' Word Health Organisation https://www.who.int/en/news-room/fact-sheets/detail/household-air-pollution-and-health Accessed 31 Aug 2020.

Winrock International, 2017. 'Clean and efficient cooking technologies and fuels.' https://www.usaid.gov/sites/default/files/documents/1865/cookstoves-toolkit-2017-mod8-collaboration.pdf. Accessed 06 November 2019

Zhang, J. and Smith, K.R., 2007. ‘Household air pollution from coal and biomass fuels in China: Measurements, health impacts, and interventions.’ *Environmental Health Perspectives*, **115(6)**: 848-855.

Zhang, Y., Pemberton-Pigott, C., Zhang, Z., Ding, H., Zhou, Y. and Dong, R., 2014. ‘Key differences of performance test protocols for household biomass cookstoves.’ Twenty-Second Conference on the Domestic Use of Energy, Cape Town, South Africa, 2014, *IEEE Xplore*: doi: 10.1109/DUE.2014.6827753, 11 pp.

Zhang, Z., Zhang, Y., Zhou, Y., Ahmad, R., Pemberton-Pigott, C., Annegarn, H. and Dong, R., 2017. ‘Systematic and conceptual errors in standards and protocols for thermal performance of biomass stoves.’ *Renewable and Sustainable Energy Reviews*, **72**: 1343-1354.

Zube, D.J., 2010. ‘Heat transfer efficiency of biomass cookstoves.’ MSc thesis, Colorado State University, Colorado, United States.