Development and Performance Evaluation of Methanol and Ethanol Operated Cookstoves

A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

by

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STATEMENT

This is to certify that the research work presented in this thesis entitled "**Development and Performance Evaluation of Methanol and Ethanol Operated Cookstoves**" has been carried out by me at the School of Energy Science and Engineering, Indian Institute of Technology Guwahati, under the esteemed supervision of Prof. P. Muthukumar and Dr. R. Anandalakshmi.

I hereby assure that there is no conflict of interest related to the research work and the results presented in this thesis were obtained by me and have not been submitted to any other Institute or University for the award of any other degree or diploma.

As per the general practice and ethics of reporting scientific information, due acknowledgements and citations have been made wherever the work described is based on the findings of other investigations.

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THESIS CERTIFICATE

It is certified that the work embodied in the thesis entitled **Development and Performance Evaluation of Methanol and Ethanol Operated Cookstoves** by **Pratibha Maurya**, a student in the School of Energy Science and Engineering, Indian Institute of Technology Guwahati, India, for the award of the degree of the **Doctor of Philosophy** has been carried out under my supervision and that the work has not been submitted elsewhere for the grant of any other degree.

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My family and Shri Krishna

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Abstract

In developing countries, about 2.8 billion people live in energy deficient region and risking their lives every day while cooking in a hazardous environment due to the use of solid fuels such as firewood, crop waste and dung. Liquid and gaseous fuels are often seen as clean cooking solutions and use of these fuels significantly alleviates the health hazards posed by indoor air pollution. Nearly 40 % of the world's population lack access to clean cooking fuels and technologies. For instance, in India, although a growing number of households are converting to non-solid fuels for cooking, still 44 % of households rely on firewood, cow dung cakes, kerosene and agricultural residues. World Health Organisation (WHO) guidelines for indoor air pollution from household fuel combustion differentiates cooking fuels and technologies as clean and polluting in nature. Commonly used clean cooking fuels are liquefied petroleum gas (LPG), biogas and alcohol (methanol and ethanol). Although these fuels provide numerous benefits, still there are barriers for their adoption and use in households. The barriers with LPG are that they are expensive relative to other fuels and thus less attractive for the poor. Biogas is also a cleaner alternative in rural areas but the problems associated with biogas are regular availability and lack of efficient burners.

In view of the above, it is amply clear that in order to increase the access of clean cooking fuel, other clean fuel sources for cooking need to be explored. One such clean cooking source is methanol and ethanol, which find traction in recent years. Prominent programs have been launched around the world for promoting methanol and ethanol based cookstoves. Currently, government of various African countries are promoting methanol and ethanol as a cleaner cooking option. Governments of sub-Saharan African countries have undertaken various measures including dissemination of methanol and ethanol based cookstoves to know the user views in the pilot studies. Overall results of pilot studies were encouraging. However, various studies also highlighted the drawbacks of cookstove i.e., low firepower, overheating of fuel regulating lever (Swanepoel and Niekerk, 2001) (Masekameni et al., 2015) and soot formation (Robinson, 2006) (Masekameni et al., 2015). In recent years, the problem associated with low firepower and soot formation in conventional devices based on Free Flame Combustion (FFC) are addressed by the use of technology that works on the principle of Porous Media Combustion (PMC) (Kaushik and Muthukumar, 2019).

The above observations led to the hypothesis that the methanol and ethanol present itself as a high possible substitute for cleaner cooking fuel option. With this vision, Government of India is also promoting methanol to replace conventional cooking fuels, by launching "Methanol Cooking Fuel Program" in 2018. However, no study reported on methanol based cookstoves from Indian perspectives and standards to evaluate the performance. Further, the shortcomings of the conventional canister-based methanol cookstoves (low power) and ethanol cookstoves (soot formation), which are used in other sub-Saharan African countries, are not addressed yet. This is the motivation of the thesis and the thesis objectives were framed accordingly.

In this regard, the main objectives of the thesis are –

1. To evaluate the performance, usability, safety and sustainability studies of FFC based methanol cookstoves
2. To develop a PMC based methanol cookstove
3. To assess the feasibility of ethanol as a cooking fuel in FFC and PMC based cookstove
4. To analyse the Indoor Air Quality (IAQ) due to use of PMC based cookstoves and compare it with the existing FFC based cookstove
5. To develop an Indian standard which consist of set of test and safety instruction for the use of methanol and ethanol based cookstove in Indian home

The present study was carried out to introduce methanol and ethanol as a cleaner cooking alternative from Indian perspectives along with overcoming the drawbacks associated with such cookstoves. Considering the methanol cooking program started by government of India, initially studies were carried out by assessment of methanol cookstove. The thermal and emission performances and usability, safety and sustainability studies of Free Flame Combustion (FFC) based methanol cookstove was compared with the LPG cookstove. The experimental results showed that the methanol cookstove yielded a maximum efficiency of 63.4%, whereas the same for LPG cookstoves was 59.1%. The methanol cookstove showed the combustion efficiency of 99.5% which was similar to that of the LPG cookstove. Further, the performance of methanol cookstove as a possible substitute for LPG cookstoves in terms of usability (fuel convenience, cooking performance, operability, maintenance and comfort) and safety (temperature of touchable parts, and mechanical stability) attributes were also evaluated. The usability study reflects that methanol score is equal in terms of maintenance, comfort and mechanical stability. The result of user survey highlights that most widely reported favourable trait (over 90% of the users) was that the stove was safe in use and clean. In identifying the problems faced, around 30% of the users found difficulty in frequent refilling of the canister. The stove taking more time for cooking as compared to LPG was also the concern expressed by 16% of users. The foremost suggestion by the users (over 90%) was to increase the capacity or size of the canister to avoid frequent refilling. The fuel sustainability studies also reflect that with 10% methanol penetration, 3.69 MMT of LPG can be replaced by 2030 and the production of methanol with coal and biomass are found to be economically viable indigenous resources in India.

Towards improving the performance of FFC based methanol cookstove, the experimental investigation was carried out for the development of PMC based methanol cookstove. The development was carried out in two phases. The first phase explores the use of a conventional pressurized kerosene cookstove and operates it with methanol. However, sustainable flame (flame extinguishes after a certain time) was not attained. Therefore, the second phase utilizes the concept of PMC for developing the methanol cookstove. The developed PMC based methanol cookstove's PRB consists of a vaporizer and porous matrix of SiC. The newly developed cookstove can operate at 3.5 kW and yield a maximum thermal efficiency of 66.6% at 1.8 kW. Further, CO/CO_2 ratio was found to be 70% and 60% lower than the prescribed limit (0.02), for low FP (1.8 kW) and High FP (3.5 kW), respectively. Comparison study on FFC and PMC based methanol cookstoves showed that there is increase in thermal efficiency and decrease in CO/CO_2 ratio by 4.8% and 33.3% respectively, due to use of PMC based cookstove.

The feasibility of ethanol as a cooking fuel was also studied in FFC and PMC based cookstoves. The study compares the performances of FFC based fixed and removable canister type ethanol cookstoves with PMC based ethanol cookstoves. The findings of the performance research revealed that the PMC based ethanol cookstove exhibit the highest maximum efficiency of 60.3% among all examined cookstoves at low FP (1 kW) settings. The advantages of using PMC based ethanol cookstove from user perspective was its higher FP of 3.5 kW which was limited to 2 kW for FFC based fixed canister type and removable canister type cookstoves. Furthermore, the Control Cooking Test (CCT) results show that the PMC-based ethanol cookstove requires 7.2% and 9.7% less cooking time, as well as 4.5% and 2.9% less fuel usage, than the FFC based fixed canister and removable canister cookstoves, respectively. The existing study also addressed the issue of soot formation caused using ethanol fuel in conventional cookstoves by optimising the ethanol/water blend percentage. The optimal mix proportion for optimum visible soot reduction is 93% ethanol and 7% water (E93W7).

Another aspect of the present research work is to study the emission mitigation ability of a PMC technology based cookstove (CS_{PMC}) and compare the same with that of a FFC technology based cookstove (CS_{FFC}). Emission of pollutants i.e., $PM_{2.5}$, PM_{10} and CO caused due to burning of fuels namely methanol, ethanol, kerosene and LPG in the kitchen environment were measured. The study included extensive real-time indoor air quality (IAQ) measurements and documented the temporal fluctuation of observed pollutant concentrations over a 2 h period (morning meal duration). Furthermore, the 24 h average concentration of the pollutants detected was compared to the limitations given in WHO guidelines for residential settings. The results emphasized that the utilization of CS_{PMC} would help in improving the IAQ of the kitchen area by decreasing the concentrations of $PM_{2.5}$, PM_{10} and CO. For 2 h duration measurements, the methanol cookstove based on PMC reduced the concentrations of $PM_{2.5}$, PM_{10} and CO by 7.7%, 8.1% and 17.2%, respectively, compared to FFC cookstove. Similarly, in the case of PMC based LPG cookstove (CS_{PMC}^{LPG}) and kerosene cookstove ($CS_{PMC}^{Kerosene}$), the respective values were 11.7%, 20.4% and 41.6% and 55.3%, 62.6% and 66.6%, respectively. Among all the tested cookstoves, CS_{PMC}^{LPG} achieved the lowest emission values ($PM_{2.5}$: 20.6 $\mu g/m^3$; PM_{10}: 31.3 $\mu g/m^3$ and CO: 1 ppm) which are lower than the values prescribed by WHO ($PM_{2.5}$: 25 $\mu g/m^3$; PM_{10}: 50 $\mu g/m^3$ and CO: 6 ppm).

Further, the research work was also extended for the development of Indian standards for the FFC based methanol/ethanol cookstoves. Presently, there are no Indian standards available, which consist of a set of instructions for performance assessment and safety issues related to such cookstoves. Therefore, various parameters i.e., optimized water quantity for thermal efficiency evaluation, the allowable leakage rate of vapour during non-burning and burning conditions, and limiting emission values of CO, CO_2, NO_x, and SO_x helped in providing technical input for the standardization. With the help of all the mentioned tests, the final set of instructions for safety was developed for all the studied cookstoves. From the insights obtained from technical input a standard was developed for assessing the cookstove performance and its safe usage by users for household applications.

Nomenclature		Unit
a	Distance between nozzle and burner surface	mm
C	Specific heat capacity	kJ/kgk
d	Diameter	mm
D	Diffusion coefficient	m^2/s
H	Convective heat transfer coefficient	W/m^2 K
h	Hour	h
k	Thermal Conductivity	W/mk
m	Mass	kg
Nu	Nusselt number	-
m	Mass	kg
p	Pressure	N/m^2
Pr	Prandtl number	-
Re	Reynold number	-
T	Temperature	°C
$\vec{V}$	Velocity	m/s
$\dot{\omega}$	Species production/destruction rate	-
Y	Mass fraction	-

Symbols

φ	Porosity	-
Φ	Equivalence Ratio	-
ρ	Density	kg/m^3
μ	Dynamic viscosity	kg/ms
η_{th}	Thermal efficiency	(%)
η_{comb}	Combustion efficiency	(%)
ε	Emissivity	-

Subscripts

f	final

h	hydraulic
i	initial
mix	mixture
s	solid
g	gas
p	pore
v	volumetric
w	water

Abbreviations

APL	Assam Petrochemical Limited
BR	Burning Rate
CCT	Controlled Cooking Test
CS	Cookstove
CZ	Combustion Zone
FFC	Free Flame Combustion
FP	Fire Power
IAQ	Indoor Air Quality
KPT	Kitchen Performance Test
LCV	Lower calorific value
LPG	Liquefied Petroleum Gas
MMT	Million Metric Tonnes
PEL	Permissible Exposure Limit
PM	Porous Matrix
PMC	Porous Media Combustion
PRB	Porous Radiant Burner
ppm	Parts Per Million
SFC	Specific Fuel Consumption
TDR	Turn Down Ratio
WBT	Water Boiling Test
WHO	World Health Organization

Contents

List of Tables

List of Figures

Chapter 1 Introduction

Preface

Indoor air pollutants associated with the combustion of cooking fuels in households of developing countries are now recognized as a major source of health risks. The problems associated with solid cooking fuel combustion are mainly tackled by cleaner alternatives like LPG, PNG, etc. In this regard, LPG has been a boon to mankind as it is abundant in supply and has high energy density with relatively clean combustion characteristics. However, in recent times LPG has become expensive and unaffordable due to growing demands and depletion of their reserves. Consequently, there is a pressing need to explore renewable energy sources that are readily available and environment friendly to address these challenges.

The present chapter puts forward methanol and ethanol as clean energy options for cooking. Detail of cookstoves, working principle, design and performance assessments are explained. At the end, the outline of the thesis work is presented.

1.1 Background

Almost 2.4 billion people around the globe use inefficient cookstoves and polluting fuels like charcoal, agricultural waste, dung, kerosene, and wood for cooking (IEA, 2022). The usages of such cookstoves and fuels cause several health issues. They emit a variety of health-damaging pollutants that penetrate deep into the lungs and enter the bloodstream, affecting the health of the user. Indoor smoke consists of different types of fine particles which are injurious to the respiratory systems of human beings. Women and children, who spend the majority of their time near the domestic kitchen, are particularly vulnerable to such exposure. Figure 1.1 describes the various health issues caused by pollutants released from the inefficient cookstoves (Puzzolo, 2014).

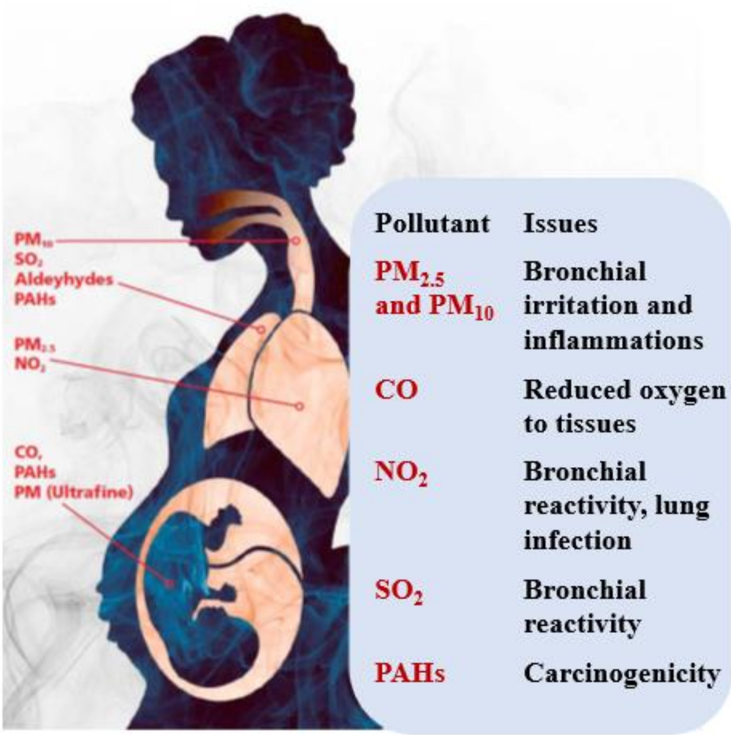


Figure 1.1 Health issues caused by air pollutants (Puzzolo, 2014)

As per the World Health Organization (WHO), household air pollution contributed to 3.2 million illness-related fatalities in 2022, of which 32% are from ischaemic heart disease, 23% are due to stroke, 21% are due to lower respiratory infection, 19% are due to Chronic Obstructive Pulmonary Disease (COPD) and 6% are due to lung cancer (WHO, 2022). Apart from ill health to users, the inefficient combustion and heat loss from biomass cookstoves consumes excess fuel resulting in the rapid depletion of forests and fossil fuels. A study carried out by a charity named “Practical Action” (commissioned by Global alliance for Clean Cookstoves) found that on average, women spend approximately 374 h every year collecting firewood in India (Bloomfield, 2014). Approximately one gigaton of carbon dioxide per year is released into the atmosphere due to the incomplete combustion of wood used for cooking (Bailis et al., 2016). Figure 1.2 presents the distribution of clean cooking fuels and technologies across the world. Over the past decade, access to clean fuels and technologies for cooking increased by only 12%. If the current trend continues and no pace is maintained between the population growth and the provision of access to the clear cooking technologies, a quarter of the world’s population will lack the access to the clean cooking fuels by 2030.

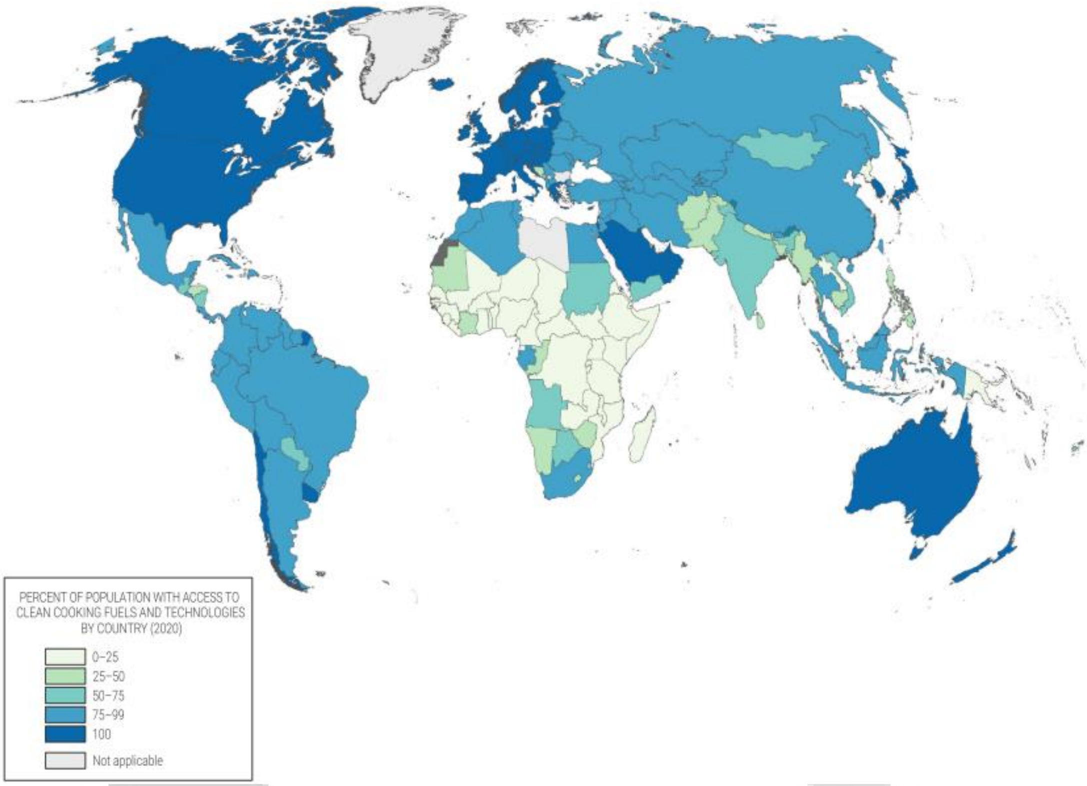


Figure 1.2 Percentage of population with access to clean cooking fuels and technologies (WHO, 2022)

In 2014, WHO differentiates cooking fuels into clean (biogas, Liquefied Petroleum Gas (LPG), natural gas, and alcohol fuels) and polluting fuels (kerosene, coal and dung cake). Some of the important clean cooking fuels and technologies are explained below in brief:

(i) Biogas: Biogas is a clean form of bioenergy that can be produced through anaerobic digestion or fermentation of a variety of biomass sources. It typically consists of 50–75% methane, which provides its energy content, and 25–50% carbon dioxide, which potentially can be captured and stored. Roughly 50 million biogas plants have been installed worldwide, and the number is growing at a rate of 10% annually (IRENA, 2014). While the use of biogas for cooking has substantial benefits, the deployment and implementation need to overcome several barriers to reach its potential. The major barriers to the adoption of biogas are the upfront cost of digester installation, limited feedstock availability, maintenance expertise, lack of efficient biogas stoves, and a range of behavioral and cultural factors (Putti et al., 2015).

(ii) Liquified Petroleum Gas (LPG): LPG is derived from fossil fuels and consists of a flammable mixture of hydrocarbon gases, specifically propane and butane. LPG burns cleanly without any soot formation, and is simple to use, but requires large investments and higher recurring costs compared to common polluting fuels like wood, kerosene, and charcoal. Subsidies can encourage the LPG adoption by reducing upfront cookstove costs and/or recurring fuel costs for cash-constrained consumers.

(iii) Methanol: Methanol is primarily prepared from natural gas, but can also be produced from wood, bagasse, grass, or agricultural wastes. Methanol is nearly a perfect fuel for cooking as there is no soot formation while burning because of its one carbon atom is preoxygenated. It can only add more oxygen and become carbon dioxide, releasing heat in the process. The molecule also contains net hydrogen that burns into water. Also, NOx is at negligible level. Methanol for cooking is still in its infancy, partially due to the fear of the potentially damaging health effects.

(iv) Ethanol: Ethanol is a liquid fuel that can be distilled from starch which first has to be converted into sugar, or sugar-containing biomass feedstock. Ethanol can be used in the form of liquid or in the form of gel. Ethanol gel is made from ethanol combined with a thickening agent to make it viscous and easier to handle as fuel.

(v) Solar cooker: A solar cooker is a device that uses the solar energy to heat, cook or pasteurize milk and other food items. Many solar cookers currently in use are relatively inexpensive, user-friendly and eco-friendly devices. Since, there is no fuel cost and operational cost for operating solar cooker, many nonprofit organizations are promoting the usage of solar cookers worldwide to reduce the economic burden and air pollution. The major drawback of solar cookers is that they are not as efficient as other cooking methods as it is dependable on sunlight to cook food.

(vi) Electricity based cookstoves: There is a range of electricity-based cooking appliances such as induction stoves, microwaves, electricity-based pressure cookers, electric kettles, electric coil stoves. The introduction of electricity-based cooking technologies can enhance access to clean cooking technologies taking advantage of high electrification rates.

1.2 Accessibility of fuels and cooking technology

In low and middle-income countries, the use of gaseous fuels increased consistently from 36% in 2000 to 52% in 2020, overtaking the use of unprocessed biomass fuels as the dominant cooking fuel over the past decade. The use of electricity for cooking has also increased from 3% in 2000 to 11% in 2020, though the increase was far more notable in the urban area. Between 2000 and 2010, the increase in the use of clean fuels was accompanied by a steep decline in the use of coal, particularly in rural areas where the use of coal dropped from 11% in 2000 to 1% in 2020. The use of kerosene, particularly in urban areas, was dropped from 8% in 2000 to 2% in 2020. Around 2010, the use of unprocessed biomass fuels (wood, crop waste, and dung) has shown persistent declines, from 68% in 2010 to 52% in 2020, primarily in rural areas.

Table 1.1 Fuels and cooking technology accessibility (IEA et al., 2021)

Fuels/ Technologies	Population accessibility (%) in 2020	%Increase (↑)/decrease (↓) in accessibility in the last 10 years	Advantages	Disadvantages
Gaseous fuels (LPG, Natural gas and biogas)	52	36 (↑)	Clean fuel and high energy density	High capital cost, non-renewable fuel
Electricity based cookstoves	11	3 (↑)	Clean fuel and ecofriendly	Expensive
Coal	1	11 (↓)	High energy density	Fossil fuel
Kerosene	2	8 (↓)	Easily available	Non clean fuel, produces higher CO emissions
Unprocessed biomass (wood, crop waste and dung)	52	68 (↓)	Cheaper and easily available in rural areas	Produce high level of pollutants, deforestation

To increase access to clean cooking fuels and technologies various clean cooking program has been launched all over the world mainly in low- and middle-income countries. Some of the important programs are discussed below.

1.3 Clean cooking program scenario around the World

To achieve sustainable development goal 7.1, governments around the world took various initiatives to increase access to the clean cooking fuels in rural and urban sectors. Some of the important programs are discussed below:

i. **Efficient, Clean Cooking and Heating (ECCH) Program:** In 2015, the World Bank's Energy Sector Management Assistance Program (ESMAP) launched the Efficient, Clean Cooking and Heating (ECCH) Program. Between 2015 and 2020, the ECCH program has invested more than $380 million across 24 countries in promoting the use of clean cooking fuel and cookstoves. With ECCH support Bangladesh, China, Egypt, Indonesia, Mongolia, Senegal, and Uganda have been provided the accesses to the leaner cooking solution to about 20 million peoples.

ii. **Smokeless Cookstove Training Program:** The Smokeless Cookstove Foundation (SCF) is a non-profit organization working towards reducing the problem of Household Air Pollution (HAP). SCF's training program i.e., Smokeless Cookstove Revolution (SCR), imparts skills and knowledge required in making a virtually zero-cost, improved cookstove that significantly reduces the indoor emission of noxious fumes and use of biofuel input.

iii. **Project Gaia:** Project Gaia is a U.S. non-governmental, non-profit organization involved in the creation of a commercially viable household market for methanol and ethanol fuels in Ethiopia and other countries in the developing world. The project considers fuels to be a solution to fuel shortages, environmental damage, and public health issues caused by traditional cooking. Project Gaia currently works in Ethiopia, Nigeria, Brazil, Haiti, and Madagascar, and is in the planning stage of projects in several other countries.

iv. **Global Clean Cooking Program:** This program is mainly started for removing barriers to the development of a sustainable market for the adoption of Improved Cookstoves (ICS) in Bangladesh. About 66% of Bangladesh's population live in rural areas, where women predominantly do the cooking using traditional, wood based cookstoves. Currently, only 3-5% of households in the country use ICS. The project provides technical assistance to support partner organizations and local entrepreneurs to produce ICS, raise awareness, and carry out research and development of cookstoves.

1.4 Clean cooking program scenario in India

The Government of India has made efforts to enhance access to clean cooking energy by promoting biogas, ICS, and LPG through various policies and programs. The following section elaborates key programs launched for clean cooking in India.

i. **National Biogas and Manure Management Program (NBMMP):** The National Project on Biogas Development (NPBD), launched in 1981, was the first national policy for promoting biogas plants. The program offers Central Financial Assistance (CFA) for family-type biogas plants. MNRE (Ministry of New and Renewable Energy) provides support for training users, turnkey workers, and staff on the benefits of biogas plants and regular operations and maintenance (O&M) requirements.

ii. **The National Program on Improved Chulhas (NPIC):** It was the first program to support ICS, and introduced 35 million chulhas (1986-2002). In 2009, MNRE launched the National Biomass Cookstoves Initiative (NBCI) to continue R&D in ICS, with several pilot projects being launched to improve cookstove efficiency and to demonstrate the benefits of ICS using existing technology. It also included initiatives on carbon finance for biomass cookstoves to reduce prices and increase affordability.

iii. **Pradhan Mantri Ujjwala Yojana (PMUY):** The Pradhan Mantri Ujjwala Yojana (PMUY) is the most prominent scheme in India, which has provided subsidized LPG connections to over 77 million households. However, Jain et. al (2018) claimed that in some energy access-deprived states (Bihar, Jharkhand, Madhya Pradesh, Odisha, Uttar Pradesh, and West Bengal) only about one-third of the rural population use LPG as their primary cooking fuel.

iv. **Unnat Chulha Abhiyan:** National program launched in 2014 for the promotion of ICS in all the State/Union Territories for providing clean cooking energy solutions and reducing the burden of users and emissions. The implementation of this program is to be done by the State government, Non-governmental Organizations (NGO) and business development organizations. It targets: (i) Households (ii) Kitchens of Mid-day Meal Schemes, Angandwadi, Forest Rest Houses, (iii) Tribal/SC/BC Hostels etc. and (iv) Roadside dhabas and small hotels. Under this program, special finance assistance schemes are outlined according to which community cookstoves are deployed for anganwadis, tribal kitchens and mid-day meals. About 33 Models and 18 manufacturers of ICS approved by MNRE for deployment under this program.

v. **Methanol Cooking Fuel Program:** Northeast and Assam Petro-chemicals, a state-owned company launched Asia's first canisters based and India's first "Methanol Cooking Fuel Program." This program is an extension of India's vision of reducing the import of crude oil and striving toward the provision of clean, cost-effective and pollution-free fuel. The methanol cooking program will be further scaled up to 1,00,000 households in the states of Uttar Pradesh, Maharashtra, Gujarat, Telangana, Andhra Pradesh, Goa, Karnataka, Jharkhand and Manipur in the upcoming years.

1.5 Constraints of the clean cooking program

All the above-mentioned programs increase the accessibility of clean cooking fuels but the rate of adoption is found to be slow despite the introduction of various programs to promote such fuels. The main problem with LPG is that it is expensive relative to other fuels and thus less attractive for the poor. The use of LPG by rural households is hampered by distribution systems and high cost of the LPG (Adjei-Mantey and Takeuchi, 2022; Gould and Urpelainen, 2018). Similarly, biogas which is promoted as a key alternative to firewood, dungcake, charcoal, kerosene and coal in rural areas is also faced difficulty in its adoption (Hazra et al., 2014; Pizarro-Loaiza et al., 2021). The key issues are high investment costs for the digester, gas cookstove and installations cost (Ahmad et al., 2023). Similarly, ICS which is promoted as a cleaner alternative also suffers from various issues, as ICS technologies generally remain costly for poor households unless large subsidies are provided and it failed to deliver sufficient benefits to justify their adoption by users. The major constraints in adoption are difficulty in cooking specific culturally important types of food, insufficient fuel supply and lack of technical and repair support by the promoters of these technologies (Bhojvaid et al., 2014). In the case of methanol, till now there is no study reported that details about the performance assessments of methanol cookstoves. Standardization of these cookstoves is yet to be finalized. The adoption studies of methanol cookstoves from an Indian user perspective is not yet reported.

1.6 Strategies for constraints

Considering the constraints associated with the above-mentioned fuels and technologies for cleaner cooking, methanol and ethanol fuel can be a boon with lesser effort. Methanol and ethanol can also be derived from biomass feedstock and can be cheaper than its counterparts. Being a liquid fuel, it is easy to store and transport compared to gaseous fuels. Therefore, to make methanol and ethanol as popular clean cooking fuels and accessible to all, it is essential to develop an energy efficient stove and develop a standard protocol for the performance assessments. The design of clean and energy-efficient cookstoves based on methanol and ethanol requires intensive research work and thus, a detailed investigation on these aspects is necessary. The following section presents a brief description about the various types of methanol and ethanol-based cookstoves.

1.7 Types of methanol/ethanol based cookstoves

In this section, different types of methanol/ethanol cookstoves are presented. The liquid fuel burners used in these cookstoves are classified based on the mechanisms employed to vaporize the liquid fuel and then mix it with an oxidizer. These cookstoves are mainly classified as:

1. Pressurized cookstoves
2. Non-pressurized cookstoves
3. Self -pressurizing cookstoves
4. Evaporative cookstoves

Pressurized cookstove: In this type of cookstove, fuel is stored inside the pressurized tank. The tank is pressurized using a hand pump. The methanol or ethanol is pushed through a tube to a nozzle and sprayed into the burner. The vaporization process is initiated when a little quantity of methanol/ethanol is burnt in the spirit cup (provided just below the burner). The liberated heat is transferred to the vaporizer, and vaporized fuel moves down through descending fuel tubes and is ejected from a central nozzle. The fuel vapour from the nozzle burns near the vaporizer and downward heat transfer from the flame sustains combustion in the burner. The burner is designed to promote air mixing and to produce a flame of a particular size and shape. The pressure cookstoves require frequent pumping to maintain pressure in the tank. The fuel tank of these stoves tends to leak because of the dehydration of the gasket material around the pump shaft connected to the tank. This promotes the failure of the gasket. As a result, gasketed seams need to be repaired regularly to prevent leaking. NARI cookstove presented in Figure 1.3 (a), is an example of a pressurized cookstove.

Non-pressurized cookstoves: This type of cookstove stores methanol /ethanol in an open container, where it burns immediately above its surface. The methanol/ethanol is either in liquid or gel form. If it is in liquid form, the methanol/ethanol is contained in a porous or fibrous medium that draws the methanol/ethanol from the reservoir to its surface through direct contact. However, in gel form, only a reservoir is required. The most common example of non-pressurized cookstove is ethanol-based gel cookstove (Figure 1.3 (b)). This type of cookstove does not provide optimal combustion due to poor air-fuel mixing. Combustion is incomplete and results in higher emission of carbon monoxide. Ethanol in gel form contains less energy because water is usually added (most gel fuels contain 20% water).

(a) (b)

Figure 1.3 Pictorial view of (a) NARI cookstove (Rajvanshi et al., 2007) and (b) Ethanol gel cookstove (Masekameni et al., 2015)

Self-pressurizing cookstoves: This cookstove converts methanol/ethanol from liquid to gas in a restricted space and uses the consequent pressure to force it out of a series of small openings, nozzle, burner element, or mantle into a flame. The “SuperBlu” cookstove is an example of self-pressurized cookstove (Figure 1.4 (a)). The fuel reservoir is close to the flame and essentially is contained within the burner, so there is a chance of explosion, inability to adjust flame, inability to turn on and off and inability to operate for long duration.

(a) (b)

Figure 1.4 Pictorial view of (a) SuperBlu cookstove (Robinson, 2006) (b) CleanCook cookstove (Maurya et al., 2022)

Evaporative cookstove: The most common example of an evaporative cookstove is *CleanCook* cookstove (Figure 1.4 (b)). It has a unique fuel storage and delivery system that allows the fuel to be delivered to the cookstove burner as a gas through evaporation. The liquid fuel (methanol/ethanol) moves by capillary action from all parts of the canister to the evaporative surface at the top. The canister opening is sized to fit under the combustion chimney in the cookstove body so that the fuel from the canister evaporates directly into the chimney. Air is let into the chimney from side vents. Fuel vapour and air form a combustible mixture in the chimney. To light the cookstove, a flame is introduced at the top of the chimney. As the chimney heats, a self- pressurizing effect is achieved, as the rate of fuel evaporation from the fuel canister increases. Since the chimney heats quickly, the peak flow is achieved in few seconds. Increased convection pulls more air in through the side vents. A flame spreader at the top of the chimney acts as a diffuser and promotes fuel-air mixing at the top of the flame. The size of the flame (the rate of fuel flow) into the combustion chimney is controlled by a regulator that slides across the mouth of the canister. When the regulator is slid across the entire surface, the fuel vapor is shut off and the flame is extinguished.

From above mentioned cookstoves, *CleanCook* cookstove is the most used because of its ease in operation. However, this cookstove suffers from many issues like low thermal efficiency, low fire power and low operating hours. One of the reasons behind the low efficiency of such burners is their dependency on Free Flame Combustion (FFC). A brief discussion of FFC based cookstoves is given below.

1.8 Principle of FFC based Cookstoves

In Free Flame Combustion (FFC), the combustion of fuel air mixture takes place in the open-air environment, and the entire flame is exposed to the surroundings, where the main mode of heat transfer is convection as shown in Figure 1.5. As flames are gases and the gases are characterized by low thermal conductivity and emissivity, due to which contributions of conduction and radiation heat transfer from combustible gases to incoming fuel air mixture for preheating the unburnt air-fuel mixture is negligible. Consequently, owing to poor heat transfer, the FFC based cookstoves are less efficient, and they possess unwanted characteristics such as high emission of toxic pollutants, inferior stable flame limits, and low power density.

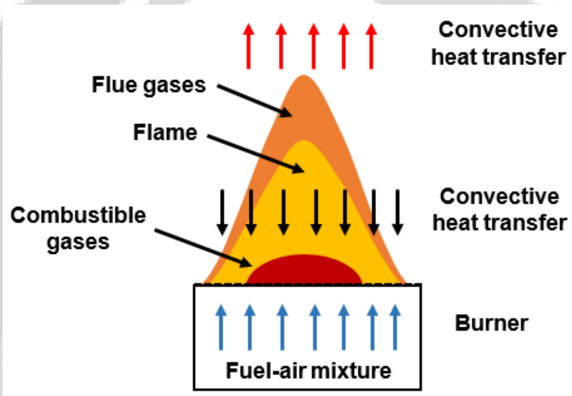


Figure 1.5 Heat transfer in FFC cookstoves

1.9 Principle of PMC based Cookstoves

In recent years, one cooking technology that is expanding its footprints in designing efficient and clean cookstoves is Porous Media Combustion (PMC) technology and it is decisively proved that the cookstoves working on this principle can provide a better alternative to the FFC based cookstoves (Deb et al., 2021).

The PMC works on the principle of utilizing a 3D porous matrix for the combustion of fuel inside the porous structure as shown in Figure 1.6. The combustion of air-fuel mixture within a porous matrix helps in stabilizing flame within the pore structure of the solid matrix/media. The combustion of fuel leads to the generation of heat and the production of species. Heat generation in the combustion zone gives rise to heat transfer by convection from the gas to the porous media. The combustion zone being conducting and radiating, heat transfer by conduction and radiation manifests in the entire volume of the combustion zone. In the upstream of the reaction zone, conduction and radiation elevate the temperature of the porous zone, and mainly through conduction and radiation heat transfer, the incoming fuel-air mixture gets preheated. Downstream to the reaction zone, owing to the additional contribution of energy transfer by convection as the porous media is at high temperature, convective heat transfer takes place from the gas (combustion products) to the solid. A radiation can play a role in heat transfer during PMC, its contribution to the overall heat transfer process can vary depending on several factors ((Deb and Muthukumar, 2021).

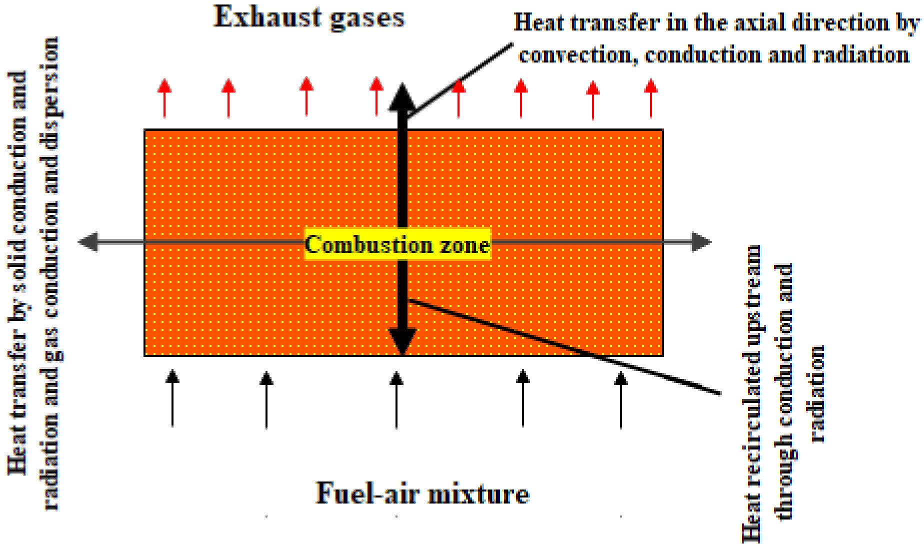


Figure 1.6 Heat transfer mechanism in porous matrix of a PMC based burner

Figure 1.7 compares the enthalpy histories in adiabatic system for two scenarios: one with FFC (without heat recirculation) and one with PMC (with heat recirculation). In the case where heat recirculation is present, heat is transferred from the exhaust gas back to the combustion air (Q_{pre}), while the system maintains a constant heat input (Q_{in}). As a result of heat recirculation, the enthalpy and flame temperature in the system are significantly increased and heat loss due to flue gases (Q_{loss}) decreased compared to the scenario without heat recirculation. This elevated enthalpy and flame temperature enable the system to generate a greater amount of useful energy (Q_a) compared to the case without heat recirculation.

In PMC, super-adiabatic combustion caused by the recirculation of hot combustion products to the unburnt air-fuel mixture favours complete combustion of the fuel and reduction of CO and unburnt hydrocarbon emissions. Superadiabatic combustion is a process in which the combustion of a fuel-air mixture occurs at temperatures higher than the adiabatic flame temperature. The adiabatic flame temperature is the maximum temperature that can be achieved during combustion without any heat loss to the surroundings.

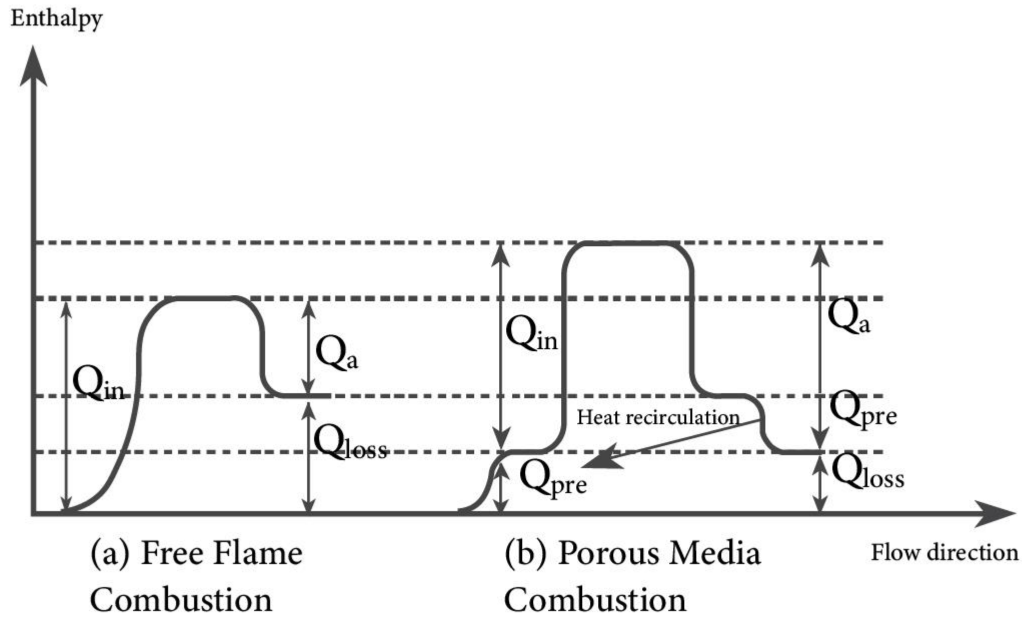


Figure 1.7 Comparison of enthalpy history between FFC and PMC (Jugjai and Rungsimuntuchart, 2002)

1.10 Testing of cookstove

Testing of cookstoves is performed in the laboratory as well as in the field. The Water Boiling Test (WBT) is the most common of all laboratory tests, and it has several derivatives. The other main laboratory test, which is performed by users, is the Controlled Cooking Test (CCT). There are many possible field tests to be done (typically customized to a specific project), and historically the most frequently used is the Kitchen Performance Test (KPT). Details of the above-mentioned tests i.e., WBT, CCT and KPT are discussed below.

1.10.1 Laboratory based testing

Water Boiling Test (WBT): It is the preliminary test performed to measure the thermal efficiency of cookstoves. It is used to measure how efficiently a fuel can be used to heat the water under controlled conditions. It is done to test a newly developed cookstove and ensure that it meets the intended performance (PCIA & Global Alliance, 2013). Performance evaluation of the cookstove is done as per standards prescribed by a regulatory organization.

Controlled Cooking Test (CCT): It is a laboratory test that evaluates the performance of the cookstoves using a standardized local cooking task (Bailis, 2004). This method evaluates the behavior of the cookstove under ideal cooking conditions in a laboratory. The menu for cooking is prepared by consulting the local people. The test is performed in accordance with the set-out procedures. It may also be performed to get an estimation of the cookstoves that can be sent for field testing (Lask et al., 2015). The results of the cookstove can be replicated, provided the menu and the cooking conditions are the same. Specialized cooks are required to prepare the meals. The outcomes of CCT for one project area cannot be translated to a different project area. It cannot measure the effectiveness and sustainability of a cookstove. Therefore, more detailed survey is necessary to evaluate the actual performance of a cookstove.

1.10.2 Field based testing

Usability Test: The usability test evaluates the cookstove performance in six major aspects i.e., fuel convenience, cooking performance, operability, maintenance, comfort, and location-specific needs (Moses and Maccarty, 2018).

Kitchen Performance Test (KPT): The results of WBT or CCT are not sufficient to determine whether a cookstove can be launched in the market because both of them are performed in laboratory environment. KPT measures the performance of cookstoves in the households under the real operating conditions (Bailis et al., 2018). This method assesses the impact of cookstoves on fuel use and utilization trends over long term. It can predict the outcomes of uncontrolled usage of the cookstoves in actual practice.

1.11 Standards for testing of cookstove

Standards are essential for ensuring that cookstoves used in homes are safe, work well, and do not have a negative impact on health. When standards are effectively enforced, governments and their agencies can establish rules and stimulate product innovation to ensure that products entering the market are safe and satisfy the needs and expectations of consumers. Requirements and guidance are provided for evaluation of thermal efficiency, Fire Power (FP), fuel consumption, emissions and safety. Some of the important Indian standards for testing of cookstoves are discussed below:

IS 4246 (2002) (https://law.resource.org/pub/in/bis/S08/is.4246.2002.pdf)**:** This standard specifies construction, operation, safety requirements and tests for LPG based cookstoves for household application. The standard provides a set of instruction for measurement of fuel consumption rate, thermal efficiency and emissions (CO and CO_2).

IS 11760 (1986) (https://law.resource.org/pub/in/bis/S08/is.11760.1986.pdf)**:** This standard specifies the construction, operation and safety requirements and tests for kerosene wick cookstove.

IS 10109 (2002) (https://law.resource.org/pub/in/bis/S08/is.10109.2002.pdf): This standard covers the requirements and tests for kerosene pressure cookstoves working in a pressure range of 100 kN/mm^2 to 200 kN/mm^2.

1.12 Outline of thesis

Following the present chapter, the second chapter provides an overview of the previous research works reported on methanol and ethanol based cookstoves. Further, the review has been extended about the porous radiant burner based on liquid fuels, with a focus on the development and performance evaluation of the burners. Additionally, the IAQ studies related to the conventional LPG, kerosene and methanol and ethanol based cookstoves are also presented. The identification of the literature gaps led to the outlining of the objectives for the present thesis work.

The third chapter represents the assessments of a methanol cookstove in terms of thermal and emission performances (Laboratory study) along with usability and safety studies (Field study). The study compares its performance with commonly available LPG cookstoves in terms of thermal efficiency and combustion efficiency, usability attributes (fuel convenience, cooking performance, operability, maintenance and comfort) and safety attributes (temperature of touchable parts and mechanical stability) from Indian user perspective.

The fourth chapter presents the design and development of a PMC based methanol cookstove. The chapter reports, performance investigation in terms of technical assessment (thermal efficiency and effect of various parameters on thermal efficiency and emission parameters (CO and NO_x emissions, combustion efficiency (η_{comb}) and CO/CO_2 ratio).

The fifth chapter presents the comparative study of FFC based ethanol cookstoves (fixed and removable canister type) with PMC based ethanol cookstove. A comparative analysis was done for FFC based ethanol cookstove and PMC based ethanol cookstove in terms of thermal parameters (thermal efficiency, fire power, burning rate, specific fuel consumption and turn down ratio) and emission parameters (CO/CO_2 and combustion efficiency). In addition, a CCT was also conducted to know the fuel consumption with the use of such cookstoves.

The sixth chapter presents the emission mitigation ability of PMC based cookstove as compared to FFC based cookstove. The level of pollutant emissions such as particulate matter ($PM_{2.5}$ and PM_{10}) and carbon monoxide (CO) for ethanol, methanol, kerosene and LPG fuelled cookstoves under indoor cooking conditions are presented in this chapter.

The seventh chapter describes about the formation of Indian standard for testing the performances of the methanol and ethanol based cookstove.

The eighth chapter presents the outline of key conclusions drawn from the present study and the limitations of the methanol and ethanol cookstoves. The chapter also reports the future prospective of the present research works.

1.13 Summary

The present chapter on introduction emphasizes the need to explore the cleaner cooking options to reduce Indoor Air Pollution (IAP) caused using traditional fuels. The focus is given on highlighting the benefits of alcohol fuels (methanol and ethanol) as compared to other clean cooking options i.e., LPG, Biogas, solar cooker, and electricity based cookstoves. Further, the accessibility to these fuels through various clean cooking programs are presented. The various designs of methanol and ethanol based cookstoves and their testing methods for performance evaluation are also presented. Finally, the outline of thesis is elaborated.

Chapter 2 Literature review

Preface

Methanol and ethanol are cleaner cooking alternatives that offer a potential solution to important issues like fossil fuels depletion and emissions. Methanol and ethanol fuels find application in various domains such as IC engines, fuel cells, cookstoves, etc. The present thesis is intended to analyse methanol and ethanol as fuel for domestic cooking by evaluating its thermal and emission performance along with its user feedback. Further, Porous Media Combustion (PMC) technology is introduced to develop efficient and environment friendly methanol and ethanol cookstoves.

Therefore, the literature review is focused on the various laboratory and field studies reported around the world. An extensive literature survey on PMC technology for liquid fuel for cooking applications is also presented. Also, investigations related to Indoor Air Quality due to the use of conventional cookstoves is also summarized. From the various corollaries obtained from the literature survey, the literature gap has been identified and the objectives of the present research work are presented.

2.1 Methanol and ethanol as cleaner cooking alternative

In 1999, Governments and development practitioners in Central America, the Caribbean and Africa introduced the concept of bringing alcohol powered appliances, available in Europe and North America, to the developing countries as cleaner cooking alternatives (Stokes and Ebbeson, 2005) through an initiative known as Project Gaia. The project considered alcohol fuels as a solution to fuel shortage, environmental damage, and public health issues caused by traditional cooking in the developing nations. Pilot studies carried out with methanol and ethanol under project Gaia are discussed below.

Methanol: The first case study on methanol operated "*Origo 3000* cookstove" has been done in South Africa in 2001. The study was conducted to establish the specification of *Origo 3000* cookstove which was developed for domestic use by low-income households and also to assess whether methanol can become a fuel of preference for domestic cooking. The study revealed that the users were impressed with the appearance and put it with the level of LPG cookstoves. However, found difficulties in operating the power regulating knob which became hot during continuous usage. Some respondents burned their fingers and others were concerned that the hot knobs may burn children's fingers (Swanepoel and Niekerk, 2001).

To overcome the above-mentioned shortcomings, design improvement was made and *CleanCook* cookstove was introduced by Dometic AB, a Swedish company in Addis Ababa. The improved cookstove was more stable, stronger and larger than the earlier prototype i.e., *Origo 3000*. A pilot study was conducted in 2004 for the commercialization of *CleanCook* cookstoves in which 800 cookstoves were distributed on a trial basis. The pilot study mainly addressed the issues related to existing cookstove design, consumer safety and affordability and highlighted that the fuel is safe as compared to most used kerosene and gasoline fuels. The cookstove also burns efficiently, without any odour, soot or smoke, and pots stay clean and bright. The results highlight that *CleanCook* cookstoves can replace kerosene and fuel wood in low and middle income countries (Stokes, 2005). Further, in 2007, Project Gaia conducted a mini-pilot study in Nigeria to determine the feasibility of *CleanCook*. Dometic AB provided 15 new prototype *CleanCook* cookstoves specially designed for this project. Around 97% of the respondents showed positive responses and agreed that methanol was a very safe fuel and can be used to cook in the *CleanCook* cookstove. Around 36% of the respondents suggested to increase the capacity of canisters for having more operating hours up to 10 h. The most common suggestion provided by the users was that the edges were too sharp which resulted in injuries and oftentimes, it was difficult for them to extinguish the flames with the cookstove regulators after the cookstove gets hot due to prolonged usage (Obueh, 2008).

Ethanol: Ethiopia is the first country to introduce ethanol cookstove program in refugee camps in 2004. Almost 4000 *CleanCook* cookstoves were distributed through the help of the Gaia Association to know the user perception regarding safety compared to other fuels and cookstoves, in comparison with kerosene. About 95% of users responded that ethanol was safer than kerosene and 74.6% of users left the use of kerosene cookstove after using *CleanCook* cookstove. Overall, 98% of users were satisfied with the *CleanCook* cookstove in terms of ease of use, fuel efficiency, cookstove safety, ease to clean, size, lighting the cookstove, smoke emissions, heat/burner regulator and cookstove quality (Murren, 2006).

In 2006, a pilot study was conducted using *SuperBlu* cookstoves in Malawi. Among the distributed cookstoves, 35% were defective and not used for response accumulation. Users also experienced problems in operating the cookstove at low power and were not able to stop easily and complained of an ethanol smell, eye irritation along with soot deposition (Robinson, 2006).

In 2010, a pilot study was conducted in Madagascar to analyse the health benefits due to the use of *CleanCook* cookstoves. The study showed a maximum reduction of 93% and 72% in CO and $PM_{2.5}$ emission, respectively as compared to charcoal baseline cookstoves. Along with the reduction in emissions, there were no burning casualties observed after the installation of *CleanCook* cookstove (Charron et al., 2011).

A study was conducted in Mozambique for 341 households regarding the user perception of the adoption of ethanol fuel and *CleanCook* cookstoves. The study revealed that from the sampled households only 17% maintained continuous usage of ethanol cookstoves, while 12% had discontinued its usage and 71% never used it. It has been found that the distributed cookstove malfunctions due to poor design which influenced many *CleanCook* cookstove adopters to quit it. Also, it has been found that to increase the effective uptake of ethanol as cooking fuel, problems like - high initial and operational costs, poor fuel quality, unreliable fuel supply, and poor cookstove design need to be addressed (Mudombi et al., 2018).

A study conducted in 2018 represented the result of a 13-year implementation program, which was started in 2005 by Gaia Association to know the outcomes of ethanol *CleanCook* cookstove in the refugee camp and urban settings of Ethiopia. A total of 8731 *CleanCook* cookstoves were distributed to refugee households. The study reported that users explored different cookstoves instead of *CleanCook* cookstoves due to the high price of ethanol fuel (Benka-Coker et al., 2018).

2.2 Performance analysis of FFC based methanol and ethanol cookstoves

Methanol: Very few studies have been reported on the performance testing of methanol cookstoves (Table 2.1). Methanol cookstove was tested with 6 L of water, which showed a thermal efficiency of 67% (Masekameni et al., 2015). Makonese et al., (2020) tested three types of methanol cookstoves (having different construction materials, size of the fuel reservoir, and re-fuelling styles) and reported thermal efficiency in the range of 58 to 67%. In all the above-mentioned cookstoves, different testing protocols have been used to evaluate thermal efficiency. However, Fire Power (FP) in all the above-mentioned cookstoves was limited to 1 kW. The pictorial view of all the studied cookstoves are given in Figure 2.1.

Table 2.1 Summary of methanol based cookstoves thermal performance

Cookstove	Thermal efficiency (%)	FP (kW)	Testing protocol	Ref.
Protostar	58	1	HTP	(Makonese et al., 2020)
Dometic	67	1	HTP	(Makonese et al., 2020)
Meca	60	0.97	HTP	(Makonese et al., 2020)

(a) (b) (c)

Figure 2.1 Different types of methanol cookstove reported in literature - (a) Protostar (Makonese et al., 2020), (b) Dometic (Makonese et al., 2020) and Meca (Makonese et al., 2020))

Ethanol: Only very few studies were reported the performance testing of ethanol cookstoves, details of which are highlighted in Table 2.2. The reported thermal efficiency of *SuperBlu* cookstove was 43% at 1.4 kW with 2 L of water quantity. A pressurized cookstove developed by Nimbkar Agricultural Research Institute (NARI) runs on a 50% ethanol-water concentration (v/v). The thermal efficiency ranged between 44% to 46% when tested at Fire Power (FP) range of 0.9 kW to 2.45 kW. It has been also observed that the higher percentage of water reduces the flame temperature and consequently the efficiency (Rajvanshi et al., 2007). Another study was conducted with 50% ethanol-water concentration with non-pressure VOHAJA cookstove and it has been found that the stove yielded an average efficiency of 57.1% at 1.6 kW. Another ethanol gel cookstove was also studied which showed the thermal efficiency of 52% (Oketch, 2013) and 73% (Masekameni et al., 2015) due to use of different testing protocol. The pictorial view of all the studied cookstoves are given in Figure 2.2.

Table 2.2 Summary of ethanol cookstoves in thermal performance

Cookstove	Thermal efficiency (%)	FP (kW)	Testing protocol	Ref.
SuperBlu	43	1.4	ISO	(Robinson, 2006)
NARI	44-46	0.9-2.45	-	(Rajvanshi et al., 2007)
VOHAJA	57.1	1.6	ISO	(Hajamalala, 2014)
Ethanol gel	52	1.1	ISO-4.1.2	(Oketch, 2013)
Ethanol gel	73	1.2	HTP	(Masekameni et al., 2015)

(a) (b) (c) (d)

Figure 2.1 Different types of ethanol cookstove reported in literature- (a) SuperBlu (Robinson, 2006), (b) NARI (Rajvanshi et al., 2007), (c) VOAHAJA (Hajamalala, 2014)) (d) Ethanol gel (Masekameni et al., 2015)

There is only one study reported that studied the *CleanCook* cookstove performance by using the blend of methanol and ethanol (52.5-55.0 % methanol and 42.5-46.5 % ethanol). The studied cookstove showed a thermal efficiency of 56% at 0.712 kW with a 2 L water quantity having a fuel blend of ethanol and methanol (Jetter and Ebersviller, 2015).

From the above literature survey, it was observed that the alcohol based cookstoves i.e., *CleanCook*, *Origo 3000*, *SuperBlu* and *ethanol gel* were operated at low FP. In the case of methanol and ethanol cookstoves, the FP was limited to 1 kW (Table 2.1) and 1.6 kW (Table 2.2), respectively. The ethanol based *SuperBlu* cookstove showed soot formation and the most common *CleanCook* cookstove faced difficulty in closing the lever after prolonged hours of operation. All these factors together lead to discouragement in its use and make the cookstove unpopular from users' perspectives. As all the above-mentioned cookstoves operate based on the principle of FFC technology where convection is the main mode of heat transfer. As combustion products are treated as gases and are characterized by low heat transfer coefficient, thermal conductivity and emissivity which leads to lower heat transfer from burner surface to vessel.

2.3 Investigation of PMC technology for liquid fuel combustion

In recent years, the low FP and heat transfer problems associated with cookstoves were addressed using PMC technology. However, researchers from only one institute reported the successful development of cookstoves for liquid fuel (kerosene and waste cooking oil only). The major contributions to the development of liquid fuel cookstoves with PMC technology are discussed below.

The use of a suitable vaporization technique and optimum vaporizer arrangement in the burner are the two essential criteria for proper and stable combustion. The first attempt was reported by Kakati et al. (Kakati et al., 2007) from Indian Institute of Technology Guwahati, who examined the performance of a domestic burner with porous inserts of pottery clay, sodium silicate, and sawdust in terms of thermal efficiency, kerosene consumption rate and emissions. Later this work was extended by Sharma et al. (Sharma et al., 2009) by using different Porous Matrix (PM) namely, wire mesh rolls filled with metal balls, alumina, zirconia (ZrO_2), and silicon carbide (SiC). They reported that at an optimum fuel flow rate of 130-140 g/h and vessel size of 260 mm diameter, the thermal efficiency increased for all PM. The burner with SiC was found to have a maximum of 7% increase in thermal efficiency. The efficiency was further increased by insulating the heat shield ring. In their subsequent study (Sharma et al., 2011), the cookstove was further modified by incorporating a ceramic (alumina) heat shield, which could improve the thermal efficiency by 15%. They also experimented with three different burner casings, viz. straight cylindrical, tapered, and conical in a cookstove consisting of two-layer PM of alumina balls and SiC honeycomb structure (Sharma et al., 2016a). At a fuel flow rate of 220 g/h, the burner with a conical casing showed the highest improvement of 10% in thermal efficiency. They also investigated how the burner diameter affected thermal efficiency, emissions, and temperature distribution at various air and fuel flow rates in the same burner

(Sharma et al., 2016b). The above-developed burners were operated with an external air supply, which makes these burners inapt for domestic applications.

To overcome the mentioned problem, with a new vaporizer design, Sinha and Muthukumar (2019) developed a pressurized kerosene cookstove with self-aspirated PRB for FP of 1.5-3 kW, claiming around 15% improvement in thermal efficiency (Sinha and Muthukumar, 2019). However, a decline in efficiency from 64% to 55.5% was observed for FP of 1.5 to 3 kW. Their published patent contains information on the design and functionality of vaporizers (Sinha, 2017). Further, Kaushik and Muthukumar (Kaushik and Muthukumar, 2020) found that up to 50% blending of Waste Cooking Oil with kerosene sustains stable combustion in PRB.

2.4 Indoor Air Quality (IAQ) due to use of various cookstoves

A lab study conducted by Kandpal et al. (Kandpal et al., 1995) in the kitchen environment of dimensions 2.6×2.8×2.3 (m^3) showed that the use of LPG cookstoves generates lower CO emissions than kerosene cookstoves. The field study conducted by World Bank to investigate the IAQ in India showed that fuel type, kitchen type, and kitchen ventilation are the major parameters that need to be considered for emission measurements. Further, the findings of this study revealed that the households using cow dung had the living area emission concentrations were five times higher than households using kerosene or LPG (Balakrishnan et al., 2004). Another field study was conducted to assess the IAQ for 55 households on the usage of fuels such as cow dung, wood, LPG, propane and kerosene. The results showed the presence of polyaromatic hydrocarbon emission from all the tested fuels (Gautam et al., 2013). A study conducted in Nigeria among kerosene users showed that the emission of mean PM_{10} (246 $\mu g/m^3$) was ten folds higher than the WHO's guideline limit of PM_{10} (50 $\mu g/m^3$) (Adeniji et al., 2015). A lab study was also conducted to compare the emissions of CO and $PM_{2.5}$ from kerosene cookstoves, ethanol gel cookstoves and methanol cookstoves (Masekameni et al., 2015). The results revealed that the ethanol gel cookstove generated less $PM_{2.5}$ emission compared to the methanol and kerosene cookstove and all the emissions (CO and $PM_{2.5}$) have been measured through the hood method (BIS, 1986) in which flue gases were separated from the surrounding air for measurement of exhaust emissions. Sidhu et al. (2017) compared the indoor and outdoor kitchen emissions from LPG cookstoves. The study depicted that the indoor kitchen showed the highest pollutants concentration (CO: 9.3 ppm; $PM_{2.5}$: 696.5 $\mu g/m^3$) followed by the outdoor kitchen (CO: 5.8 ppm; $PM_{2.5}$: 539.5 $\mu g/m^3$) (Sidhu et al., 2017). The concentration of pollutants was found to vary depending on the style of the kitchen, the type of fuel used and the location of the kitchen. Tagle et al. (2019) conducted a field study in Paraguay and measured the time-integrated samples (24 h) of $PM_{2.5}$ and continuous CO concentrations in kitchens that used wood, charcoal, LPG and electricity for cooking applications (Tagle et al., 2019). The results showed that the kitchens using LPG resulted in the lowest CO and $PM_{2.5}$ concentrations. The field study conducted by Oluoch and Nyamasyo (2020) revealed that kerosene produced 1.2 and 1.6 times higher $PM_{2.5}$ than charcoal and LPG cookstoves (Oluoch and Nyamasyo, 2020). To determine the exposure to $PM_{2.5}$ among pregnant women after LPG intervention, a pilot study was carried out in India, Rwanda, and Guatemala. The results showed that the LPG intervention reduced the kitchen $PM_{2.5}$ levels by 92% (Liao et al., 2021). The summary of the above-mentioned studies is presented in Table 2.3.

Table 2.3 Reported emission values from various cooking fuels with FFC burners

Fuel	Usage duration (h)	Location	Kitchen volume (m^3)/area (m^2)	$PM_{2.5}$/ PM_{10} ($\mu g/m^3$)	CO (ppm)	Study	Ref.
LPG	1	India	16.7 (m^3)	-	1 (1 h average)	Lab	(Kandpal et al., 1995)
Kerosene	1	India	16.7 (m^3)	-	3 (1 h average)	Lab	(Kandpal et al., 1995)
LPG	-	India	-	73 (PM_{10})	-	Field	(Balakrishnan et al., 2004)
Kerosene (wick)	-	India	-	203 (PM_{10})	-	Field	(Balakrishnan et al., 2004)
LPG	-	India	-	342 (24 h average/$PM_{2.5}$)	-	Field	(Gautam et al. 2013)
Kerosene	-	Nigeria	2.80 ×2.38 (m^2)	246.6±13.5 (24 h average/ PM_{10})	-	Field	(Adeniji et al., 2015)
Ethanol	1	South Africa	-	99.5 (1 h average/$PM_{2.5}$)	7500 (1 h average)	Lab	(Masekameni et al., 2015)

Methanol	1	South Africa	-	992.6 (1 h average/$PM_{2.5}$)	3200 (1 h average)	Lab	(Masekameni et al., 2015)
Kerosene	1	South Africa	-	3180 (1 h average/$PM_{2.5}$)	9300 (1 h average)	Lab	(Masekameni et al., 2015)
LPG	-	India	-	78.8 (24 h average /$PM_{2.5}$)	1.05 (24 h average)	Field	(Masekameni et al., 2015)
LPG	3.4±1.3	Paraguay	40.1±13.8 (m^3)	52.3±18.9 (24 h average/ $PM_{2.5}$)	0.5±0.6 (24 h average)	Field	(Tagle et al., 2019)
LPG	-	Guatemala	31.6±10.2 (m^3)	27±13 (24 h average/ $PM_{2.5}$)	-	Field	(Liao et al., 2021)

2.5 Research Gap

From the literature review on pilot studies, performance evaluation studies, PMC based liquid cookstoves and IAQ studies, the following important gaps are identified.

i. No work on the feasibility studies on methanol and ethanol cookstoves has been reported in Asian countries.

ii. Comparative performance of methanol and ethanol cookstoves to LPG cookstoves is not yet reported.

iii. No study reported the safety aspects related to methanol and ethanol cookstoves.

iv. The problems associated with the low FP and soot formation in methanol and ethanol cookstoves, respectively, are not addressed so far.

v. There is no investigation on IAQ with methanol and ethanol in conventional cookstoves and PMC based cookstoves in the actual kitchen environment.

vi. No standards available for the evaluation of methanol and ethanol based cookstove performance from an Indian perspective.

2.6 Objectives of Thesis

The above stated research gaps form the studied literature serve as the motivation of the thesis work and the core objectives are framed accordingly.

The main objectives are –

- To evaluate the thermal and emission performances, usability, safety and sustainability of FFC based methanol cookstoves and compare with LPG operated cookstoves
- To develop a PMC based methanol cookstove and test its performances
- To assess the feasibility of ethanol as a cooking fuel in FFC and PMC based cookstoves
- To analyse the IAQ of PMC based cookstoves and compare with the existing FFC based cookstoves
- To develop Indian standards (BIS) of methanol and ethanol based cookstoves

2.7 Summary

An elaborate review of the literature concerning field and lab studies on the performance evaluation of liquid fuel based cookstoves is presented. Additionally, summarized the studies reported on the application of PMC technology for the development of cookstoves. Further, the literature survey regarding indoor air quality assessment of households due to the use of cooking fuels is also presented. From the literature review, the literature gaps are identified and the objectives for the present thesis work are outlined.

Chapter 3 FFC based Methanol cookstove: Performance, Usability, Safety and Sustainability Studies

Preface

A combination of lab and field studies were conducted on FFC based methanol cookstoves in terms of thermal and emission performances (lab study), usability and safety (field study) and fuel sustainability. These studies were conducted mainly to know the viability of methanol cookstoves in India.

The present study followed a three-step approach, with the initial step involving the evaluation and comparison of thermal and emission performances of a methanol cookstove with an LPG cookstove available in the market. In the second step, the usability and safety attributes of the methanol cookstove were assessed and compared with the LPG cookstove. In the last step, methanol sustainability analysis was performed, mainly to substitute methanol as a cleaner alternative to LPG.

3.1 Cookstove characteristics

The characteristics of FFC based methanol and LPG cookstove are explained in this section. The methanol cookstove was provided by Assam Petrochemical Limited (APL), India whereas the LPG cookstove was purchased from commercial outlets. The design specification of all the selected cookstoves is given in Table 3.1.

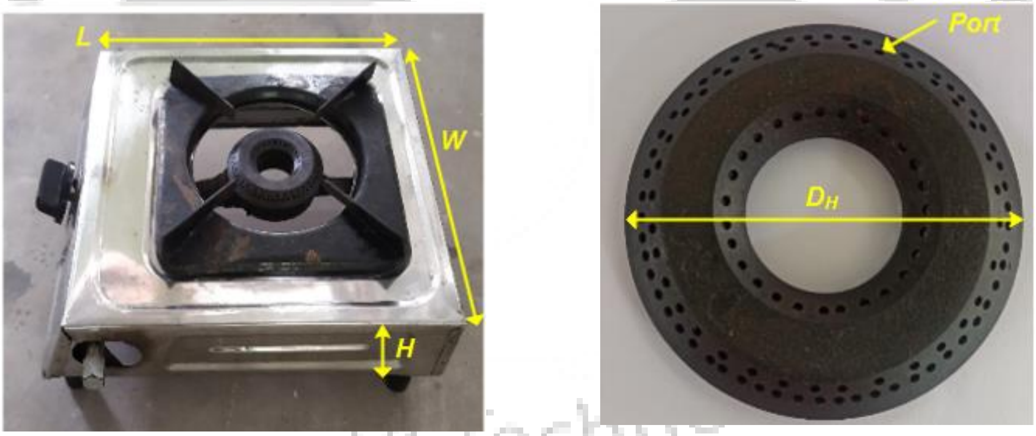
Table 3.1 Design specification of the methanol and LPG cookstove

Cookstove type	**LPG cookstove**	**Methanol cookstove**
Burner (s)	Single burner	Double canister (mineral wool-900 g)
Dimensions (mm)	$L \times W \times H$= 330×260×100; Port dia. = 1.5; No. of port = 118; D_H = 80 (Figure 3.1)	$L \times W \times H$= 650×310×100 (Figure 3.2)
Tank capacity:	14.2 kg cylinder	1.8 litre

Lower Calorific value	45.6 MJ/kg	18.5 MJ/kg

3.1.1 FFC based LPG cookstove

The pictorial view of a household LPG cookstove is shown in Figure 3.1. It consists of a fixed orifice for fuel inlet, two slots for primary air entrainment, a venturi-shaped mixing tube and a burner head with ports (holes) fitted on top of the mixing chamber. The high-velocity fuel jet from the orifice creates low static pressure which causes the suction of primary air through the two slots. Air and fuel mix in the mixing tube and through the mixing chamber, the mixture comes out in the form of jets through the ports of the burner head. The gas flow rate is controlled by a valve in the fuel line. Combustion takes place on top of the burner head. The ports are closely located circumferentially and thus the jet flames from the individual ports merge to form a single flame. The secondary air is entrained to the combustion zone from the bottom of the mixing chamber and air also diffuses to the combustion zone from the circumferential area surrounding the flame. Hence, the combustion in the burner of a household LPG cookstove is a partially premixed one.



(a) (b)

Figure 3.1 Pictorial view of (a) household LPG cookstove and (b) burner

3.1.2 FFC based methanol cookstove

The pictorial view of FFC based methanol cookstove is shown in Figure 3.2. It is also called as canister-based methanol cookstove and is an evaporative cookstove (as explained in section 1.4 (b)) that delivers heat by burning the methanol vapour from the canister through evaporation. The methanol cookstove consists of stainless-steel structure (stove body) provided with pot support at the top and provisions at the sides to facilitate the insertion/removal of the canister. The canister is made up of a stainless-steel material in which mineral wool is placed to hold the methanol. The cookstove has a power control lever for regulating the fuel supply. The fuel is adsorbed in densely packed mineral wool contained inside the canister. The liquid methanol moves by capillary action from the mineral wool to the evaporative surface at the top, i.e., the opening of the canister top. The canister opening is sized to fit under the combustion chimney, and the side vents allow air to enter the chimney. Methanol vapour and air form a combustible mixture in the chimney, and the combustion takes place above the surface of the canister opening on the ignition. As the chimney heats, a self-sustained flame is achieved. A flame spreader at the top of the chimney acts as a diffuser and promotes fuel-air mixing. Refilling is not possible when the stove is in operation.

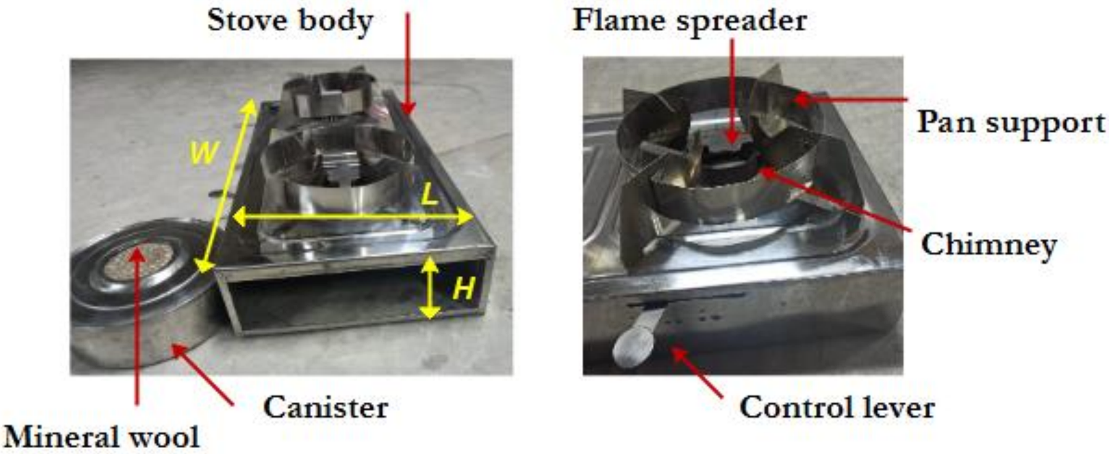


Figure 3.2 Photographic view of canister-based methanol cookstove

3.2 Performance parameters

Performance tests were conducted under laboratory conditions to measure the thermal and emission performances of the cookstove. The FFC based methanol cookstove was tested following the guidelines of the Water Boiling Test (WBT) as per International Organization for Standardization (ISO) version 4.2.3 and emission as per IS 11760:1986. The thermal performance consists of thermal efficiency, Burning Rate (BR), Fire Power (FP), Specific Fuel Consumption (SFC), and Turn Down Ratio (TDR) and emission performance consists of CO and NOx emission values, CO/CO_2 and combustion efficiency. Also, the effect of mineral wool quantity on fuel capacity of canister.

3.2.1 Effect of mineral wool quantity

There are two different types of mineral wool one is ceramic wool (top layer) and another is rockwool (bottom layer) as shown in Figure 3.3. Ceramic wool is used on the top surface due to its high temperature resistance properties and its quantity is fixed inside the canister. Rockwool quantity is varied from 600 g to 900 g to know the effect of mineral wool quantity on adsorption of methanol.

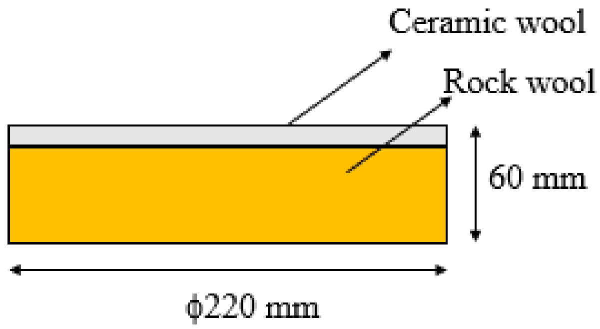


Figure 3.3 Mineral wool quantity arrangement inside the canister

3.2.2 Thermal performance and measurement procedure

Thermal performance of cookstove consists of various parameters i.e., thermal efficiency (η_{th}), Burning Rate (BR), Fire Power (FP), Specific Fuel Consumption (SFC), and Turn Down Ratio (TDR).

The evaluation of thermal efficiency was done through the Water Boiling Test (WBT) as mentioned in ISO protocol which specifies that the cookstove should be tested at high Fire Power (FP) (cold and hot start phases) and low FP (simmer phase) settings. The cold start phase begins when the cookstove is at ambient temperature, and the hot start phase begins when the cookstove is at operating temperature. During both phases, the cookstove is operated at high FP to heat the water in the vessel from ambient to boiling temperature. During the simmer phase, the cookstove is operated at low FP to maintain the target water temperature at 3°C below the boiling point. In all tests, the cookstove is fired at room temperature (25 ± 2°C). In each run, 2.5 kg of water is heated in a vessel of 3.5-litre capacity without a lid to the local water boiling point (99.8°C), for the test location, Guwahati (PCIA

& Global Alliance, 2013) in the hot and cold start phase. Fuel burning rate determines the FP levels. Therefore, care has been taken to maintain the same fuel burning rates during the experiments. The thermal efficiency of the cookstove is the ratio of energy consumed during heating and evaporation of water to the energy given by burning the fuel. Thermal efficiency is calculated using Eq.3.1(PCIA & Global Alliance, 2013).

$$\eta_{th} = \frac{4.186\left(T_f - T_i\right) \times (m_{vw} - m_v) + 2260.\,m_{evap}}{m_{fuel} \times LCV_{fuel}} \tag{3.1}$$

The notations T, m and LCV denotes the temperature (°C), mass (kg) and Lower calorific value (MJ/kg), respectively, while the subscripts f, i v, w,vw and $evap$ denote final, initial, vessel, water, vessel and water; and evaporated water, respectively.

The other performance parameters, including Burning Rate (BR), Fire Power (FP), Specific Fuel Consumption (SFC), and Turn Down Ratio (TDR) are calculated using Eqs. (3.2-3.5).

$$BR = \frac{m_{fuel}}{\Delta t} \tag{3.2}$$

$$FP = \frac{m_{fuel} \times LCV_{fuel}}{\Delta t \times 60} \tag{3.3}$$

$$SFC = \frac{m_{fuel}}{m_r} \tag{3.4}$$

$$TDR = \frac{FP_{high}}{FP_{low}} \tag{3.5}$$

where, Δt is the time taken to reach the local boiling point temperature from initial water temperature (min), and m_r is the effective mass of water boiled (g). m_r is calculated by subtracting the mass of the vessel from the final mass of the vessel and water.

3.2.3 Emission performance and measurement procedure

Emission performance of the cookstove consists of various parameters i.e., CO and NO_x emissions along with CO/CO_2 ratio (R) and combustion efficiency (η_{comb}). In the present work, the flue gas sampling was done by the hood method as described in IS 11760 :1986 to determine the emissions from the cookstove. As per Hood method, for exhaust emission measurement, flue gases are isolated from the atmospheric air by using a hood and then emissions (CO and NO_x) are recorded by the portable flue gas analyser (Testo-350). For data logging, the flue gas analyser is connected to a computer. At 10 s intervals, data points are captured. The analyser is automatically calibrated daily at start-up through its zero-calibration function. The reported emission concentrations refer to dry-basis measurements, with a correction to a 3% fixed oxygen level.

The CO/CO_2 ratio (R) is calculated as the representation of efficient combustion as given by various Indian standards i.e., IS 4246:2002 and IS 11760:1986. As per these standards, the value of this ratio should not exceed to 0.02. The combustion efficiency (η_{comb}) measures how efficiently the energy content of the fuel is converted into utilizable heat. The quantity of CO_2 and CO present in the flue gases are the primary indicators of combustion efficiency. Higher combustion efficiency denotes that there is more conversion of CO into CO_2 which indicates more efficient combustion. Eq. 3.6 is used to calculate the combustion efficiency.

$$\eta_{comb} = \frac{CO_2}{CO_2 + CO} \times 100 \tag{3.6}$$

3.3 Usability and safety attributes

Usability is a critical factor which influences the decision of cookstove purchase and adaptation for a long term. The usability assessment evaluates the cookstove performance in six major aspects i.e., fuel convenience, cooking performance, operability, maintenance, comfort and location-specific needs as per Usability Testing Protocols (UTP) developed by the Oregon State University (Moses and Maccarty, 2018). Whereas the attributes related to safety concerns of cookstove i.e., temperature of touchable parts and mechanical stability when the cookstove is in operation is termed as safety attributes. The schematic representation of the usability and safety attributes is shown in Figure 3.4.

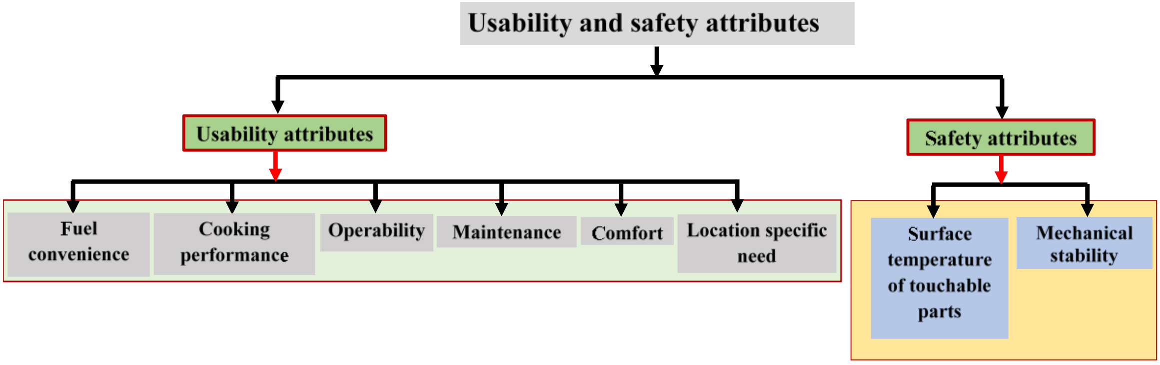


Figure 3.4 Schematic representation of the usability and safety attributes

Both field and laboratory testing methods have been used to evaluate the usability and safety attributes, respectively. A brief discussion on field and laboratory-testing methods adopted in the present work is given below.

Field testing: The field study was carried out at APL community in Guwahati city of Assam State. The selected households were given a free methanol cookstove for the study duration of 10 months i.e., from January 2019 to October 2019. At the start of the study, four fuel canisters filled with methanol were provided to the participants, with the expectation that they were responsible for depositing empty canisters and purchasing the refilled ones from the APL.

Laboratory testing: The cookstove characteristics evaluation was conducted at combustion laboratory of the Indian Institute of Technology, Guwahati, Assam, India, which surface temperature and mechanical stability of cookstove.

The evaluation of these attributes through field and laboratory testing method was started with the selection of cookstoves that are similar in nature and by providing an appropriate scoring criterion for the given attributes.

3.3.1 Selection of cookstove for comparison

The Indian government has initiated the methanol economy program with the motive to reduce the import of oil and to provide clean cooking fuel in the rural areas ("Methanol Economy," 2018). With the support of Project Gaia, the Government of Assam, India got the access to the usage and distribution of the methanol cookstoves. The methanol cookstove is actively being promoted as an alternative to the LPG cookstove, as the

Ministry of Petroleum and Natural Gas is estimated to spend $ 1.8947 million on LPG subsidy in 2021-22 (IEA, 2021). Also, LPG and methanol cookstoves operate on fuel, which represents the cleanest household energy solutions (PPAC, 2020). Therefore, for a fair assessment, the performance of the methanol cookstove in terms of usability and safety attributes is compared with the LPG cookstove and properties of both the fuels are listed in Table 3.2 (Dinesh et al., 2022).

Table 3.2 Properties of Methanol and LPG

Properties	Methanol	LPG
Density (kg/m^3)	790	545
Boiling point (^{o}C)	65	45
Enthalpy of vaporization (kJ/kg)	1110	360
Autoignition temperature (^{o}C)	470	445
Flammability limit (%volume)	6.7-36	2.4-9.5
Stoichiometric air-fuel ratio	6.5	15.7

3.3.2 Usability scoring criteria

In all the six main usability criteria's, the rank is evaluated as a weighted average of sub-criteria (listed beneath each main usability criteria). Weights are generally calculated from the Likert-scale questions addressing the importance of each sub-criterion to the user and are assigned a value from 0-4. The given protocol is meant for assessing the wood-burning and charcoal cookstoves. Therefore, some of the aspects of this protocol are modified carefully for the assessment of gas (LPG) and liquid (methanol) fuel cookstoves. A brief introduction and rank scoring system for each attribute is discussed in Appendix II-A.

3.3.3 Usability measurement procedure

This section explains a detailed procedure adopted for evaluating the usability attributes of the tested cookstove. The cookstove usability tests are structured into three sections/phases based on the type of analysis requirements (Table 3.3). A brief overview of each section/phase and its requirements are discussed below.

Table 3.3 Overview of usability attributes testing methods

Section No.	Section/Phase Name	Method	When this section of the test should be done	Who should conduct this section of the test

1.	Participant Identification	(none)	Upon arrival at the household	Test administrator
2.	Cookstove Characteristics Evaluation	Quantitative (Laboratory and testing)	Before cooking starts, or after it is finished	Someone familiar with common stove designs
3.	User Cooking Event Observation	Quantitative (Field testing)	During preparation for cooking and throughout the cooking process	Someone familiar with common stove designs

Participant identification

This is the first phase for usability attributes measurement which identifies the participant, cookstove model(s), and test administrator(s) participating in the test. The entries were noted in a data collection form. One hundred cooks/participants from local households were selected from the Assam Petrochemical Limited (APL) community. The following criteria were used to select the participants:

a) Use LPG as primary cooking fuel;
b) No strategic transfer in the next 3-5 months;
c) Average family size of 4-5 people;
d) Age group of 25-40 years;
e) Native of Guwahati region with the basic educational degree;

The cookstove model for methanol was provided by APL, whereas the LPG stove was purchased from the commercial outlet. An APL staff as a local expert in terms of culture and cooking, administered the qualitative portion of the UTP test protocol as the test administrator.

Cookstove characteristic evaluation

The evaluation of second phase was done basically to measure the performance of the cookstove in terms of ease of lighting, fuel feed entry or loading area size, indoor soot evaluation and burner count for the given cookstove model.

User cooking event observation

For the evaluation of third phase, cooks/participants were asked to prepare the main meal of the day as described in Table 3.4 as they normally do in the kitchen environment. Along with meal preparation, they were asked to observe and note the fuel preparation time, lighting time, cooking time, visibility of fire and soot deposited on vessel for the given stove.

Table 3.4 Average quantity of food for cooking

Food	Quantity (g)
Rice	1000
Pulse	300
Vegetables (Potato)	250
Wheat flour	250

3.3.4 Safety attributes and scoring criteria

The safety attributes i.e., surface temperature and mechanical stability of the tested cookstove are measured as per IS 11760:1986. The scoring criteria for safety attributes is made as per the studies conducted by Kimemia and Van Niererk (Kimemia and Van Niekerk, 2017) and the same is presented in Appendix II-B.

3.3.5 Safety attributes measurement procedure

Surface temperature of touchable parts

The cookstove is filled with the maximum recommended level i.e., 1.8 L of methanol and operated at maximum FP before starting the temperature measurement. Water of 2.8 L is filled in an aluminium vessel which is 205 mm in diameter and 110 mm in depth and placed over each burner of the cookstove. The temperature of lever/fuel regulating knob of the cookstove which may be necessary to touch during its operation is measured by using a T-Type thermocouple. The temperature of each such part is measured thrice every 50 min until equilibrium is reached. Whereas, in case of LPG cookstove same procedure has been performed with the charged cylinder of 14.2 kg capacity.

Mechanical stability (Assessment of overturning)

The test of stability for methanol cookstove is conducted in both the condition, when the canister is full of fuel and empty. Whereas for LPG test is performed in normal operating conditions (Kimemia and Van Niekerk, 2017). During assessment of mechanical stability, the cookstove should be able to turn without overturning upto an angle of 20° on being released. The test is repeated thrice and the stable angle (at which no overturning takes place) is measured.

3.4 User survey

After the completion of usability and safety attributes evaluation, cooks/participants were asked to answer the question of the test administrator, mentioned in the usability protocol. Participants were interviewed once in every month for the period of 10 months and the time weighted average score for each attribute has been presented. A questionnaire was prepared for conducting the survey. A set of survey includes the question related to average cooking time per day, types of food cooked, nature of ventilation, the benefit obtained, problems faced and suggestions. The general objective was to know the response of users regarding the adoption of canister-based methanol stoves for long-term use. Table 3.5 illustrates the various attributes used in the feedback and their respective explanation.

Table 3.5 Attributes used in the feedback and their respective explanation

Attributes of canister based stove	Explanation
Safe and clean stove	No explosion and no formation of soot
Portable	Stove is easy to carry from one place to another
Compact	Stove is compact in structure
Refilling	Methanol is required to be filled in the canister, once the fuel is consumed
No problem	There is no problem in operating the stove
Height of the stove	The height of the given stove is found to be higher than conventional LPG stove
Slower than LPG	The stove takes more cooking time compared to LPG stove
Increase capacity of canister	Canister fuel carrying capacity should be increased in order to avoid frequent refilling

3.5 The Uncertainty analysis

Table 3.6 presents the specifications of the instruments involved in the present experimental studies. The relative uncertainty associated with the calculation of various parameters (η_{th} and η_{comb}) is evaluated using the sequential perturbation technique (Devi et al., 2019). The uncertainties in the measurement of η_{th}, η_{comb} and CO/CO_2 ratio are obtained from the

Eqs. 3.9, 3.10 and 3.11. The maximum relative uncertainty for η_{th}, η_{comb} and R and are ±1.4%, ± 0.14% and ± 4.7%, respectively.

Table 3.6 Specification of the instruments used in the experiments

Measured Parameters		**Instrument**	**Accuracy**
Mass of water and pan		Electronic weighing balance	0.1 g
Temperature of water		Thermometer	±0.5°C
Emissions	CO	Testo-350, Flue gas analyser	±1 ppm (0-199 ppm) ±5% of reading (200-20000 ppm)
	CO_2		±1% of reading
	NO_x		±1 ppm (0-99 ppm)

$$\delta(\eta_{th}) = \left(\left(\frac{\partial \eta_{th}}{\partial m_{fuel}}\right)^2 \times (\delta m_{fuel})^2 + \left(\frac{\partial \eta_{th}}{\partial m_{vw}}\right)^2 \times (\delta m_{wv})^2 + \left(\frac{\partial \eta_{th}}{\partial (m_{vw} - m_v)}\right)^2 \times (\delta (m_{vw} - m_v)^2) + \left(\left(\frac{\partial \eta_{th}}{\partial \Delta T}\right)^2\right) \times (\delta \Delta T)^2\right)^{1/2} \tag{3.9}$$

$$\delta(\eta_{comb}) = \left(\left(\frac{\partial \eta_{comb}}{\partial CO_2}\right)^2 \times (\delta CO_2)^2 + \left(\frac{\partial \eta_{comb}}{\partial (CO + CO_2)}\right)^2 \times (\delta (CO + CO_2))^2\right)^{1/2} \tag{3.10}$$

$$\delta(R) = \left(\left(\frac{\partial R}{\partial CO}\right)^2 \times (\delta CO)^2 + \left(\frac{\partial R}{\partial (CO_2)}\right)^2 \times (\delta (CO_2))^2\right)^{1/2} \tag{3.11}$$

3.6 Results and Discussions

The results obtained from thermal performance (Optimized mineral wool quantity, η_{th}, BR, SFC, FP and TDR), emission performance (CO, NO_x emission, CO/CO_2 ratio and η_{comb}), usability and safety attributes and user survey analysis are discussed in details.

3.6.1 Effect of mineral wool quantity

The fuel capacity and mineral wool quantity mentioned in Table 3.1 for the methanol cookstove were modified by varying the mineral wool quantity in the canister. It was observed that 900 g of mineral wool can adsorb the maximum amount methanol i.e., 1.8 litre. As illustrated in Figure 3.3, the maximum variation of 20% in methanol loading capacity is observed by varying the mineral wool quantity from 600 g to 900 g.

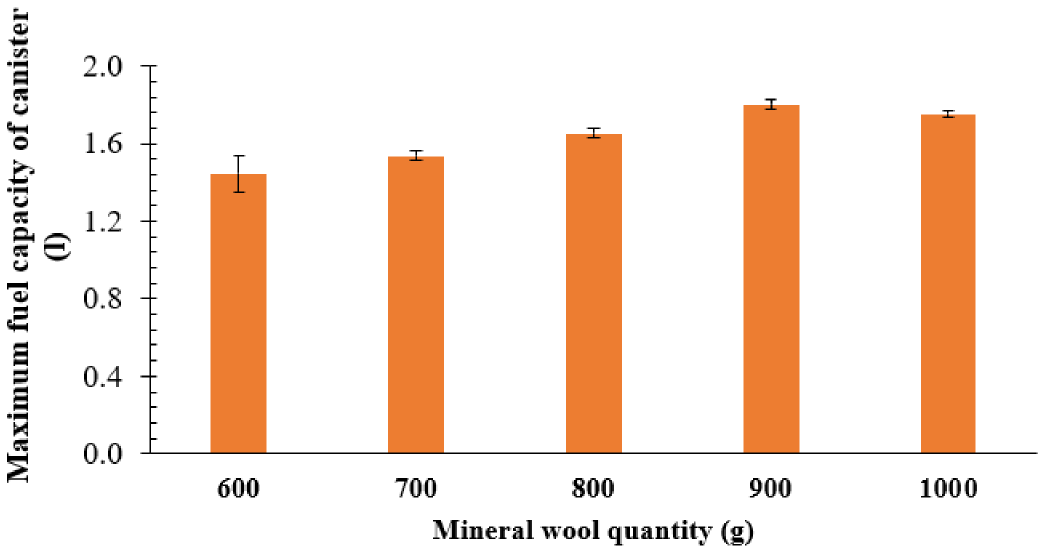


Figure 3.5 Maximum fuel capacity vs mineral wool quantity in the canister

3.6.2 Thermal efficiency

Table 3.7 shows the result obtained from the performance assessment of the tested cookstoves using WBT prescribed by ISO in terms of η_{th}, BR, SFC, FP and TDR. In WBT, the cookstoves were tested at high FP (cold and hot start) and low FP (simmer) settings. At high FP setting, the methanol cookstove has the highest thermal efficiency of 63.4% at high FP setting. However, in a low FP setting, the LPG cookstove offered the highest thermal efficiency of 57.8%. The methanol cookstove shows higher SFC and BR which is due to the lower energy content of fuel that increases the rate of fuel consumption. With a TDR ratio of 1.1, the methanol cookstove shows the lowest degree of FP modulation which is due to prolonged heating operation (simmer phase), which in turn increases the rate of evaporation of fuel even after partial closing of the canister opening by the cookstove lever.

Table 3.7 Thermal parameters of methanol and LPG cookstoves

Parameters	FP	Methanol cookstove	LPG cookstove
η_{th} (%)	High	63.4	59.1
	Low (simmer)	50.1	57.8
BR (g/min)	High	5.3	3.3
	Low (simmer)	4.8	1.7
SFC (g/l)	High	39.7	15.1
	Low (simmer)	130	50.2
FP (kW)	High	1.6	2.5
	Low (simmer)	1.4	1.3
TDR		1.1	1.9

3.6.3 Emission performance

The results of exhaust gas emission measurement and combustion efficiency are shown in Table 3.8. The maximum CO emission from methanol and LPG cookstoves were 123 and 44 ppm, respectively. For high and low FP settings, the η_{comb} for the methanol cookstove were 99.5% and 99.2%, whereas in case of LPG cookstoves, the corresponding values were 99.5% and 99.8%. The methanol cookstove showed equal combustion efficiency at high FP, which is mainly due to limitation of maximum FP in case of methanol cookstove (1.6 kW). However, the methanol cookstoves showed lower combustion efficiency as compared to LPG cookstove because of prolonged heating operation of methanol cookstove in simmer phase which leads to increase in the fuel evaporation rate. In the case of methanol and LPG cookstove, the soot formation is negligible.

Table 3.8 Emissions and combustion efficiency from tested cookstoves

Emission Parameters	FP	Methanol cookstove	LPG cookstove
CO (ppm)	High	81	89
	Low (simmer)	123	44
NO_x (ppm)	High	0.3	25
	Low (simmer)	0.1	5
CO/CO_2	High	0.005	0.004
	Low (simmer)	0.008	0.001
η_{comb}	High	99.5	99.5
	Low (simmer)	99.2	99.8

3.6.4 Usability and Safety Attributes

User feedback was collected through the data collection form and calculations were carried in the data processing spreadsheet for all the usability attributes. Scores for each of the usability and safety attributes were calculated as a weighted average of sub-criterion scores for sample size (n = 100) and 95% confidence level. For all the criteria studied, the relative weightage for both the cookstove in each sub-criterion obtained a score of 3 or above 3, reflecting the positive response of the participants. For both the cookstoves, lower margin of error (ME) of less than 0.5 represents (as per protocol) a strong agreement between all participants.

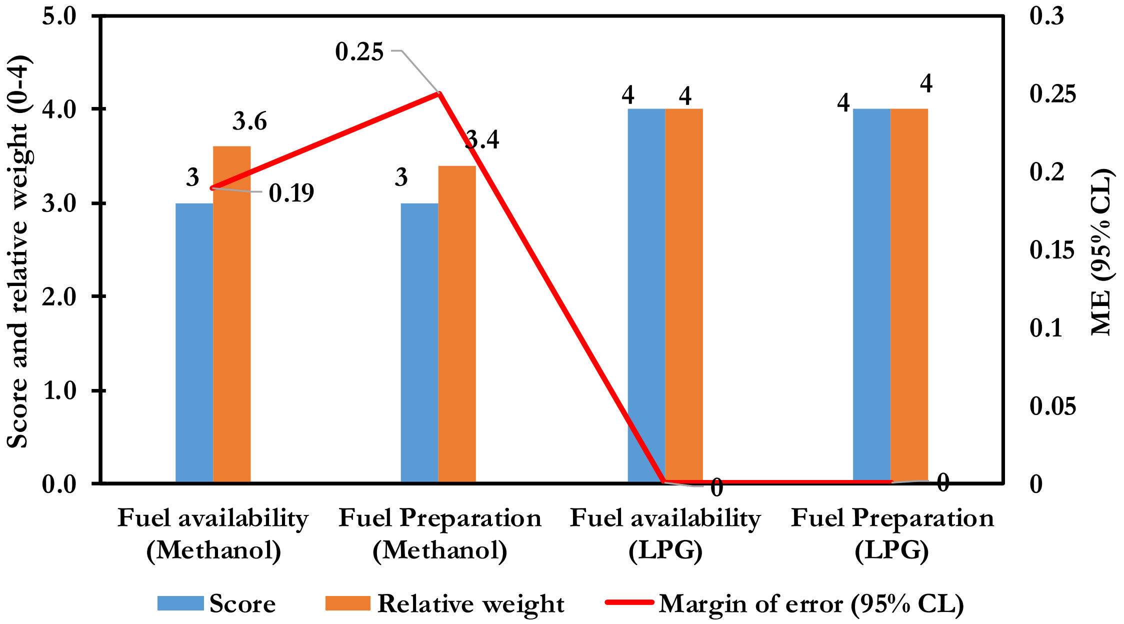


Figure 3.6 Fuel convenience results for both methanol and LPG cookstoves

Fuel convenience

Figure 3.6 shows the fuel convenience score evaluated in terms of sub-criteria fuel availability and preparation. The availability of methanol fuel scored 3, as all the participants were residents of the community near the production site of methanol, which makes the fuel procuring time in the range of 5-15 min. In the case of fuel preparation time, methanol cookstove required less than one min for inserting the canister inside the cookstove body and thus secured a score of 3. LPG cookstove secured a score of 4 (Best) in the sub-criterion of fuel availability, as LPG distribution is well established in the APL township and readily available to houses by home delivery system. The fuel preparation time for the LPG cookstove secured a score of 4 as there was no time required for the preparation of the cookstove.

Cooking performance

Participants observed that the average cooking time for the methanol cookstove was twice that of the LPG cookstove as shown in Table 3.9 which is due to lower energy content of fuel i.e., 18.5 MJ/kg, whereas, the same for LPG is 45.6 MJ/kg. The cooking performance score and the corresponding sub-criteria score are presented in Table 3.10. Participants faced difficulty in controlling the FP, as methanol cookstoves were observed to operate at the same FP for all the lever positions. The reason for such behaviour is due to poor lever design which cannot control the vaporisation of methanol from canister opening. Both the cookstove secured a rank of 4 in terms of versatility, which demonstrated their compatibility with available pots/vessels sizes. The cooking performance also revealed that 10134.3 MJ of energy is consumed in case of methanol cookstove and 8094 MJ with LPG cookstove. Methanol cookstoves requires 20.2% higher energy for cooking as compared with LPG.

Operability

The operability of a cookstove is judged according to the various sub-criteria as mentioned in Table 3.11. In terms of operability, the methanol cookstove shows an overall score of 2.9 compared to 4 for the LPG cookstove. The lower score is primarily due to refuelling time because for an average family size of 4-5 people with a frequency of cooking 3 times per day, the refuelling frequency for methanol cookstoves was found to be 5-6 days, while the same for LPG cookstoves was 28 days.

Table 3.9 Average fuel consumption and cooking time for selected meal

S. No.	**Food item**	**Methanol cookstove**		**LPG cookstove**	
		Cooking time (min)	Fuel (g)	Cooking time (min)	Fuel consumption (g)
1.	Rice (1 kg)	20.2	103.2	10.3	36.5
2.	Chapattis (0.25 kg)	12.2	42.6	8.1	24.8
3.	Dal (0.3 kg)	51.2	269.7	23.1	76.7
4.	Potato (0.25 kg)	25.1	132.3	12.3	39.5
Total		108.7	547.8	53.8	177.5

Table 3.10 Cooking performance results for both methanol and LPG cookstoves

Cooking performance		Methanol cookstove			LPG cookstove		
		n=100 Score	Relative weight	ME (95% CL)	n=100 Score	Relative weight	ME (95% CL)
A.	Cooking speed	1.2	4.0	0.17	3.4	4.0	0.28
	Cooking duration (measured: h:min)	1:49		0:05	00:54		0:02
B.	FP control	1.9	4.0	0.12	4.0	4.0	0.00
C.	FP range	1.6	4.0	0.13	4.0	4.0	0.00
D.	Versatility	4.0	4.0	0.00	4.0	4.0	0.00
Overall performance tier:				2.2			3.9
Highest subcategory ME:				0.17			0.28

Another contributing factor towards a lower score in methanol cookstove is flame visibility. The methanol flame is difficult to see in daylight. Methanol burns with a cooler flame lower flame temperature (600-750°C) due to lower heat of combustion and produces no carbonaceous particle and the flame radiates at infrared wavelength. Whereas, LPG cookstoves showed better performance in terms of flame visibility due to higher flame temperature. Both the cookstoves do not require any specific time for lighting because they ignite instantly because of their low flash point temperature. In case of methanol, the flash point is 12°C and for LPG, it is -104°C. There is no fire start up delay for both the cookstove as the vessel can be placed instantly on the cookstove after lighting the cookstove.

Table 3.11 Operability results for both methanol and LPG cookstoves

Operability		Methanol cookstove			LPG cookstove		
		n = 100			n = 100		
		Score	Relative weight	ME (95% CL)	Score	Relative weight	ME (95% CL)
A.	Refuelling time	1.0	4.0	0.00	4.0	4.0	0.00
B.	Visibility of fire	2.4	4.0	0.18	4.0	4.0	0.00
C.	Ease of lighting	4.0	4.0	0.00	4.0	4.0	0.00
D.	Fire start-up delay	4.0	4.0	0.00	4.0	4.0	0.00
Overall performance tier				2.9			4.0
Highest subcategory ME				0.18			0.00

Maintenance

As shown in Figure 3.7, both the cookstoves scored the same ranking in the overall maintenance criteria, which shows that the cookstoves are free from wear and can be declared as a long lasting cookstove. The bodies of both the cookstoves are made of stainless steel and have no pumping system, which makes them more suitable in case of both long and short terms of maintenance. In the present case, for methanol cookstoves, participants have provided their response based on 10 months' operation.

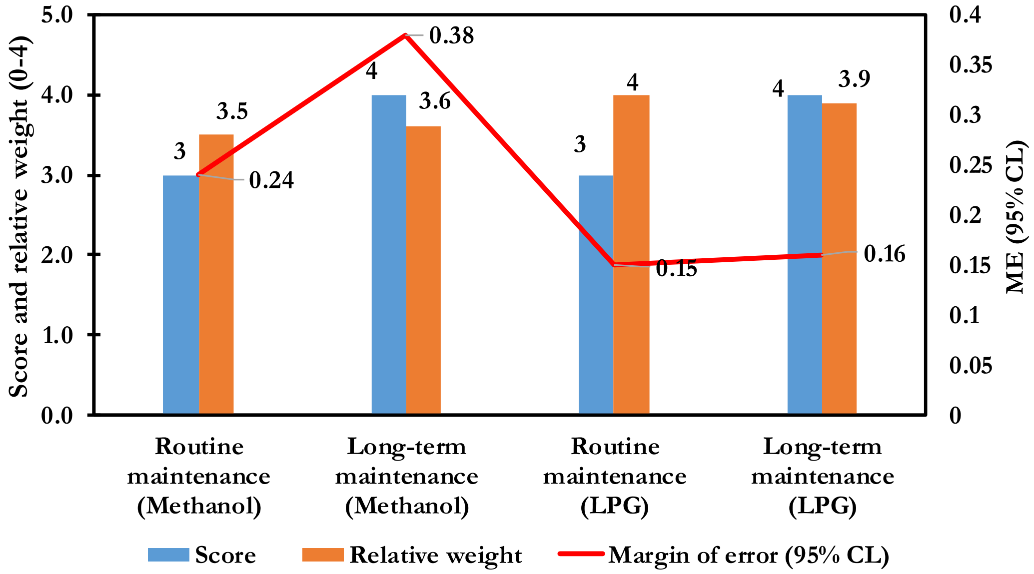


Figure 3.7 Maintenance results for both methanol and LPG cookstoves

Comfort

Table 3.12 shows the scores of all the sub-criteria which is responsible for the estimation of comfort score for both the cookstoves.

Table 3.12 Comfort results for both methanol and LPG cookstoves

Comfort		Methanol cookstove			LPG cookstove		
		Score	Relative weight	ME (95% CL)	Score	Relative weight	ME (95% CL)
A.	Perceived safety	4.0	4.0	0.00	4.0	4.0	0.00
B.	Perceived smoke exposure	4.0	4.0	0.00	4.0	4.0	0.00
C.	Cooking area soot deposit	4.0	2.0	0.00	4.0	2.0	0.00
D.	Vessel soot deposits	4.0	2.0	0.00	4.0	2.0	0.00
E.	Cooking height	4.0	4.0	0.00	4.0	4.0	0.00

F.	Stove aesthetics	4.0	4.0	0.00	4.0	4.0	0.00
G.	Perceived durability	4.0	4.0	0.00	4.0	4.0	0.00
H.	Perceived value	4.0	4.0	0.00	4.0	4.0	0.00
I.	Taste	2.0	4.0	0.00	2.0	4.0	0.00
Overall performance tier:				3.8			3.8
Highest subcategory ME				0.00			0.00

Based on the scores provided by the participants, both the tested cookstoves were found to be best in a way that makes them more suitable in all aspects. In the case of perceived safety, both the cookstoves got the most positive response of “It feels very safe to use”. In terms of other sub-criteria viz. smoke exposure, soot deposit, cooking height, aesthetics, durability and perceived value, equivalent scores were obtained for both LPG and methanol cookstove. Both the cookstoves were similar in construction material (stainless steel) and appearance. In terms of taste added to the food, users responded as “Neither better nor worse” for both the cookstove leads to a fair performance in the given sub-criteria.

Temperature of touchable parts

The temperature of the methanol cookstove (lever) after a 2 h burn cycle exhibited a rise in temperature of 58°C when operating at the highest FP rating. The cookstoves were subjected to higher contact burn chances while operating for long working hours and thus scored 1 in such attributes. The cookstove lever being made of stainless steel of high thermal conductivity, undergoes a rapid rise in temperature, and therefore an insulating cover over the lever is suggested. Whereas in case of the LPG cookstoves, the lever or flame regulation valve is made up of heat resistant material which leads to a lower temperature rise of 40 °C.

Mechanical stability

At a stability angle of 20°, both the cookstoves were found to be mechanically stable and secured a score of perfect 4. A repeat of the stability tests with and without loading of fuel canister in case of methanol cookstove revealed that the cookstove is stable in both cases.

3.6.5 Overall observation from usability and safety attributes

A summary of the overall score in the usability and safety attributes for both the cookstove are presented in Table 3.13. The methanol cookstove displays equal scores in maintenance, comfort and mechanical stability criteria. Among six other evaluated usability and safety attributes, methanol cookstove demonstrated relatively lower scores as compared to LPG stove. This may not necessarily indicate that the cookstove is less efficient, but that the results for each sub-criterion should be examined in more detail once the methanol cookstove becomes a well-established cooking technology.

Table 3.13 Overall usability and safety results: Methanol and LPG cookstove

S No.	Attributes	Methanol cookstove		LPG cookstove	
		Score	Highest sub-cat. ME (95% CL)	Score	Highest sub-cat. ME (95% CL)
1.	Fuel convenience	3.0	0.25	4.0	0.00
2.	Cooking performance	2.2	0.17	3.9	0.28
3.	Operability	2.9	0.18	4.0	0.00
4.	Maintenance	3.5	0.38	3.5	0.16
5.	Comfort	3.8	0.00	3.8	0.00
6.	Location-specific needs	N/A		N/A	
7.	Temperature of touchable parts (°C)	1.0		3.0	
8.	Mechanical stability	4.0		4.0	

3.6.6 User survey analysis

Users were asked to list out the benefits, problems faced and suggestions for improvement of the methanol stove. The feedback collected from the users is shown in Figure 3.8. The most widely reported favourable trait (over 90% of the user) was that the stove was safe in use and clean. No smoke and soot formation were observed. In identifying the problems faced, around 30% of the user's found difficulty in frequently refilling the canister with methanol as one canister holds only 1.8-litre of methanol. The stove taking more time for cooking as compared to LPG was also the concern expressed by 16% of users. The foremost suggestion by the users (over 90%) was to increase the capacity or size of the canister to avoid frequent refilling. Few users (less than 8%) suggested decreasing the height of the stove, but 40% of respondents did not have any complaints about the distributed stove.

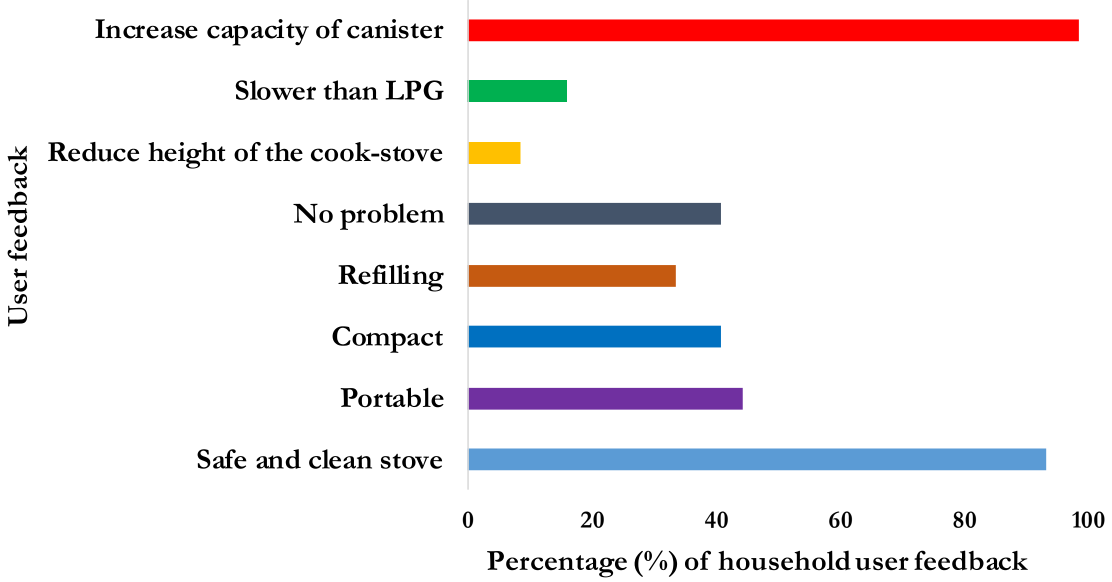


Figure 3.8 User feedback for canister based methanol cookstove

3.7 Fuel sustainability

Methanol is a clean-burning and biodegradable liquid fuel that can be obtained from non-renewable and renewable feedstocks. The non-renewable resources i.e., coal and natural gas-based methanol production is a well-established technology but have twice the carbon footprint as gasoline production (Natarajan, 2018). Production of methanol from renewable resources i.e., CO_2 captured from the atmosphere, agricultural residue and municipal solid waste is a promising and upcoming low-carbon technology. Compared to non-renewable resources, methanol production from renewable resources reduces carbon emissions by 65 to 95% depending on the feedstock and conversion process, which is one of the highest potential reductions of any fuel currently being developed to replace gasoline, diesel, coal and methane (Statista, 2018). Methanol mostly comes from the inedible portion of biomass crops, lignin and cellulose; rather than the starches and sugars required for ethanol production (Stokes and Crocco, 2005). Additionally, the combustion of pure methanol results in negligible NO_x, sulfur oxides (SO_x) and particulate matter.

Worldwide commonly used feedstock for the production of methanol is natural gas. The global production capacity of methanol is expected to double in twelve years from 2018, from approximately 140 Million Metric Tonne (MMT) in 2018 to around 280 MMT by 2030 (Statista, 2018). The methanol industry spans the entire globe, with production in Asia, North and South America, Europe, Africa and the Middle East. The global methanol industry generates $ 53.85 billion in economic activity each year, while creating over 90,000 jobs around the world (Methanol Institute, 2020).

In India, the methanol economy program was initiated by National Institution for Transforming India (NITI Aayog) with the aim of reducing the oil import bill dependency by 15%, and to lower the emission intensity of its GDP by 33-35%, by 2030 ("Methanol Economy," 2018). Above mentioned program plans to set up production plants with a total production capacity of 20 MMT/annum. Methanol can replace both petrol and diesel in the transport and energy sector along with retail cooking fuel i.e., LPG, Kerosene and wood charcoal. Among all the sectors, the replacement of methanol in the domestic cooking sector is the main concern of the methanol economy program. The major challenges of existing commonly used cooking fuels in India include shortage and unstable supply, affordability, availability, cost, safety and environmental considerations. These constraints made it necessary to replace the commonly used cooking fuels such as LPG with an alternative.

Methanol fuel Substitution Policy

In order to minimize the financial burden on Indian Government for providing LPG subsidy, there is a need for a sustainable alternate fuel for cooking that can bring down the subsidy allocated on LPG. Recently, the methanol fuel substitution policy has been explored by the Government to reduce the burden on the LPG import. Figure 3.9**Figure *3.9*** represents the LPG and kerosene demand projections for 2030 in India with and without penetration of methanol. As per the data provided by the Petroleum Planning and Analysis Cell of the Ministry of Petroleum and Natural Gas, the LPG and kerosene demand for 2020 was 30.32 MMT. The LPG projection for the year 2030 (36.9 MMT) is only considered for further analysis whereas, kerosene demand for the year 2030 is not taken into account. As the kerosene consumption registered a de-growth of 18.7% during July 2020 and a cumulative de-growth of 35.5% during April-July 2020 as compared to the same period of the previous year, which is mainly due to various government initiatives for the promotion of cleaner fuels such as LPG (Petroleum Planning & Analysis Cell, 2020).

Chemanalyst (Chemanalyst, 2020) forecasted the demand and production of methanol for the years 2020 and 2030. The analysis shows that the projected methanol production by the year 2030 (1.156 MMT) is going to result only 1.56% penetration rate. However, to achieve a penetration rate of 10% by 2030, 9.23 MMT methanol needs to be produced. The above-mentioned quantity of methanol can replace 3.69 MMT (equivalent amount) of LPG. The lower quantity of LPG is because of 2.5 times higher calorific value than that of methanol (18.5 MJ/kg). This means that burning almost two and a half times the quantity of methanol will provide the same amount of energy, as compared to LPG. With this reduction in demand for LPG, LPG import will be reduced by 22.2%.

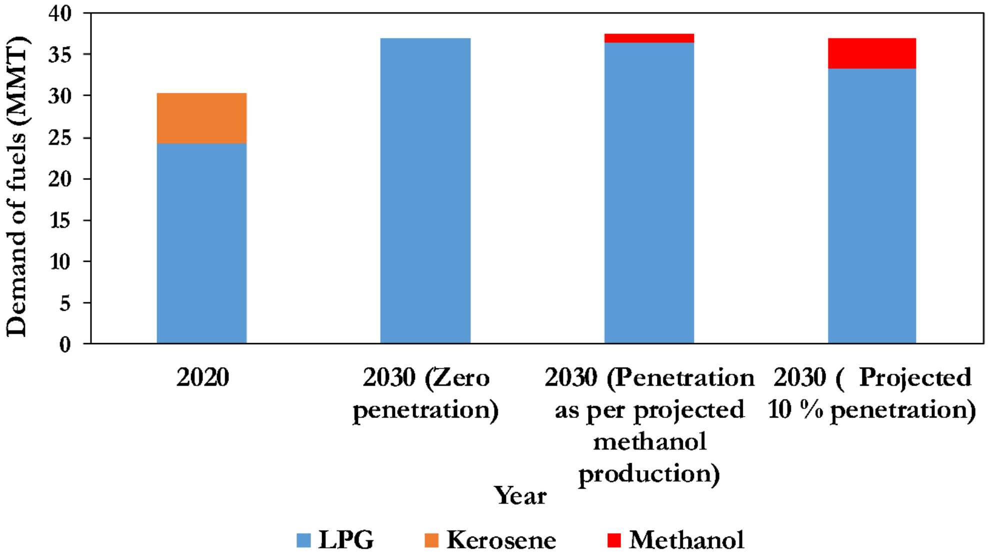


Figure 3.9 LPG and kerosene demand projections for 2030 with and without methanol

Methanol production strategies

Currently, India is producing methanol from imported natural gas. To make it economically viable, India should produce methanol from local coal and biomass resources. India has 319.02 billion tonnes of coal reserves as per the data provided by the Government of India (Ministry of Coal, 2018) and has been producing around 200 MMT of surplus biomass residues annually (Natarajan, 2018). With these resources, methanol can be produced in large quantities that lead to a significant reduction in the production cost of methanol. For example, if methanol is produced from coal, the expected cost of production will be $ 0.29–0.32 per kg (Saraswat and Bansal, 2017). Considering the present cost scenario of methanol (as provided by APL is 0.41 $/kg) and LPG (0.79 $/kg)(Indian Oil Corporation, 2021), it is found that LPG equivalent methanol cost is 27.6 % higher than LPG cost. Methanol production in terms of indigenous resources and technology can reduce the methanol cost by 32.2 % (Saraswat and Bansal, 2017), which leads to a decrement in the LPG equivalent methanol cost by 3.8 %. Based on the above-reduced methanol cost, LPG displacement by

10 % of methanol penetration can lead to LPG import cost saving of $ 311.42 million per annum. Harnessing methanol on a large scale will also set India on the road to achieving energy independence along with the creation of millions of jobs for the local community. Further, penetration of methanol into the cooking application will reduce environmental pollution to a larger extent.

3.8 Challenges and way forward

Usability and safety assessments of methanol cookstove provide an opportunity to address some of the complexities and challenges faced during the operation. Some problems emerged during usage of the methanol cookstove were identified after long-term use in both lab and field study. Results of user survey and semi-structured interview in the field study highlighted that the methanol cookstove with low cooking speed, as well as stove malfunctions due to poor design may influence many methanol cookstove adopters to quit it. For an effective adoption of methanol cookstove, it will be necessary to address the factors that tend to discourage its use, particularly lower capacity of the canister and poor stove design. Some of the of the challenges of the existing methanol stove and their way forward are given in Table 3.14.

Table 3.14 Challenges and way forward for methanol cookstove

S. No	Study(s)	Challenges	Way forward
1.	Laboratory	Temperature rises of 50-60°C in lever/handle part after 2h of continuous operation.	Lever should be covered with thermosetting plastic to avoid unwanted heating
2.	Laboratory and field	There is no marking of 'ON' and 'OFF' on the lever part of stove body which leads difficulty in operating the stove	Lever should be marked with 'ON' and 'OFF' position
3.	Laboratory	Immediate removal of canister after working operation from stove body leads to higher concentration of methanol vapour accumulation on the top surface which can affect the eyes	Avoid direct eye contact during removal of canister from the cookstove. Remove the canister after 10 min from switching off the stove.
4.	Laboratory	Leakage of methanol from canister inside the stove body due to poor design	Canister should be taken out after operation from stove body and cover with the lid

			(10 min after the lever is turned off)
5.	Laboratory and field	Low fire power and cooking speed	Methanol should be tested with pressurized stoves
6.	Laboratory and field	Sometime lever is not able to turn off the flame even after closing the lever in 'OFF' position	Operate the lever of stove body from 'ON' to 'OFF' position several times until the flame from the canister turns off or remove the canister from stove body by using protective gloves and turn off the flame by putting woollen clothes on the canister opening.

Note-The conclusion of 10 min duration has been made based on the observation made during the removal of canister from stove. As instant removal of canister leads to burning sensation in the eye of user who removes the canister from stove due to sudden escape of methanol vapour from the canister. Rigorous tests have been performed and it has been concluded that 10 min (considering safety limit) is sufficient time for removal of canister without any burning sensation in eyes.

3.9 Summary

A canister-based methanol cookstove thermal performance was optimized with respect to mineral wool (900 g) and fuel quantity (1.8 L). The methanol cookstove performance was compared with the available LPG cookstove in terms of thermal and emission performance along with usability and safety attributes. The experimental results showed that the methanol cookstove yielded a maximum efficiency of 63.4%, whereas the same was 59.1% for LPG cookstove. The methanol cookstove showed clean-burning as the emission of CO was limited to 123 ppm and the same was comparable to that of the LPG cookstove. Methanol cookstove performs extraordinarily with the score of 3.5, 3.8 and 4 in terms of maintenance, comfort and mechanical stability criteria which are similar to the score of LPG cookstove. The result of user survey analysis showed that 90% of user are satisfied with the cookstove in terms of safety and cleanliness whereas 30% and 16% user showed concern about its frequent refilling and longer cooking time compare to LPG. Fuel sustainability analysis highlights that methanol is a cleaner cooking fuel option, which can play a crucial part to achieve Sustainable Development Goals (SDGs). Analysis shows that with 10% methanol penetration, 3.69 MMT of LPG can be replaced by 2030 and the production of methanol with coal and biomass are found to be economically viable indigenous resources in India. The challenges faced during studies were also highlighted. Therefore, the present study recommends the Government of India and other role players in India to set affirmative action programs with budgets, targets and timelines for the promotion of methanol cookstove.

Chapter 4 Development of PMC based methanol cookstoves

Preface

In order to address the shortcomings of FFC based methanol cookstoves as discussed in earlier chapter like higher cooking time, low Fire Power (FP) and heating of lever part due to prolong operating hours, a PMC based methanol cookstove was developed in pressurized mode. Initially, an attempt was made with the conventional pressurised cookstove which leads to a conclusion that such cookstove with FFC based burners are not able to sustain the flame and stop after few minutes. However, the use of PMC based burner i.e., Porous Radiant Burner due to its enhance combustion characteristics and newly designed vaporizer leads to stable operation of cookstove.

4.1 Challenges in FFC based Pressurised Methanol Cookstove

Development of PMC based pressurised methanol cookstove have been carried out in two phases. In phase I, the development was initiated with a pressurised kerosene cookstove with FFC based burner to understand combustion characteristics of methanol in a pressurised cookstove. Shortcoming of FFC based burner of studied pressurised cookstove was then addressed in phase II by replacing it with PMC based burner. In phase I of development, the FFC based conventional pressurized kerosene cookstove was operated by filling the methanol inside the tank. Generally, three types of burners (venus, silent and roarer) of conventional pressurized kerosene cookstove are available in Indian market. All these burners consist of two ascending tube and two descending tubes and contain a vaporizer or flame holder. These burners differ only in terms of vaporizer designs. The roarer burner gives the higher heat generation due to better fuel vaporization technique but leads to more noisy operation. The silencer burner basically covered with a copper cap with holes to reduce the noisy operation but leads to lower heat generation as compared to a roarer burner. Whereas venus burner is more efficient as compared to both other burner due to better vaporization mechanism. A series of experiments were conducted on these burners (Figure 4.1).

(a) (b) (c)

Figure 4.1 Conventional pressurized kerosene cookstove burners: (a) venus, (b) silencer and (c) roarer

From the initial experimentations, it was observed that the available conventional pressurized kerosene cookstove with above listed burners cannot be operated with methanol as there was no sustained flame. After that modification was made with regards to orifice diameters. Larger orifice diameters were used in conventional pressurized kerosene cookstove. From the tested orifice diameters i.e., 0.4 mm, 0.6 mm, 0.8 mm, 1 mm and 1.2 mm, sustainable flame was observed with only 1 mm orifice diameter (Table 4.1).

Table 4.1 Observations from diameter variations in methanol operated conventional pressurized kerosene cookstove

S. No	Nozzle diameter (mm)	Observation	Burner types
1.	0.4	Extinction of flame after ~3 s	(a) venus
		Extinction of flame after ~6 s	(b) silencer
		Extinction of flame after ~4 s	(c) roarer
2.	0.6	Extinction of flame after ~30 s	(a) venus
		Extinction of flame after ~45 s	(b) silencer
		Extinction of flame after ~38 s	(c) roarer
3.	0.8	Extinction of flame after ~5 min	(a) venus
		Extinction of flame after ~7 min	(b) silencer
		Extinction of flame after ~6 min	(c) roarer
4.	1	Sustainable flame	a) venus, (b) silencer and (c) roarer

5.	1.2	Abrupt burning	a) venus, (b) silencer and (c) roarer

The details of the observations made with orifice diameter of 1 mm are listed in Table 4.2.

Table 4.2 Observations from methanol operated conventional pressurized kerosene cookstove with orifice diameter of 1 mm

Burner types	Observation
Venus	• Operates in the pressure range of 0.5-1 bar • Operates in the flow range of 300-430 g/h • Increase in pressure leads to noisy operation • Yellowish orange flames • Fluctuating flames • Flashback occurs • Discontinuous and abrupt burning at higher power input
Silencer	• Operates in the pressure range of 0.5-1 bar • Operates in the flow range of 300-450 g/h • Less noisy in operation • Yellowish orange flames • Fluctuating flames • Flashback occurs • Higher pressure i.e. (1-1.5 bar) leads to removal of burner head • Discontinuous and abrupt burning at higher power input
Roarer	• Operates in the pressure range of 0.5-1 bar • Operates in the flow range of 300-430 g/h • Increase in pressure leads to noisy operation • Yellowish orange flames • Fluctuating flames • Flashback occurs • Discontinuous and abrupt burning at higher power input

Further a vaporizer was fabricated with multiple holes (orifices) (Figure 4.2). The vaporizer is of helical arrangement of copper pipe (6 mm ID) with 12 no. of holes at the top. However, this design also found to be not suited for methanol operation.

Figure 4.2 Conventional modified vaporizer

From the experiments, it was concluded that with methanol, conventional pressurized kerosene cookstove with venus, silencer, roarer modified burners failed to produce quality sustainable flame. The main reasons can be because of different thermophysical properties of methanol and kerosene. The thermophysical properties of the fuels viz., methanol and kerosene are given in Table 4.3. The properties of methanol, high miscibility in water and high latent heat of vaporization as compared to kerosene, results in the above observed cookstove operations. The effects of these properties on the combustion of methanol in conventional pressurized kerosene cookstove are given below:

High miscibility in water: Since methanol is completely miscible in water, before or during methanol droplet burning in air, methanol will absorb water. The effect of water absorption results in a non-d-square combustion behavior and promotes flame extinction. During non-d-square combustion, the square of the droplet diameter does not decrease linearly with time. This phenomenon is characterized by a small Damkohler number, which represents the ratio of diffusion time to reaction time. When the Damkohler number becomes too small, there is insufficient time for the chemical heat release to occur in the flame surrounding the liquid sphere. As a result, the flame is extinguished.

High latent heat of vaporization: Methanol has higher latent heat of vaporization than kerosene because of which it extracts more heat as it vaporizes that leads to more cooling effect on the incoming air mixture resulting in flame extinction.

Table 4.3 Thermophysical properties of methanol and kerosene

Properties	Methanol	Kerosene
Latent heat of vaporization (kJ/kg)	1100	251
Flammability limit, vol % in air	6.7-36	0.7-5

Vapour density	1.42	4.5
Dynamic viscosity (20°C) (mPas)	0.57	1.92
Lower calorific value (MJ/kg)	18.5*	43.9*
***** *The properties are evaluated at IITG laboratory.*		

Therefore, the experimented cookstove needs to be modified to overcome the above limitations of methanol. For which in next phase PMC technology based PRB for pressurized methanol cookstove are developed.

Therefore, the experimented cookstove needs to be modified to overcome the above limitations of methanol. For which in next phase PMC based PRB for pressurized methanol cookstove are developed.

4.2 Development of PMC based Methanol Cookstove

Developed pressurized methanol cookstove consists of a PRB (vaporizer and porous matrix of Silicon Carbide (SiC)) and a cookstove body. The cookstove body is kept similar to that of the conventional one and the focus is on the development of PRB. Design of the intended PRB involved (i) selection of vaporiser, (ii) selection of size of porous matrix and (iii) selection of orifice diameter and position.

(i) Selection of vaporiser: Two different shaped vaporisers were fabricated (Table 4.4) with main aim to increase heat transfer from porous matrix to the incoming air fuel mixture. Vaporizers were fabricated with copper tube of standard size of 3/8 inch. Between the tested vaporizer configurations, configuration 2 showed better performance. Improved performance was due to availability of increased surface area for heat transfer from porous matrix to the vaporizer.

Table 4.4 Different designs of methanol vaporizer

S. No.	**Vaporiser**		**Configuration**
1.			• 2 ascending and 2 descending copper pipes (6 mm ID) are interconnected at the nozzle in the form of helical structure

2.			• 2 ascending and 2 descending copper pipes (6 mm ID) are interconnected at the top

(ii) Selection of porous matrix: Proper selection of porous matrix is the key factor for achieving better thermal efficiency and lower emissions. In order to study the effect of porous matrix diameter on the PRB operation, series of experiments have been performed. The work done by the earlier researchers lead to the selection of Silicon Carbide (SiC) as porous matrix of 90% porosity (Monikankana Sharma et al., 2009; Gyan Sagar Sinha and Muthukumar, 2019). SiC porous matrix is available in the commercial market in the range of 60-120 mm diameter with thickness 20 mm. In the present case, SiC porous matrix of 65 mm, 75 mm and 85 mm were tested (Figure 4.3). It was found that the PRB with 65 mm diameter yielded the complete red hot of the burner surface (Figure 4.4). Which was later used for detailed cookstove performance assessment. Burner casing to hold the porous matrix was made up of mild steel.

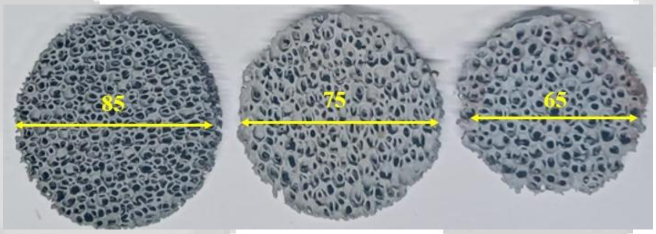
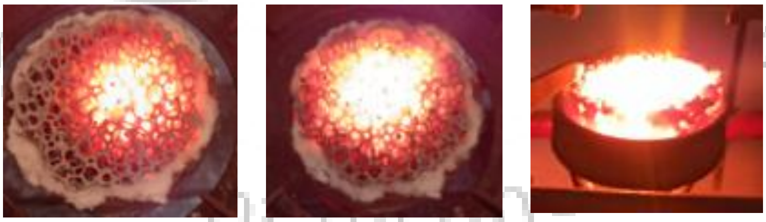


Figure 4.3 SiC porous matrix of different diameter



85 mm | 75 mm | 65 mm

Figure 4.4 PRB operation with SiC porous matrix of different diameter

Using the above selected vaporizer (configuration 2) and SiC porous matrix (65 mm) pressurised methanol cookstove has been fabricated. Pictorial view of the developed pressurised methanol cookstove and schematic of PRB used are shown in Figure 4.5 and Figure 4.6, respectively.

Figure 4.5 Pictorial view of PRB based pressurised methanol cookstove

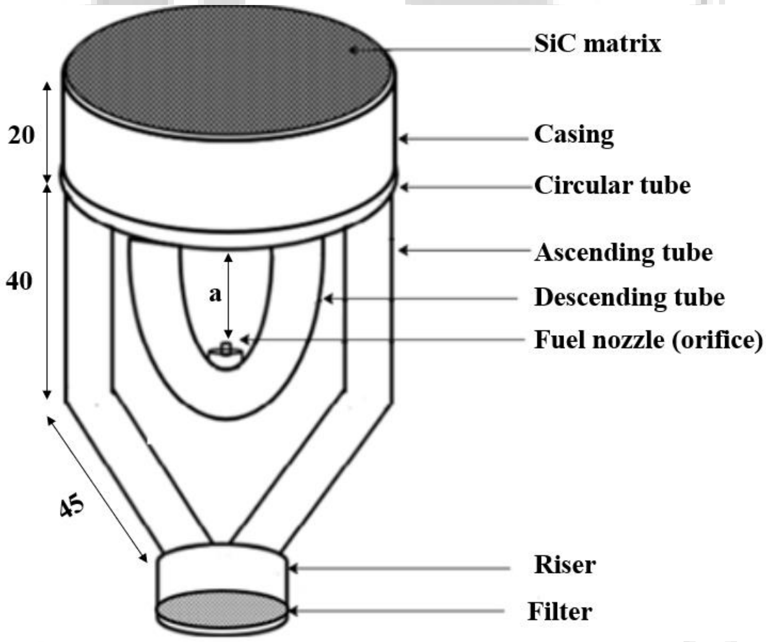


Figure 4.6 Schematic of PRB used in pressurised methanol cookstove

(iii) Selection of orifice diameter and position: In order to select the orifice diameter and position, stability assessment of the above developed pressurised methanol cookstove was carried with various combinations of orifice diameters and position (distance between nozzle and SiC matrix bottom surface) as shown in Table 4.5. The stability analysis was carried out at minimum FP of the developed pressurised methanol cookstove. The stable flame was observed for two combinations of orifice diameter and positions. With 55 mm orifice position, 0.8 mm and 1 mm orifice diameters resulted in stable flame. However, in case of 1 mm orifice diameter, operation was very noisy. Therefore, for detailed thermal and emission performance assessment 0.8 mm orifice diameter was selected.

Table 4.5 Effect of orifice diameter and position on flame stability

Orifice		Stability
diameter (mm)	position (mm)	
0.4	35	No sustainable flame
0.6	35	No sustainable flame
0.8	35	Flame with flashback
0.8	45	Flame with flashback
0.8	55	Stable flame
0.8	65	Extended flame ~ 100 mm (blowoff)
1	55	Stable flame

4.3 Performance parameters

As the developed cookstove was operating in pressurized mode, the thermal and emission performances were measured by conducting Water Boiling Test (WBT) and hood method by following the guidelines given in Indian standard for pressurized kerosene cookstove (IS 10109:2002). The performance parameters evaluated for PMC based methanol cookstoves are thermal efficiency, CO/CO_2 ratio and radial temperature.

4.3.1 Thermal efficiency

The thermal efficiency of the cookstove signifies the degree to which the chemical energy of the fuel is transferred to useful heat. The Water Boiling Test (WBT), is conducted to estimate the thermal efficiency of PMC based methanol cookstove. WBT is conducted by heating the water in flat bottomed aluminium vessel (size of the vessel and quantity of water are selected as per IS 10109:2002, depending upon the fuel consumption rate). The water in the vessel is heated from an initial temperature of 25 ± 2°C to a temperature of 90°C which is below the boiling point of water. The size of the vessel and quantity of water considered in the experiments are presented in Table 4.6.

Table 4.6 Aluminium vessel for thermal efficiency test as per BIS guidelines

Fuel consumption rate g/h	Vessel diameter ±5 mm	Vessel height ±5 mm	Total vessel weight with lid, g ±10%	Mass of water in vessel, kg
600-680	320	175	1100	11.4
300-370	245	130	632	4.8

$$\eta_{th} = \frac{(m_v \times C_v + m_w \times C_w) \times (T_f - T_i)}{m_{fuel} \times LCV_{fuel}} \quad (4.1)$$

The notations T, m, C and LCV denotes the temperature (°C), mass (kg), specific heat (kJ/kg K) and Lower calorific value (MJ/kg), respectively, while the subscripts f, i v and w denote final, initial, vessel, water, and evaporated water, respectively.

4.3.2 Emissions

CO and NO_x emission and CO/CO_2 are measured through the hood method as explained in section 3.2.3. As per IS guidelines CO/CO2 ratio is the measure of efficient combustion and its value should lie below 0.02 for efficient combustion.

4.3.3 Radial temperature

Temperature distribution in the radial directions of the PRB plays a vital role in thermal performance. It gives the reason for the variation of thermal efficiency and emissions at different FP. The radial temperature is measured along the surface of the PRB. K-type thermocouples are employed for the measurement of temperature and the respective thermocouple positions are shown in Figure 4.7.

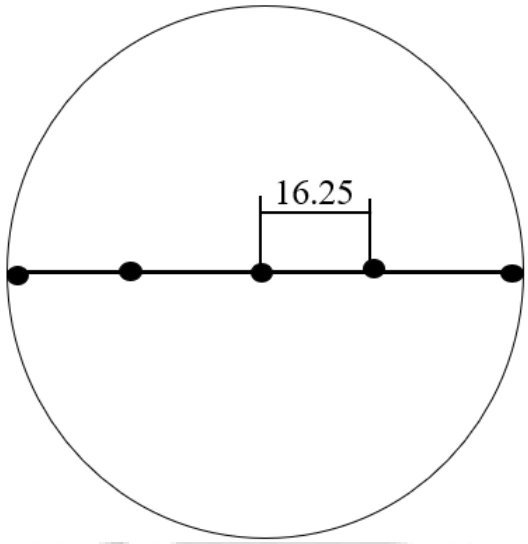


Figure 4.7 Radial positions of thermocouples on top surface of the PRB (in mm)

4.4 Results and discussion

4.4.1 Thermal efficiency

The thermal efficiency was measured for two FP condition i.e., 1.8 kW (370 g/h) and 3.5 kW (680 g/h), as the developed PMC based cookstove showed stable operation for this FP range. The results were presented in Table 4.7.

Table 4.7 Thermal efficiency variation with Fire Power

Fire Power (FP)	Thermal efficiency (%)
1.8 kW	66.6
3.5 kW	60.2

4.4.2 Emission performance

Emission performance includes parameters i.e., CO and NO_x emissions and combustion efficiency (η_{comb}). The measured and evaluated values are given in Table 4.8. It was observed that CO/CO_2 ratio was 70% and 60% lower than the prescribed limit (0.02), for low FP and high FP, respectively. Higher combustion efficiency was observed in both high and low FP conditions. This indicates efficient combustion in PMC based methanol cookstove. The NO_x emission is negligible for both the cases.

Table 4.8 Emission parameters for PMC based methanol cookstove

Parameters	Low FP (1.8 kW)	High FP (3.5 kW)
CO (ppm)	150	210
NO_x (ppm)	0.6	0.8
CO/CO_2	0.006	0.008
η_{comb} (%)	99.7	99.1

4.4.3 Radial temperature

The outputs of thermocouples were acquired through a data acquisition system, consisting of a data logger and multiplexer. The maximum temperature of 989 °C was found at the center and the minimum temperature of 590 °C was found at the periphery of the PRB. The maximum temperature at center is mainly due to rich air-fuel mixture formation near the center of the burner and with increase in distance from center, the mixture becomes leaner and losses to the surrounding also increases.

4.5 Performance comparison of FFC and PMC based methanol cookstove

The cookstoves performance was compared in terms of thermal efficiency and combustion efficiency and CO/CO_2 ratio. The results of comparison values are given in Table 4.9. It was observed that PMC based methanol cookstove yields 4.8% higher thermal efficiency than FFC based methanol cookstoves. Similarly, there is decrease in CO/CO_2 ratio by 33.3% due to use of PMC based cookstoves. The increase in compared parameters for the given FP is mainly due to use of increased heat transfer rate and efficient combustion in cookstoves (as explained in section 1.10).

Table 4.9 Performance comparison of FFC and PMC based methanol cookstoves

Performance parameters	FFC based methanol cookstove (FP-1.6 kW)	PMC based methanol cookstove (FP-1.8 kW)
Thermal efficiency (%)	63.4	66.6
Combustion efficiency (%)	99.5	99.7
CO/CO_2	0.008	0.006

4.6 Summary

The present chapter focusses on the development of PMC based methanol cookstove. The development has been carried out in two phases. The first phase explores the use of a conventional pressurized kerosene cookstove which operates methanol. However, sustainable flame (flame extinguishes after a certain time) was not attained. Therefore, the second phase utilizes the concept of PMC for developing the methanol cookstove. The developed PMC based methanol cookstove's PRB consists of a vaporizer and porous matrix of SiC. The newly developed cookstove gives maximum thermal efficiency of 66.6% at 1.8 kW. Further, CO/CO_2 ratio was found to be 70% and 60% lower than the prescribed limit (0.02), for low FP (1.8 kW) and High FP (3.5 kW), respectively. Comparison study on FFC and PMC based methanol cookstoves showed that there is increase in thermal efficiency and decrease in CO/CO_2 ratio by 4.8% and 33.3% respectively, due to PMC based cookstove.

Chapter 5 Feasibility Studies on Ethanol as Cooking fuel

Preface

The development of ethanol-based PMC cookstove require its comparison with available FFC based ethanol cookstoves. Initially, the performance of available ethanol cookstove was optimized by choosing the optimum quantity of the mineral wool filled inside the canister. And the effect of water addition on soot formation was also investigated.
Further, with the optimized FFC based ethanol cookstoves, the performance comparison was made with developed PMC based ethanol cookstove. The performance was evaluated in terms of thermal efficiency, combustion efficiency and Control Cooking Test.

5.1 Cookstove Characteristics

The FFC based fixed canister type ethanol cookstove and removable canister type ethanol cookstove were developed at IIT Guwahati through the industrial partner. Whereas, the PMC based ethanol cookstove was developed at Combustion lab of Indian Institute of Technology Guwahati, India. The design specification of all the selected cookstoves are given in Table 5.1.

Table 5.1 Design specification of the FFC and PMC based ethanol cookstove

Stove type	**FFC**		**PMC**
	Fixed	**Removable**	
Burner (s)	Double canister	Double Canister	Single burner
Cookstove body Dimensions (mm)	$L\times W\times H$: 600×250×90 d= 40; h=75 (Figure 5.1)	$L\times W\times H$: 650×310×100 d= 50; h=60 (Figure 5.2)	d = 70 h = 50 (Figure 5.3)
Canister/Tank capacity (l)	2.4	1.98	2
Burner diameter (mm)	90	80	65

5.1.1 FFC based fixed canister type ethanol cookstove

The pictorial view of a FFC based fixed canister type ethanol cookstove is shown in Figure 5.1. The cookstove consists of mild steel body which is powder coated with blue colour and the canister is fixed inside the cookstove body. The canister is cylindrical body which is filled with mineral wool to adsorb the fuel. By means of capillary action, the liquid ethanol travels from the mineral wool to the canister's top and to the evaporative surface. The side vents allow air to enter the combustion chimney, and the canister is sized to fit underneath it. In the chimney, ethanol vapour and air is combined to create a combustible mixture. When this mixture is ignited, combustion occurs above the surface of the canister opening. A self-sustained flame develops as the chimney heats. The top of the chimney has a flame spreader that serves as a diffuser and encourages fuel-air mixing.

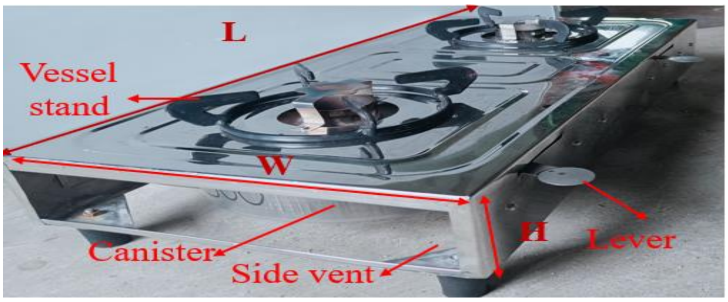
The fuel was filled inside the canister using fuel tank which consists of three slots that is to be fitted inside the gap provided on the middle of cookstove body. The anticlockwise rotation leads to filling of ethanol inside the canister and once the canister gets filled the float valve ceases the flow of ethanol inside the canister. The cookstove lever should be in shutoff position while filling of ethanol inside the canister.

(a) (b) (c)

Figure 5.1 Pictorial view of FFC based fixed canister type ethanol cookstove (a) cookstove body (b) fuel tank and (c) internal view of burner

5.1.2 FFC based removable canister type ethanol cookstove

The FFC based removable canister type ethanol cookstove is the cookstove in which canister is removable from cookstove body. It is also an evaporative cookstove and works on the same principle of methanol cookstove as explained in Chapter 3 (Section-3.1.2).



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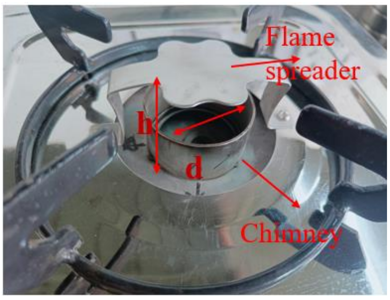


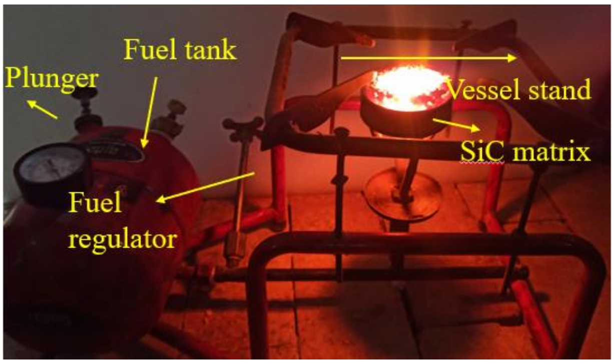
(b)

Figure 5.2 Pictorial view of FFC based removable canister type ethanol cookstove (a) cookstove body with canister and (b) internal view of burner

The FFC based removable canister type ethanol cookstove differs from above mentioned fixed canister type ethanol cookstove in terms of canister dimensions and fuel filling medium. The canister dimension for removable canister type – diameter: 220 mm and height: 60 mm whereas the same for fixed canister type – diameter: 204 mm and height: 38 mm. In case of fixed canister type cookstove there is separate fuel tank for filling the fuel inside the canister whereas in removable canister type cookstove fuel was filled inside the canister with the designated agency.

5.1.3 PMC based ethanol cookstove

The PMC based ethanol cookstove consists of Porous Radiant Burner (PRB) which is made of highly emissive (emissivity-0.9) and conductive (thermal conductivity -30 W/mK) porous ceramic matrix (Silicon Carbide). The heat transfer in PRB is completely different from that of cookstove based on FFC. In PMC a 3D porous ceramic matrix is used in the combustion zone to improve heat transfer from the burnt to the unburnt portion of the air-fuel mixture. Figure 5.3 shows a pictorial view of PMC based ethanol cookstove developed at IIT Guwahati. Details of the developed cookstove can be found in the recently filed patent (Muthukumar and Maurya, 2021).



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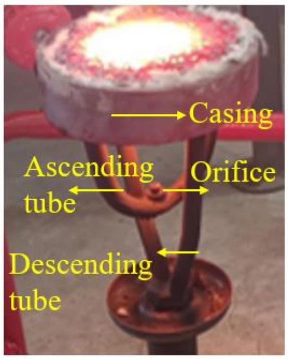


(b)

Figure 5.3 Pictorial view of PMC based ethanol cookstove (a) cookstove and (b) internal view of burner

5.2 Cookstove performance and measurement procedure

The cookstove performance was evaluated after analyzing the effect of mineral wool quantity and its arrangement inside the canister for both fixed canister type and removable canister type cookstove. Both the cookstoves were initially passed through the soot formation test as per Indian standard (IS:4246, 2002). Later, performance was assessed by evaluation of thermal and emission parameters along with Control Cooking Test (CCT).

5.2.1 Effect of mineral wool quantity

The effect of mineral wool quantity and its arrangement inside the canister was studied to increase the fuel storing capacity of canister along with minimum amount of residual fuel inside the canister. The residual fuel inside the canister refers to the condition when there is no sufficient fuel for combustion. In the present study, the canister was loaded with two different types of mineral wool i.e., ceramic and rock wool in both fixed canister type and removable type ethanol cookstove. The properties of used ceramic wool and rock wool are listed below in Table 5.2.

Table 5.2 Properties of ceramic wool and glass wool

Properties	**Ceramic wool (Top layer)**	**Rock wool (Bottom layer)**
Thermal conductivity (W/mK)	0.09	0.04
Colour	White	Yellow
Thickness (mm)	25	25

Maximum heat resistance temperature (°C)	1260	750
Density (kg/m^3)	64	48

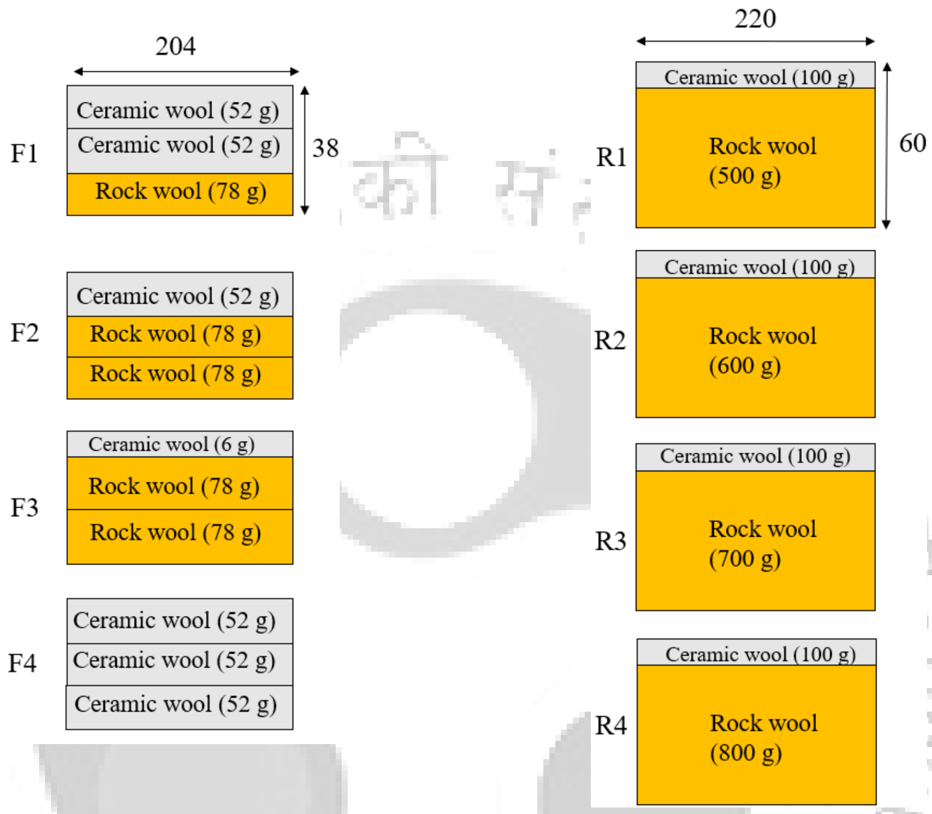


Figure 5.4 Ceramic wool and rock wool configuration for FFC based ethanol cookstoves (a) fixed canister type and (b) removable canister type

In the case of fixed canister type, the effect of mineral wool quantity was studied by varying the layers of ceramic wool and rock wool, whereas in case of removable canister type cookstove the same was studied by varying the quantity of rockwool only, which was varied from 500 to 800 g. For both the cookstoves, four different configurations were studied for optimization of mineral wool quantity inside the canister as shown in Figure 5.4. For all the studied cases, ceramic wool was kept on top surface inside the canister due to its maximum heat resistance temperature which is 68% higher than rockwool (as given in Table 5.2). The given arrangement of ceramic and rock wool is limited to such configuration because of their structural arrangement.

5.2.2 Soot formation test

A soot formation test was conducted on all the cookstove with different purity level of ethanol which consists of a blend of pure ethanol and water as given in Table 5.3. The cookstove burner must be lit at the "ON" position for one hour while a 150 mm-diameter vessel filled with water was placed on it (IS:4246 2002). Neither the burner nor the vessel's bottom should have any soot (unburned carbon) left over after the test.

Table 5.3 Calorific values for ethanol and water blend

Ethanol and water (v/v) %	Lower Calorific value (LCV) (MJ/kg)
Ethanol 99.6% (E100)	26.8
96% ethanol and 4% water (E96W4)	25.6
93% ethanol and 7% water (E93W7)	24.4

5.2.3 Thermal performance and measurement procedure

The thermal efficiency (η_{th}) and other performance indicators i.e., Burning Rate (BR), Fire Power (FP), Specific Fuel Consumption (SFC), and Turn Down Ratio (TDR) are estimated using Eqs. 3.1 and 3.2-3.5, respectively.

5.2.4 Emission performance and measurement procedure

Emission performance consists of CO and NO_x emissions, CO/CO_2 ratio (R) and combustion efficiency (η_{comb}) as mentioned in section 3.2.3. CO/CO_2 ratio is measured directly with the help of values measured through flue gas analyser and the combustion efficiency (η_{comb}) was measured using Eq. 3.6.

5.3 Uncertainty Analysis

Table 3.6 in Chapter 3 presents the specifications of the instruments used in the thermal and emission performance assessments. The uncertainties related to thermal efficiency (η_{th}) combustion efficiency (η_{comb}) and CO/CO_2 analysis were estimated using Eqs. 3.9, 3.10 and 3.11, respectively. The maximum relative uncertainty for η_{th}, η_{comb} and R and are ±1.2%, ± 0.18% and ± 4.5%, respectively.

5.4 Control Cooking Test (CCT)

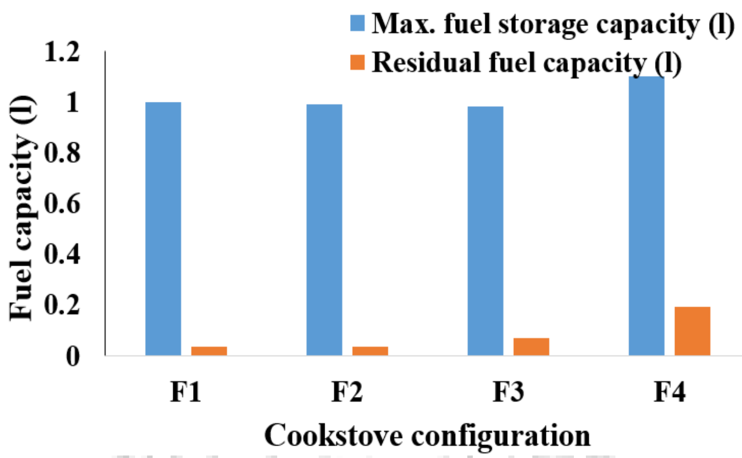
The CCT is conducted primarily to compare the performance of the stove in a standardized cooking task. The principal objective of CCT is to examine the fuel consumption and cooking time during the cooking operation. The CCT has been done based on a household of a family of 5 people. The average daily intake of food type and quantity is obtained from a survey conducted by APL, India, and accordingly, the menu is prepared for CCT.

5.5 Result and discussions

The results of optimization of mineral wool quantity and soot formation test along with the thermal performance (η_{th}, BR, SFC, FP and TDR), combustion characteristics (CO/CO_2 ratio and η_{comb}) and CCT (fuel consumption) are discussed for all the cookstoves in this section.

5.5.1 Effect of mineral wool quantity

Four different configurations of ceramic wool and rock wool were studied for the optimization of mineral wool inside the canister (refer -Figure 5.4). Figure 5.5 shows the variation of fuel capacity with a different configuration of FFC based fixed canister type ethanol cookstove and removable canister type ethanol cookstove. The result of this study demonstrated that among all the configuration of fixed canister type ethanol cookstove, F1 configuration showed the lowest residual fuel capacity of 0.034 litre and F4 configuration showed the highest maximum fuel storage capacity of 1.1 litre. Whereas, in case of removable canister type R1 configuration showed the maximum fuel storage capacity of 1.98 litre along with minimum residual fuel capacity of 0.41 litre. It was also observed that when both the cookstoves were operating at their maximum FP, operating hour for fixed and removable canister type cookstove were 2 and 4 h, respectively (per canister).



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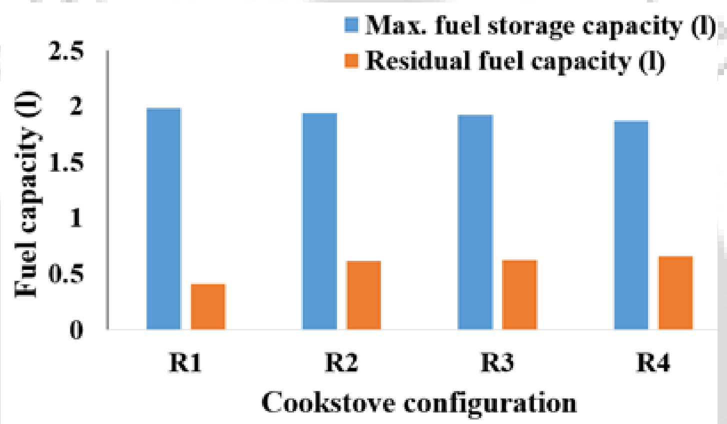


(b)

Figure 5.5 Variation of fuel capacity with different configuration of FFC based ethanol cookstove (a) fixed canister type and (b) removable canister type

5.5.2 Soot formation test

The test was conducted with three different samples of ethanol. One was the pure sample of ethanol (E100) with 100 % purity and another two were blend of ethanol and distilled water. The result of testing showed that a blend of 93% ethanol and 7% water leads to the visible reduction in soot formation in case of both fixed and removable type ethanol cookstove (as shown in Figure 5.6 and Figure 5.7). The reduction in soot formation is mainly due to increased percentage of oxygen in the fuel which leads to proper oxidation of fuel. In case of PMC based ethanol cookstove, no soot formation was observed due to complete and efficient combustion of ethanol for all the studied blend configurations (Figure 5.8).

(a) (b) (c)

Figure 5.6 Pictorial representation of soot formation variation with different blends of ethanol (E) and water (W) in removable canister type cookstove (a) E100 (b) E96W4, and (c) E93W7

(a) (b) (c)

Figure 5.7 Pictorial representation of soot formation variation with different blends of ethanol (E) and water (W) in fixed canister type cookstove (a) E100, (b) E96W4 and (c) E93W7

Figure 5.8 Pictorial representation of no soot formation in PMC based ethanol cookstove

5.5.3 Thermal efficiency

Table 5.4 shows the result obtained from the performance assessment of all the tested cookstoves using WBT prescribed by ISO in terms of η_{th}, BR, SFC, FP and TDR. It was observed that maximum FP of fixed canister type and removable canister type cookstove was limited to 2 kW (as increasing power beyond that is not possible due to limitation of cookstove construction) and whereas for PMC based ethanol cookstove, it was limited to 3.5 kW (as increasing power beyond that leads to blowoff). Therefore, in WBT, all the studied cookstoves were operated at same operating FP for fair comparison of thermal performance of cookstove. At same high operating power (FP~2 kW), the PMC based ethanol cookstove showed 6.9% and 3.7% relative higher thermal efficiency than fixed canister and removable canister type cookstoves, respectively. However, in the case of low FP setting, it was observed that the PMC based ethanol cookstove exhibited 3.6% and

12.1% relative higher thermal efficiency than fixed and removable canister type cookstove, respectively. The removable canister type showed the lowest thermal efficiency for low FP settings among all the studied cookstoves. It is mainly due to prolonged heating operation (simmering), which in turn increases the rate of evaporation of fuel even after partial closing of the canister opening by the stove lever. Among all the assessed cookstoves, PMC based ethanol cookstove showed higher thermal efficiency which is mainly due to the combined effect of radiative and convective heat transfer of the highly emissive porous material (Kaushik and Muthukumar, 2019). However, the same PMC based ethanol cookstove showed lower thermal efficiency of 49.2% at maximum FP of 3.5 kW. The decrease in thermal efficiency at higher FP is due to increase in radiative losses from porous materials at higher temperature (G.S. Sinha and Muthukumar, 2019). Similarly, PMC based ethanol cookstoves outperforms in terms of other studied parameters i.e., BR, SFC, FP and TDR.

Table 5.4 Thermal parameters of FFC and PMC based ethanol cookstoves

Parameters	**FP**	**FFC**		**PMC based ethanol cookstove (Operating FP~2 kW)**
		Fixed canister (Max. FP~2 kW)	**Removable Canister (Max. FP~2 kW)**	
η_{th} **(%)**	High	54.6	56.3	58.4
	Low (simmer)	58.2	53.8	60.3
BR **(g/min)**	High	4.7	4.6	4.5
	Low (simmer)	2.5	2.9	2.4
SFC **(g/l)**	High	31.4	29.4	28.4
	Low (simmer)	62.9	68.8	61.3
FP **(kW)**	High	1.9	1.9	1.9
	Low (simmer)	1.0	1.2	1.0
TDR		1.9	1.5	1.9

5.5.4 Emissions and combustion efficiency

The results of exhaust gas emission measurement and combustion efficiency were given in Table 5.5. The maximum CO emission from fixed canister type, removable canister type and PMC based ethanol cookstoves were 182, 168 and 145 ppm, respectively for the constant FP of ~2 kW. Removable canister type cookstove showed a maximum reduction of 8.3% in CO emission as compared to fixed canister type cookstove. This is because side vent available in case of removable canister type cookstove (Figure 5.2) leads to more air entrainment as compared to the fixed canister type cookstove. The maximum combustion efficiency was found as 99.5% for the PMC based ethanol cookstove for low FP settings. This slightly better combustion efficiency at low FP than FFC based cookstove is mainly due to increase in residence time which leads to efficient combustion of fuel. Overall, it was observed that PMC based ethanol cookstove yields lower CO emission and higher combustion efficiency than FFC based fixed canister type and removable canister type ethanol cookstoves. The CO/CO_2 ratio for all the studied cookstoves was less than prescribed limit of 0.02 (IS:4246, 2002).

Table 5.5 Emissions performance of FFC and PMC based ethanol cookstoves

Emission/ Parameters	**FP**	**FFC**		**PMC based ethanol cookstove (Operating FP~2 kW)**
		Fixed canister (Max. FP~2 kW)	**Removable Canister (Max. FP~2 kW)**	
CO (ppm)	High	182	168	145
	Low (simmer)	109	131	86
NO_x **(ppm)**	High	1.5	1.7	1.7
	Low (simmer)	2.5	2.7	2.4
CO/CO_2	High	0.009	0.008	0.007
	Low (simmer)	0.007	0.010	0.005
η_{comb} (%)	High	99.1	99.2	98.8
	Low (simmer)	99.2	98.9	99.5

Table 5.6 Cooking time and fuel consumption during CCT

Items	**FFC**				**PMC based ethanol cookstove (FP~2 kW)**	
	Fixed canister (FP~2 kW)		**Removable canister (FP~2 kW)**			
	Time (min)	**Fuel consumption (g)**	**Time (min)**	**Fuel consumption (g)**	**Time (min)**	**Fuel consumption (g)**
Rice (1 kg)	11.8	70	12.1	69.7	10.8	68
Dal	22.3	133	22.2	130	20.6	128

(0.3 kg)						
Chapatti (0.25 kg)	10.3	32.1	10.0	32.3	9.9	30.2
Potato (0.5 kg)	11.2	50	12.1	48.8	10.1	46.5
Total	55.6	285.1	56.4	280.8	51.4	272.7

5.5.5 Control Cooking Test

Results from CCT were given in Table 5.6. It was observed that the PMC based ethanol cookstove requires 7.2% and 9.7% lower cooking time and 4.5% and 2.9% lower fuel consumption than fixed canister type and removable canister type cookstoves, respectively, for the selected menu. This is mainly due to radiative mode of heat transfer from porous material which is having higher emissivity and thermal conductivity. Higher cooking time in case of fixed canister type and removable canister type cookstoves is because of convection mode of heat transfer which predominantly takes place by gases of lower heat transfer coefficient, increases the time and fuel consumption for cooking. All the cooking tests were conducted thrice and average value of time and fuel consumption is presented.

5.6 Summary

The present study compares the performance of Free Flame Combustion (FFC) based fixed canister type ethanol cookstove and removable canister type ethanol cookstove with PMC based ethanol cookstove. The results of performance analysis showed that PMC based ethanol cookstove yields a maximum efficiency of 60.3%, which was the highest amongst all compared cookstoves at low Fire Power (FP~1 kW) settings. The advantages of using PMC based ethanol cookstove from user perspective was its higher FP of 3.5 kW which was limited to 2 kW for FFC based fixed canister type and removable canister type cookstoves. Further, the result of Control Cooking Test (CCT) highlights that the PMC based ethanol cookstove requires 7.2% and 9.7% lower cooking time and 4.5% and 2.9% lower fuel consumption than FFC based fixed canister type and removable canister type cookstoves, respectively. The existing study also addressed the problems of soot formation due to use of ethanol fuel in conventional cookstoves by optimizing the blend % of ethanol and water. The optimized blend percentage with maximum visible reduction in soot formation is 93% ethanol and 7% water (E93W7).

Chapter 6 Indoor Air Quality (IAQ) Assessment

Preface

Improvement in Indoor Air Quality (IAQ) due to the adoption of alcohol fuels in the actual kitchen environment will give the true picture of its clean nature. Therefore, in this study, the level of pollutant emissions such as particulate matter ($PM_{2.5}$ and PM_{10}) and carbon monoxide (CO) for ethanol, methanol, kerosene and LPG fuelled cookstoves from the actual cooking environment are measured. Further, a comparative study on pollutant emissions emitted from FFC and PMC based cookstoves using methanol, kerosene and LPG as fuel is also performed. Therefore, this study is the first of its kind to evaluate the impact of the intervention of PMC based cookstoves in the kitchen environment. The emission of pollutants i.e., as particulate matter ($PM_{2.5}$ and PM_{10}) and carbon monoxide (CO) are the parameters for assessment of IAQ in the kitchen environment. The characteristics of cookstove used for the IAQ assessment along with the details of the kitchen model (representative of rural kitchen), monitoring plan for pollutant emissions and statistical analysis tool are discussed in subsequent sections.

6.1 Cookstoves characteristics

IAQ was measured for nine different cookstoves namely FFC based cookstoves such as FFC methanol canister cookstove ($CS_{FFC}^{Methanol}$), FFC ethanol canister cookstove ($CS_{FFC}^{Ethanol}$), FFC kerosene pressure cookstove ($CS_{FFC}^{Kerosene\ pressure}$), FFC kerosene wick cookstove ($CS_{FFC}^{Kerosene\ wick}$), FFC LPG cookstove ($CS_{FFC}^{LPG}$) and PMC based cookstoves such as PMC methanol pressure cookstove ($CS_{PMC}^{Methanol}$), PMC ethanol pressure cookstove ($CS_{PMC}^{Ethanol}$, PMC kerosene pressure cookstove ($CS_{PMC}^{Kerosene}$) and PMC LPG cookstove (CS_{PMC}^{LPG}). $CS_{FFC}^{Methanol}$and $CS_{FFC}^{Ethanol}$ were provided by the Assam Petrochemical Limited and $CS_{FFC}^{Kerosene\ pressure}$, $CS_{FFC}^{Kerosene\ wick}$ and CS_{FFC}^{LPG} were bought from the commercial outlet. $CS_{PMC}^{Methanol}$, $CS_{PMC}^{Ethanol}$ $CS_{PMC}^{Kerosene}$ and CS_{PMC}^{LPG} were developed at IIT Guwahati. The design specification of all the selected cookstoves and the characteristics of the fuels are presented in Table 6.1.

Table 6.1 Characteristics of cookstoves

Type of cookstove	Cookstove	Burner	Power input (kW)	Thermal efficiency (%)	Fuel Tank capacity (l)	Ref.
FFC based cookstove	**Methanol**	Double canister	1.0-1.5	50-63	1.8 l	Maurya et al. (2022)
	Ethanol	Double canister	1.0-2.5	50-60	1.9 l	Present study
	Kerosene Pressure	Single roarer	1.5-3	51-56	2 l	Maurya et al. (2022)
	Kerosene wick	10 number of wicks	1-3	49-59	2 l	Maurya et al. (2022)
	LPG	Double burner	1-3	60-68	24.7 l	Muthukumar et al. (2011)
PMC based cookstove	**Methanol**	Silicon carbide with 90% porosity	1.8-3.5	60-67	3 l	Muthukumar and Maurya (2021)
	Ethanol	Silicon carbide with 90% porosity	1-3.5	56-65	3 l	Muthukumar and Maurya (2021)
	Kerosene Pressure	Silicon carbide with 90% porosity	1.5-3	55-64	3 l	Sinha (2017)
	LPG	Silicon carbide with 90% porosity	1-3	75-80	24.7 l	Muthukumar and Kaushik (2018)

Note: Lower Calorific Value (LCV) of kerosene (43.9 MJ/kg), ethanol (26.7 MJ/kg) and methanol (18.5 MJ/kg) were measured by bomb calorimeter at IIT Guwahati and for LPG (45.6 MJ/kg), LCV was measured using GC.

6.1.1 Representative kitchen model

The IAQ assessment was carried out in a representative kitchen model developed at IIT Guwahati shown in Figure 6.1. The developed kitchen model is representative of the kitchen size of Indian households as per the study conducted by World Health Organization (WHO, 2014). The studies were conducted in a kitchen of dimensions 2.7×2.0×1.7 (m^3). The kitchen was provided with two windows of dimensions 0.13×0.23 (m^2) for ventilation.

The reason for selecting such household construction is to get a comparative view of the result obtained from the field studies as mentioned in Table 2.3 of Chapter 2, which were mostly conducted in rural areas to monitor the emission values of pollutants. Another reason for the selection of such households is the government scheme of promoting clean cooking fuels i.e., ethanol and methanol in rural areas. Therefore, the present household setup was developed to get the real time emission values from the cookstoves.

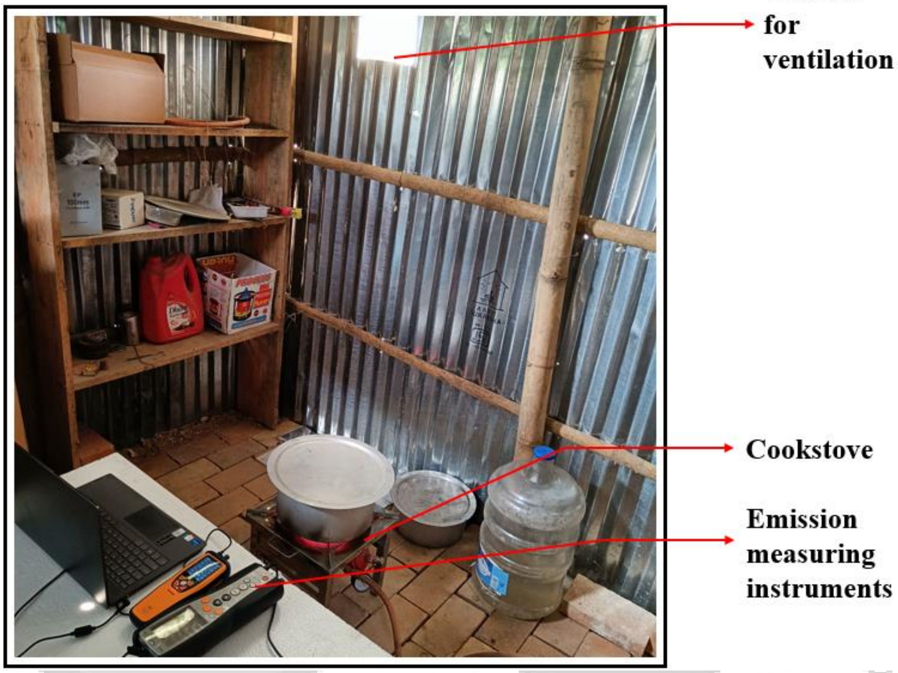


Figure 6.1 Representative kitchen model

During the experiments, the cookstoves were placed on the kitchen floor in the middle of the room. All the cookstoves were charged by the fuel up to its 75% capacity and ignited in the kitchen itself.

6.1.2 Monitoring plan

Particulate matter (PM) and carbon monoxide (CO) were measured in the above-mentioned kitchen for both cooking and non-cooking hours. The monitoring of air pollutants i.e., $PM_{2.5}$ and PM_{10} was done by the air quality meter Temtop-M 2000. This instrument is sensitive to particles of aerodynamic diameter of 2.5 µm and 10 µm, which is the size range assumed to be the most important for affecting the health of people. All the pollutant concentrations were recorded at every minute in the memory of the instrument, which was then downloaded into a personal computer. The CO level was measured by the instrument Testo

350 and the concentration was recorded every minute with the help of Testo easy emission software.

The Temtop-M 2000 air quality meter and CO monitoring device were placed next to each other on the wooden stand at a distance and height of 50 cm from cookstove in the kitchen for 24 h. The height of 50 cm correlates to a person's breathing level in the kitchen in squatting position (Kandpal et al. 1994). For each cookstove, monitoring was done for 1 day (3 replicates on each cookstove) i.e., for each cookstove monitoring of pollutants was conducted for 3 consecutive days. The experiments were conducted for 18 days and reliability in cookstove operation was sustained throughout. The characteristics of the monitoring plan are listed in Table 6.2.

Table 6.2 IAQ monitoring plan

Factors	Description
Sampling Location	IIT Guwahati (50 cm away from the cookstove and a height 50 cm away from the floor)
Ventilation	Air exchange of 3.7/h
Sampling Duration	24 h
Cooking hours	(8 A.M to 10 A.M)
Cookstove technology	FFC and PMC
Pollutant monitored	PM (PM_{10}, $PM_{2.5}$) and CO
Sampling time interval	1 min data logging

6.2 Statistical analysis

A comparison test was conducted to determine significant differences in gaseous pollutant emissions ($PM_{2.5}$, PM_{10}, and CO) between CS_{FFC} and CS_{PMC}. A two-tailed Student's t-test at a 95% confidence level ($p<0.05$) was used to evaluate statistical differences based on t and p values. The t and p values were calculated using MS Excel (Excel-2019, Version 2203).

Larger t-values indicate group differences, while smaller t-values suggest similarity. P-values, ranging from 0 to 1, were used to assess statistical significance, with $p<0.05$ indicating significance.

6.3 Results and discussions

Monitored emission values of pollutants emitted from the tested conventional CS_{FFC} are reported in this section with timeline plots and pairwise statistical comparisons with CS_{PMC}. Further, an overall comparison has been made with the WHO guidelines for 24 h average concentration of emission values. The emission of pollutants from all the tested cookstoves was measured for 2 h and 24 h duration. During the experiments, all the cookstoves were operated at FP of 2 kW except $CS_{FFC}^{Methanol}$. In case of $CS_{FFC}^{Methanol}$, the maximum FP was limited to 1.5 kW due to the cookstove design (Maurya et al., 2022).

6.3.1 Temporal variation in $PM_{2.5}$ and PM_{10} concentrations

The monitored values of $PM_{2.5}$ and PM_{10} for the cookstove operating on FFC are shown in Figure 6.2 and Figure 6.3. The $PM_{2.5}$ and PM_{10} concentrations in the kitchen area before starting the experiment were found in the range of 20-23 $\mu g/m^3$ and 38-42 $\mu g/m^3$, respectively. The observation shows that during the ignition phase (first 5 min of combustion), the $PM_{2.5}$ and PM_{10} concentrations reached peak values of about 210 $\mu g/m^3$ and 455 $\mu g/m^3$ for $CS_{FFC}^{Kerosene\ pressure}$ and 132 $\mu g/m^3$ and 200 $\mu g/m^3$ for $CS_{FFC}^{Kerosene\ wick}$, respectively and then, it decreased with time. The sudden peak in the $PM_{2.5}$ and PM_{10} concentration values during the initial phase of operation showed the unstable combustion in the conventional $CS_{FFC}^{Kerosene\ pressure}$ and $CS_{FFC}^{Kerosene\ wick}$. The increase in the concentration was observed for about 3 min for both $CS_{FFC}^{Kerosene\ pressure}$ and $CS_{FFC}^{Kerosene\ wick}$ for $PM_{2.5}$; and about 3 min for $CS_{FFC}^{Kerosene\ wick}$ and 13 min for $CS_{FFC}^{Kerosene\ pressure}$ for PM_{10}. After 13 min of operation, these cookstoves showed a decreasing trend in the emission of $PM_{2.5}$ and PM_{10} concentrations and after 30 min of operation, less variation in the range of emission value was observed. However, $CS_{FFC}^{Methanol}$, $CS_{FFC}^{Ethanol}$ and CS_{FFC}^{LPG} values were in the range of 33-39, 35-42 and 25-30 $\mu g/m^3$ for $PM_{2.5}$ and 50-60, 50-65 and 40-50 $\mu g/m^3$ for PM_{10}, respectively, throughout their burn cycle of 2 h. This showed that there was less variation in the concentration of $PM_{2.5}$ and PM_{10} during the burn cycle of cookstove which represents stable combustion of fuel in their respective cookstoves. The measured concentrations of $PM_{2.5}$ and PM_{10} for $CS_{FFC}^{Methanol}$, $CS_{FFC}^{Ethanol}$ and $CS_{FFC}^{Kerosene\ wick}$ were compared with the reported literature values. It was observed that a similar trend of $PM_{2.5}$ variation was reported in the lab study conducted by Masekameni et al. (2015) for kerosene wick cookstove (average concentration – 3180 $\mu g/m^3$ for 1 h duration). However, in case of methanol and ethanol cookstoves reported by Masekameni et al. (2015), all $PM_{2.5}$ emission has been found very high up to 5000 $\mu g/m^3$ for first five min and then showed a constant lower concentration of around 100 $\mu g/m^3$ for the burn cycle of 1 h. The higher concentration observed in their study is mainly due to use of hood method (IS 11760 1986) for measurement of emissions. The average $PM_{2.5}$ concentration of $CS_{FFC}^{Methanol}$, and $CS_{FFC}^{Ethanol}$ in the present study was 35 and 37 $\mu g/m^3$, respectively, during the burn cycle of 2 h.

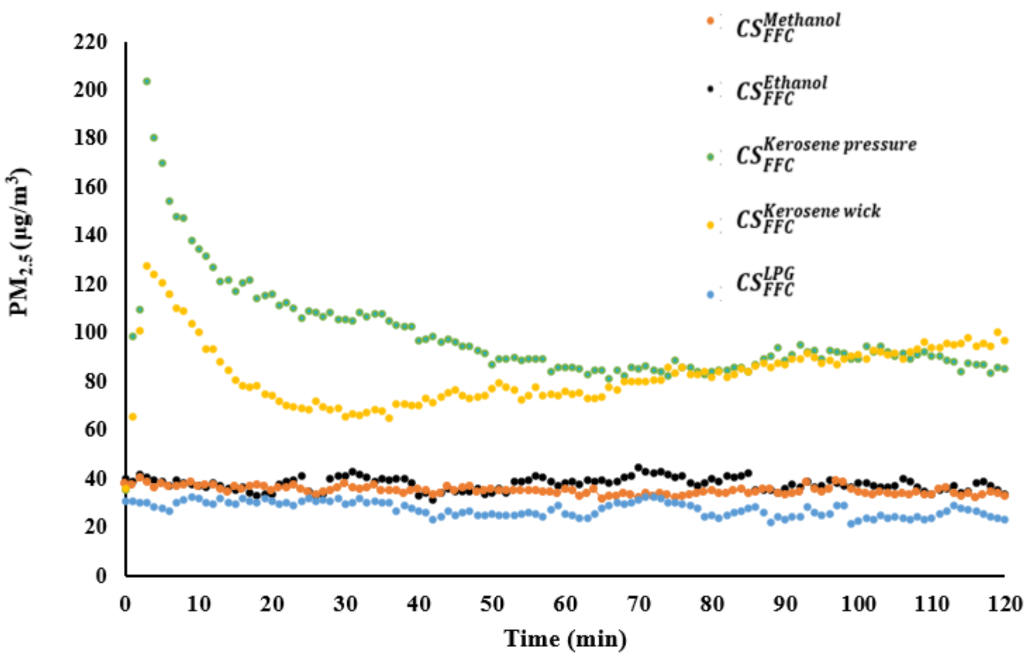


Figure 6.2 $PM_{2.5}$ concentration variation for the 2 h burn cycle of CS_{FFC}

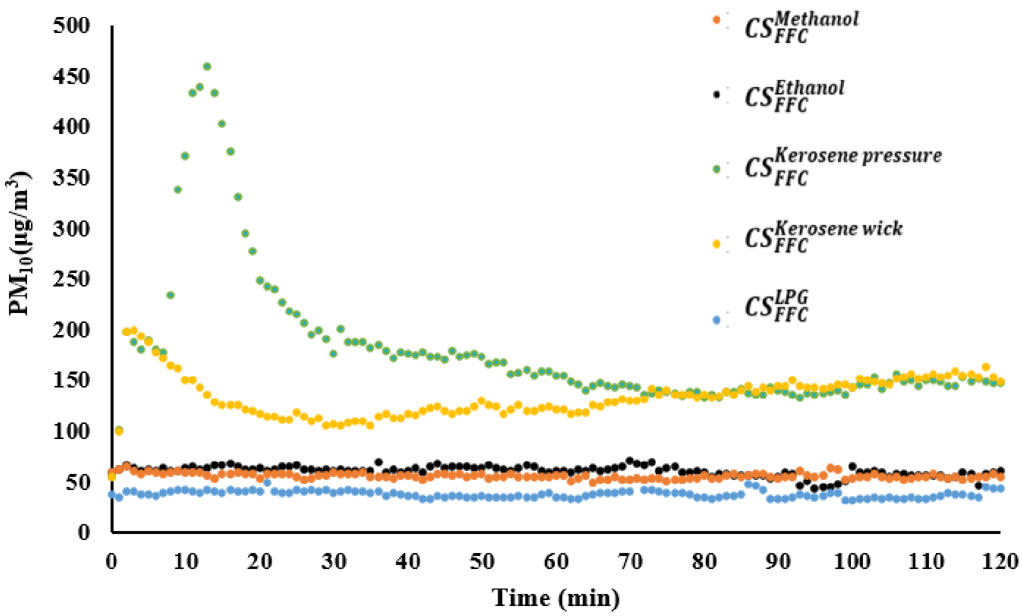


Figure 6.3 PM_{10} concentration variation for the 2 h burn cycle of CS_{FFC}

6.3.2 Temporal variation in CO concentrations for CS_{FFC}

CO emission was also recorded simultaneously along with PM observations. The measured CO concentration in the kitchen area before starting the experiment lies in the range of 0-1 ppm. As shown in Figure 6.4, the peak CO concentration reported during 2 h of burn cycle from $CS_{FFC}^{Kerosene\ pressure}$ and $CS_{FFC}^{Kerosene\ wick}$ was 18 and 16 ppm, respectively. The mean 2 h CO concentration was varied in the following order, $CS_{FFC}^{Kerosene\ pressure}$ (13.6 ppm), $CS_{FFC}^{Kerosene\ wick}$ (11.1 ppm), $CS_{FFC}^{Ethanol}$ (4.8 ppm) and $CS_{FFC}^{Methanol}$(3.1 ppm). It was observed that the $CS_{FFC}^{Methanol}$ showed the lowest CO concentration among all the tested cookstoves. This is mainly due to the lowest FP and cleaner combustion of methanol (Maurya et al. 2022). CO emission of the present study showed a similar observation that was made by Masekameni et al. (2015) for kerosene wick, ethanol and methanol cookstoves. However, the average CO concentration for kerosene wick, ethanol and methanol cookstoves were 9300 ppm, 7500 ppm and 3200 ppm, respectively, which is considerably higher than the present study. This is mainly due to the use of hood method for the measurement of CO emission.

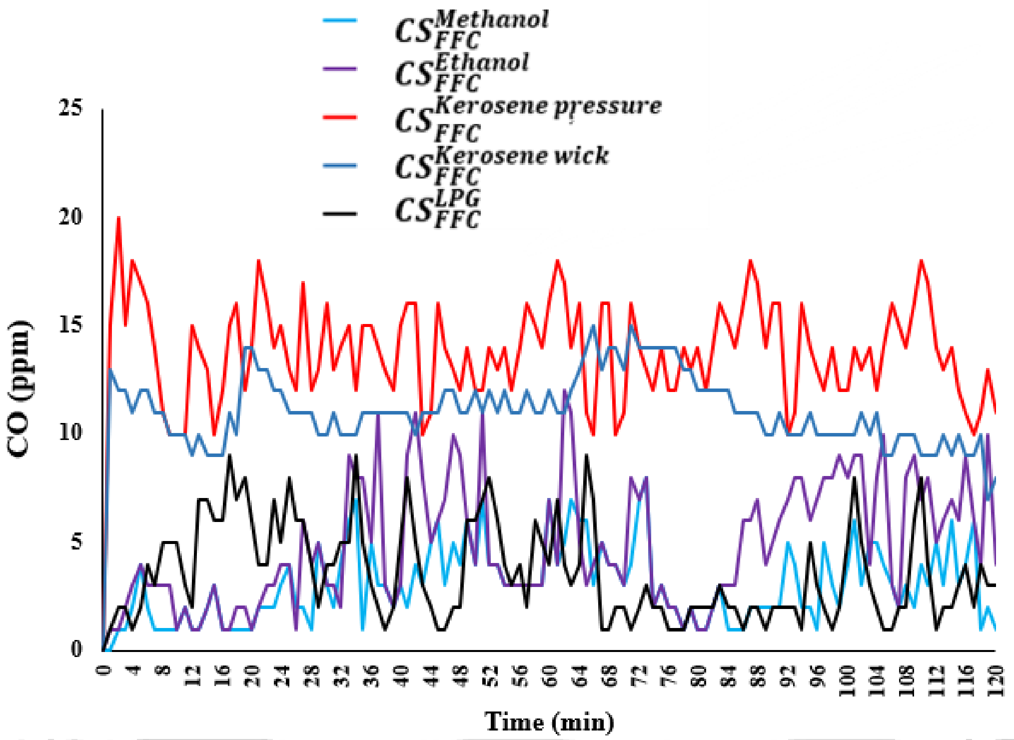


Figure 6.4 CO concentration variation for the 2 h burn cycle of CS_{FFC}

6.3.3 Comparison of IAQ due to use of FFC and PMC based cookstoves

In this section, a comparison between the IAQ due to the use of FFC and PMC based cookstoves is presented. The pairs of cookstoves considered for the comparison are- $CS_{FFC}^{Methanol}$ vs $CS_{PMC}^{Methanol}$, $CS_{FFC}^{Ethanol}$ vs $CS_{PMC}^{Ethanol}$, $CS_{FFC}^{Kerosene\ pressure}$ vs $CS_{PMC}^{Kerosene}$, $CS_{FFC}^{Kerosene\ wick}$ vs $CS_{PMC}^{Kerosene}$ and CS_{FFC}^{LPG} vs CS_{PMC}^{LPG}.

Comparison of $PM_{2.5}$ and PM_{10} emissions of CS_{FFC} and CS_{PMC}

Pairwise comparison of particulate matter i.e., $PM_{2.5}$ and PM_{10} between the CS_{FFC} and CS_{PMC} are shown in Table 6.3 and Table 6.4. The mean values (for 2 h burn cycle) of $PM_{2.5}$ and PM_{10} were found to be the lowest for CS_{PMC}^{LPG} and highest for $CS_{FFC}^{Kerosene\ pressure}$. It was found that the t-value for all pairs of cookstoves was greater than 1. And the p-value corresponding to the evaluated t-value was less than 0.05, which represents that there was a statistically significant difference between the measured emissions of all the cookstoves. Among all the paired sets of cookstove, $CS_{PMC}^{Methanol}$ and $CS_{FFC}^{Methanol}$ showed the lowest t-values among all the compared cookstoves, which reflects that there is less difference between the groups (as mentioned in section 6.1.4). Although the percentage difference in emission values is significant between $CS_{PMC}^{Methanol}$ and $CS_{FFC}^{Methanol}$ (i.e., 7.7% for $PM_{2.5}$ and 8.1% for PM_{10}) but less in comparison to other pairs of FFC and PMC based cookstoves. As all the cookstoves were operated at similar FP (2 kW) for comparison except $CS_{FFC}^{Methanol}$, which was operated at lower FP (1.5 kW) resulting in comparable emission values of $PM_{2.5}$ and PM_{10} to $CS_{PMC}^{Methanol}$. It was also observed that the $CS_{PMC}^{Kerosene}$ showed the highest 55.3% and 62.6% reduction in $PM_{2.5}$ and PM_{10}, respectively, compared to the $CS_{FFC}^{Kerosene\ pressure}$.

Table 6.3 Comparison of $PM_{2.5}$ emissions of FFC and PMC cookstoves

Cookstoves	**$PM_{2.5}$ ($\mu g/m^3$)**	**Statistical analysis**		
		t-test	**p-value**	**% Decrease**
Methanol FFC vs Methanol PMC	34.9 vs 32.2	4.2	0.01	7.7
Ethanol FFC vs Ethanol PMC	39.6 vs 35.3	4.7	0.01	10.8
Kerosene pressure FFC vs kerosene PMC	98.6 vs 44.1	27.8	0.00	55.3
Kerosene wick FFC vs kerosene PMC	82.8 vs 44.1	25.3	0.00	46.7
LPG FFC vs LPG PMC	27.3 vs 24.1	3.38	0.00	11.7

The highest percentage reduction in particulate emission is possible only due to efficient combustion in porous media. The obtained result in the present study is in the agreement with the statement of reduction of particulate matter emission with the use of PMC based technology reported by Guerrero et al. (2021) and Ciria et al. (2022).

Table 6.4 Comparison of PM_{10} emission of FFC and PMC cookstoves

Cookstoves	**PM_{10} ($\mu g/m^3$)**	**Statistical analysis**		
		t-test	**p-value**	**% Decrease**
Methanol FFC vs Methanol PMC	55.8 vs 51.3	2.5	0.01	8.1
Ethanol FFC vs Ethanol PMC	59.8 vs 52.3	2.1	0.01	12.5
Kerosene pressure FFC vs kerosene PMC	181.0 vs 67.6	16.8	0.00	62.6
Kerosene wick FFC vs kerosene PMC	134.6 vs 67.6	25.8	0.00	49.7

LPG FFC vs LPG PMC	47.5 vs 37.8	12.9	0.00	20.4

Comparison of CO emissions of CS_{FFC} and CS_{PMC}

Table 6.5 presents the pairwise comparison of mean CO emission for 2 h for CS_{PMC} and CS_{FFC}. All the CS_{PMC} showed statistically significant differences in the emissions as compared to the CS_{FFC}. The t-value is greater than 1 and p value is less than 0.05 for all the compared sets of cookstove. Among all the tested cookstoves, $CS_{FFC}^{Kerosene\ pressure}$ reported the highest decrease of 66.6%, followed by 59.4% and 41.6% for $CS_{FFC}^{Kerosene\ wick}$ and CS_{FFC}^{LPG}, respectively, in CO emission as compared to their PMC based counterparts. The percentage reduction in CO emission due to the use of CS_{PMC} is mainly due to higher surface area of porous matrix, which leads to longer residence time and results in lower CO emission (Guerrero et al. 2021). Several studies highlighted the reduction in CO emission with the use of PMC based technology (Deb and Muthukumar, 2021; Kaushik and Muthukumar, 2020; Muthukumar and Shyamkumar, 2013). The emissions reported in the above-mentioned studies are associated with the measurement by hood method, which measures the emission directly from a small opening of hood through a flue gas analyser. However, in the present study, the values of CO emissions were measured in the kitchen environment.

Table 6.5 Comparison of CO emission of FFC and PMC cookstoves

Cookstoves	CO (ppm)	Statistical analysis		
		t-value	p-value	% Decrease
Methanol FFC vs Methanol PMC	3.5 vs 2.9	4.4	0.00	17.2
Ethanol FFC vs Ethanol PMC	4.8 vs 3.4	3.1	0.00	29.2
Kerosene pressure FFC vs kerosene PMC	13.5 vs 4.5	33.1	0.00	66.6
Kerosene wick FFC vs kerosene PMC	11.1 vs 4.5	22.2	0.00	59.4
LPG FFC vs LPG PMC	3.6 vs 2.1	5.8	0.00	41.6

6.3.4 IAQ value comparison with WHO guidelines

The 24 h average concentration of $PM_{2.5}$, PM_{10} and CO from all the CS_{FFC} and CS_{PMC} are shown in Figure 6.5. The results obtained during the monitored periods are compared with the WHO guidelines. It was found that the highest concentrations of $PM_{2.5}$, PM_{10} and CO were detected during the operation of $CS_{FFC}^{Kerosene\ pressure}$, highlighting the adverse impact on IAQ. The emission value of $PM_{2.5}$ and PM_{10} for $CS_{FFC}^{Kerosene\ pressure}$ were higher by 32.4% and 27%, respectively than the limit value suggested by the WHO. Among all the tested cookstoves, CS_{PMC}^{LPG} showed the lowest emissions and were 17.6%, 37.4% and 85.1% lower than the prescribed WHO values for $PM_{2.5}$, PM_{10} and CO i.e., 25 and 50 $\mu g/m^3$ and 6 ppm, respectively. All the cookstoves were found to be emitting lower CO compared to WHO guidelines.

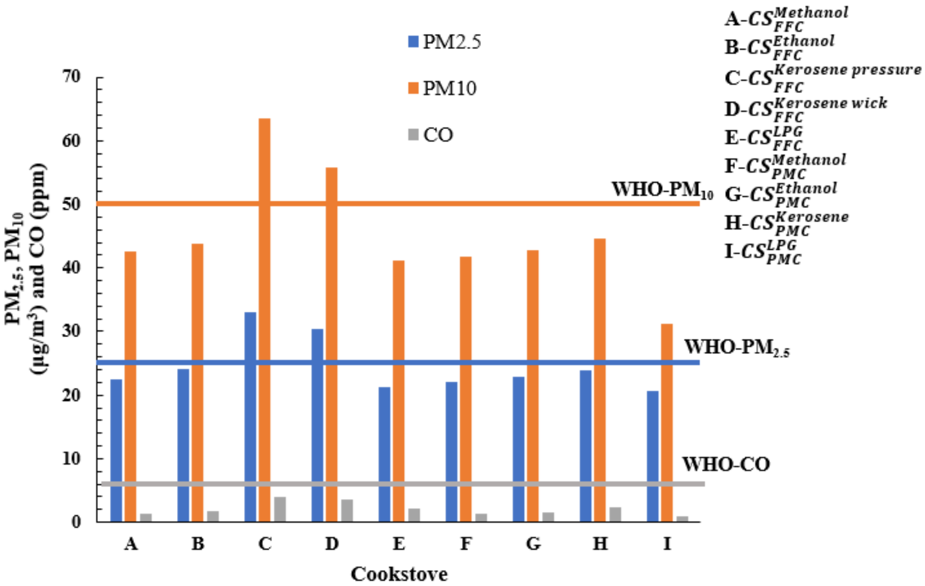


Figure 6.5 Average concentration of $PM_{2.5}$, PM_{10} and CO on 24 hr basis

6.3.5 Comparison of IAQ values with literature

Table 6.6 Comparison of $PM_{2.5}$, PM_{10} and CO emission with literature values

Cookstoves	CO (ppm)	PM_{10} ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	Monitoring time	Reference
LPG	3.6	47.5	27.3	2 h	Present study
kerosene	11.1	134.6	82.8	2 h	Present study
LPG	1.2	41.2	21.2	24 h	Present study
kerosene	3.5	55.8	30.5	24 h	Present study
LPG	3	-	-	1 h	Kandpal et al. 1995
Kerosene	6	-	-	1 h	Kandpal et al. 1995

LPG		1054	342	24 h	Gautam et al. 2013
LPG	1.05	-	78.8	24 h	Sidhu et al. 2017
LPG	0.5±0.6	-	52.3±18.9	24 h	Tagle et al. 2018
LPG		-	27±13	24 h	Liao et al. 2021

The emission values (24 h and 1 h duration) of CO and PM obtained from the conventional LPG and kerosene cookstoves from the kitchen environment that is reported in the literature were compared with the present study for FFC based cookstove only. There are no studies reported on the emission values of CO and PM in the actual kitchen equipped with PMC based LPG, kerosene, methanol and ethanol cookstoves and for conventional methanol and ethanol based cookstoves and therefore, these values were not compared with the literature.

Table 6.6 shows the comparison of $PM_{2.5}$, PM_{10} and CO emissions values with literature values. It was observed that for measured values of CO emission from the present study were similar to the studies reported in the literature. Whereas the emission of PM available in some literature was much higher than the values observed from the present study. The reason for such higher emission value is because of the adaptation of different cooking methods and fuels in their study which increases the PM emission (Gautam et al., 2013; Sidhu et al., 2017).

6.4 Summary

The present study analyses the emission mitigation ability of a Porous Media Combustion (PMC) technology based cookstove (CS_{PMC}) compared to a Free Flame Combustion (FFC) technology based cookstove (CS_{FFC}). Emission of pollutants i.e., $PM_{2.5}$, PM_{10} and CO caused due to burning of fuels namely methanol, ethanol, kerosene and LPG in the kitchen environment were measured. The study incorporated exhaustive real-time indoor air quality (IAQ) measurements and presented the temporal variation of measured pollutant concentrations for 2 h (morning meal duration). In addition, 24 h average concentration of the measured pollutants was also compared with the limits prescribed in WHO guidelines for domestic settings. The results emphasized that the utilization of CS_{PMC} would help in improving the IAQ of the kitchen area by decreasing the concentrations of $PM_{2.5}$, PM_{10} and CO. For 2 h duration measurements, the methanol cookstove based on PMC reduced the concentrations of $PM_{2.5}$, PM_{10} and CO by 7.7%, 8.1% and 17.2%, respectively, compared to FFC cookstove. Similarly, in the case of PMC based LPG cookstove (CS_{PMC}^{LPG}) and kerosene cookstove ($CS_{PMC}^{Kerosene}$), the respective values were 11.7%, 20.4% and 41.6% and 55.3%, 62.6% and 66.6%, respectively. Among all the tested cookstoves, CS_{PMC}^{LPG} achieved the lowest emission values ($PM_{2.5}$: 20.6 $\mu g/m^3$; PM_{10}: 31.3 $\mu g/m^3$ and CO: 1 ppm) which are lower than the prescribed WHO values ($PM_{2.5}$: 25 $\mu g/m^3$; PM_{10}: 50 $\mu g/m^3$ and CO: 6 ppm).

Chapter 7 Indian standard for FFC based methanol and ethanol cookstove

Preface

Chapter 3 and Chapter 5 provide the detailed overview on FFC based methanol and ethanol cookstoves. Thermal and emission performances of both the cookstoves are studied thoroughly with the help of ISO standard. However, introduction of any product in Indian market requires BIS certification, for example wick type kerosene cookstove (IS 11760: 1986) and pressurized kerosene cookstove (IS 10109: 2002).

There are no standards available for the evaluation of evaporative type FFC based methanol and ethanol cookstoves. To overcome the above shortcoming, standardization of testing protocols of FFC based methanol and ethanol cookstove was performed. During standardization, various tests were performed and results of which are presented in this chapter.

7.1 Performance evaluation of cookstove

All the tests were conducted in a standard size room of 27 m^3 at normal atmospheric conditions (the details are given by LPG Equipment Research Centre (LERC), India). Methanol of 100% and ethanol of 93% (v/v 93% ethanol and 7% distilled water) purity were used as fuels. Various tests required for BIS standardization are discussed below:

7.1.1 Resistance to draught test

There should be no extinction of the flame while operating at atmospheric pressure when the cookstove is placed in a normal (not localized) current of air with a velocity of 2 m/s, as measured with an anemometer. The location of the cookstove relative to neighboring walls and the direction of the draught should be varied to correspond to the likely conditions of appliance installation.

7.1.2 Resistance to heating test

When the cookstove is operated at its normal working pressure for a continuous period of 3 h with a vessel filled with water placed on the pan support, there should be no appreciable change in color of any part of the cookstove and the surface should not show any other signs of deterioration. This does not apply to parts, which come in direct contact with the flame.

7.1.3 Shutting off the cookstove test

Charge the cookstove to its full capacity and light the burner and adjust the flame to the highest level. Place the vessel filled with water on the pan support of the cookstove. After burning the cookstove for 1 h, turn the flame regulator to the "OFF" position and simultaneously start a stopwatch. After 5 s, turn the flame regulator to the "ON" position and check that the flame has been extinguished.

7.1.4 Durability test

Ignite the cookstove and adjust the flame to its highest level. Allow each canister inside the cookstove body to burn at this rate for 2 h. After this period, allow the cookstove to cool down to room temperature. Repeat this procedure 5 times. Inspect the cookstove and its components for any damages.

7.1.5 Normal evaporation test

The test was conducted to measure the evaporation rate of fuel from the canister (when cookstove is not operational but the flame regulator is in the "ON" position) for the given cookstove at normal atmospheric conditions.

7.1.6 Fuel consumption test

The cookstove, whose efficiency is to be determined, the canister should be filled up to 100% of its nominal capacity. The cookstove should be lit with one burner at a time and brought to working within 5 min. After burning for 5 min, the lighted cookstove should be weighed on a sensitive balance with an accuracy of one gram and the initial weight should be noted. The cookstove should be allowed to burn for 1 h with an aluminium vessel having sufficient water in it. At the end of 1 h, the mass of the cookstove should be noted after removing the aluminium vessel. The difference in the initial and final masses of the cookstove gives the fuel consumption rate in g/h.

7.1.7 Thermal efficiency test

The cookstove selected for the thermal efficiency test should be fully charged with fuel. The cookstove should be allowed to run for 5 min to obtain a steady flame height. Then, the cookstove along with two filled canisters should be placed on the weighing balance of accuracy ± 1 g for measuring the initial mass of the cookstove. After measuring the mass, the cookstove should be placed on an even surface. The aluminum vessel filled with the required amount of water along with the lid and the stirrer is kept on the cookstove.

Initial temperature of the water should be noted and should be kept within ± 2°C from the actual room temperature. Water is heated and once the water temperature reaches 80°C, for temperature uniformity, stirring should be started and continued until the end of the test when the temperature of the water reaches 90 ± 0.5°C. As soon as the temperature of the water reaches 90 ± 0.5°C, the cookstove should be switched off and the vessel along with the lid and the stirrer is taken out of the cookstove. The final mass of the cookstove along with two canisters is measured. The difference between the initial and the final mass of the cookstove along with two canisters gives the fuel consumption. The vessel should be covered with a lid fitted with a calibrated T-type thermocouple/thermometer probe inserted into the cork in such a way that the probe of the thermocouple/thermometer is immersed completely in the water of the vessel. The thermometer should be digital and T type of thermocouple probe suitable for immersion in liquids with an accuracy of ± 0.5 °C. The free end of the stirrer should come out of the lid.

7.1.8 Fuel loading capacity test

The cookstove was operated at different fuel loading conditions i.e., the canister is charged with 100%, 75% and 50% loading conditions to know the effect of fuel loading on thermal efficiency.

7.1.9 Vapour concentration test

The emission of fuel vapour during the operating hour of the cookstove should be measured. The assessment of fuel vapour within the vicinity of a cookstove is measured considering the risk of exposure to dangerous concentrations of fuel vapour (Ernstgard et al., 2005). The parameters for the measurement of concentration were selected as per

LERC, India guidelines for measuring indoor air pollutants. The details of the parameters considered for the present experimental study are highlighted in Table 7.1 for Indian kitchen settings. The concentration of fuel vapour should be measured in the breathing zone of a person. The breathing zone for cooking was considered as per the Protocol developed by UC Berkeley (University of California-Berkeley, 2005). According to this protocol the "breathing zone" is characterized as 1 m away from the cookstove and 1.45 m above the ground. The measurement of fuel vapour concentration was carried out by using a portable fuel gas monitor (Make- ATS and Model- 101M). The instrument consists of an auto suction pump operating at a pressure of 0.2 bar (absolute) and an electrochemical sensor for sampling and detection of fuel vapour, respectively.

Table 7.1 Details of monitoring plan of fuel vapour

Factors	Present study
Air exchange rate	15/hr
Kitchen volume	27 m^3
Device burn time	8 h

7.1.10 Allowable leakage test

The cookstove should be tested to know the leakage of fuel when it is not operating to know the maximum allowable leakage for both the cookstove in a room of standard kitchen size.

7.1.11 Emission test

The emission test should be conducted as per the hood method (Section 3.2.3). The hood shall be so designed that it should not interfere in any way with the normal combustion of the cookstoves and high proportion of the flue gases (CO, CO_2, NO_x and SO_x) is collected. Also, it should be such that the measured flue gas concentration represents the whole of combustion gases and not those from one particular point. Further, the carbon monoxide (CO) to carbon dioxide (CO_2) ratio of the exhaust gases of each canister, while burning with blue flame, should not exceed 0.02.

7.2 Results and discussions

All the above-mentioned tests were conducted at the normal atmospheric condition in the combustion laboratory of IIT Guwahati. The major findings of the test are discussed below:

7.2.1 Resistance to draught test

All the tested cookstoves, i.e., the removable canister type methanol cookstove, fixed canister type ethanol cookstove and removable canister type ethanol cookstove, passed the resistance to draught test. There was no flame extinction for any of the studied cookstoves when they were placed in a normal current of air with a velocity of 2 m/s, as shown in Figure 7.1.

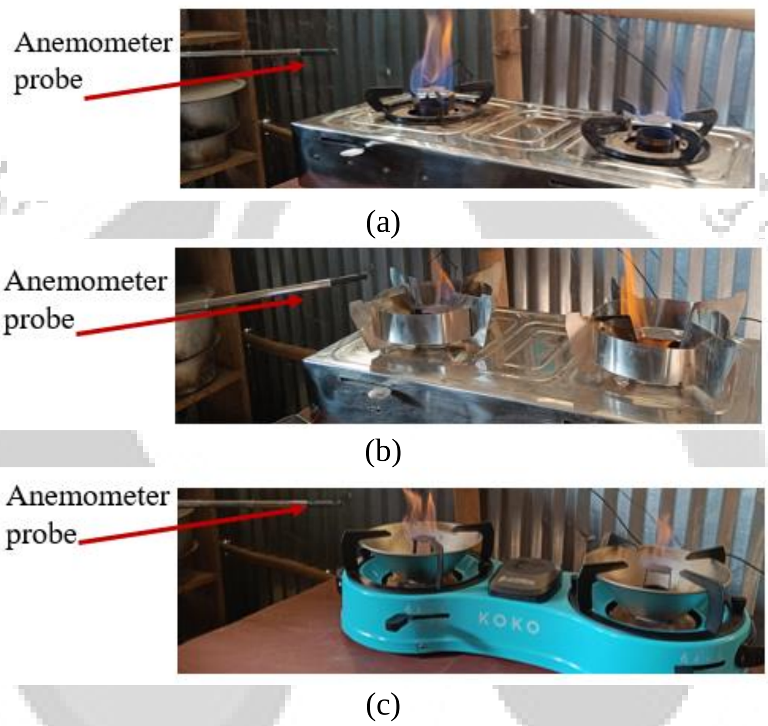


Figure 7.1 Setup of resistance to draught test (a) removable canister based methanol cookstove (b) removable canister based ethanol cookstove and (c) fixed canister based ethanol cookstove

7.2.2 Resistance to heating test

It was observed that there was no change in colour and no sign of deterioration for all the studied cookstoves after 3 hours of continuous operation. Thus, these cookstoves passed the resistance to heating test.

7.2.3 Shutting off the cookstove test

All the cookstove passes the shutting off test for the continuous operation of 1 hr. However, if the time is extended for the continuous hour of operation beyond 2 hr of duration (operating at maximum FP), the cookstove does not pass the shutting off the cookstove test as shown in Figure 7.2.

(a) (b) (c)

Figure 7.2 Setup of shutting off cookstove test (a) removable canister type methanol cookstove, (b) removable canister type ethanol cookstove and (c) fixed canister type ethanol cookstove

7.2.4 Durability test

All the cookstove passes the durability test.

7.2.5 Normal evaporation test

The result of the normal evaporation test is given in Table 7.2. It was observed that the methanol canister cookstove (removable canister type) showed a higher evaporation rate due to the higher vapour pressure of the methanol, whereas ethanol cookstove (fixed canister and removable canister type) showed lower evaporation rate due to its lower vapour pressure as compared to the methanol.

Table 7.2 Normal evaporation rates of tested cookstoves

Cookstove	Normal evaporation rate (g/h)
Removable canister type methanol cookstove	5-7
Removable canister type ethanol cookstove	3-5
Fixed canister type ethanol cookstove	3-5

7.2.6 Fuel consumption test

The result of the fuel consumption test is given in Table 7.3. The result showed that the removable canister type methanol and ethanol cookstove showed similar fuel consumption rates due to fix size of the canister opening i.e., 80 mm. Whereas fixed canister type ethanol cookstove showed a higher fuel consumption rate which is mainly due to higher canister opening i.e., 90 mm.

Table 7.3 Fuel consumption rates of tested cookstoves

Cookstove	Fuel consumption rate (g/h)
Removable canister type methanol cookstove	180-290
Removable canister type ethanol cookstove	200-300
Fixed canister type ethanol cookstove	230-330

7.2.7 Thermal efficiency test

Evaluation of thermal efficiency depends on fuel consumption, vessel size, and water quantity as given in various standards i.e., IS 11760: 1986 and IS 10109: 2002. Tests were conducted to optimize the vessel size and water quantity for given fuel consumption. Experiments were conducted with four different vessel size as given in Table 7.4. All these selected vessels were charged for their maximum capacity i.e., V-I: 3 kg, V-II: 4 kg, V-III: 6 kg and V-IV: 8 kg of water. It was observed that with increase in size of vessel there was increase in efficiency from 60.8 to 63.2 % till vessel size V-II (4 kg of water) for methanol cookstove. Beyond the vessel size V-II, there was decrease in thermal efficiency (Figure 7.3). Similarly, in case of removable and fixed canister type of cookstoves, the maximum thermal efficiency of 65.8% and 64.1% was achieved with V-III (6 kg of water). The increase in thermal efficiency was explained by increase in surface area of vessel available for heat transfer and decrease in efficiency is due to more heat loss to surroundings as compared to heat transfer to vessel.

Table 7.4 Vessel sizes for evaluation of thermal efficiency

Vessel	V-I	V-II	V-III	V-IV
Diameter (mm)	210	230	260	290
Height (mm)	110	120	140	160

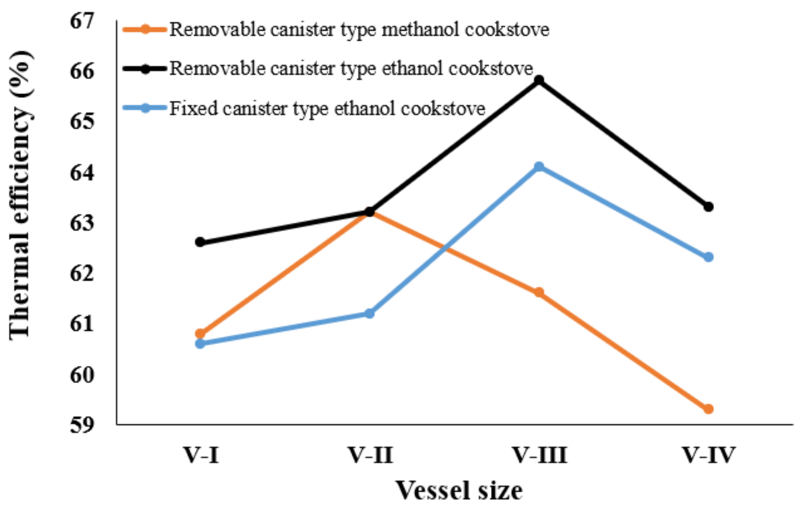


Figure 7.3 Variation in thermal efficiency with vessel sizes

The result of optimized vessel size and water quantity for evaluation of the thermal efficiency of methanol and ethanol cookstoves are presented in Table 7.5.

Table 7.5 Optimized vessel size and water quantity for tested cookstoves

Consumption Rate g/h	**Cookstove**	**Pan Diameter (external), *mm* ±5%**	**Pan height (external), *mm* ±5%**	**Total pan mass with lid, g ±10%**	**Mass of water in pan, kg**
180-290	Methanol (removable canister type)	230	120	701	4
230-330	Ethanol (removable and fixed canister type)	260	140	750	6

7.2.8 Fuel loading capacity test

Experiments were carried out at three fuel loading capacities of canister i.e., 100%, 75% and 50%, and the results are presented in Figure 7.4. A decrease of 2-3% in thermal efficiency was observed with 50% loading compared to 100% and 75% loading. This is due to lower flame height, which eventually reduces the heat transfer to the vessel. However, there was no significant variation in the efficiency between 100% and 75% loading because there is no significant change in the flame height.

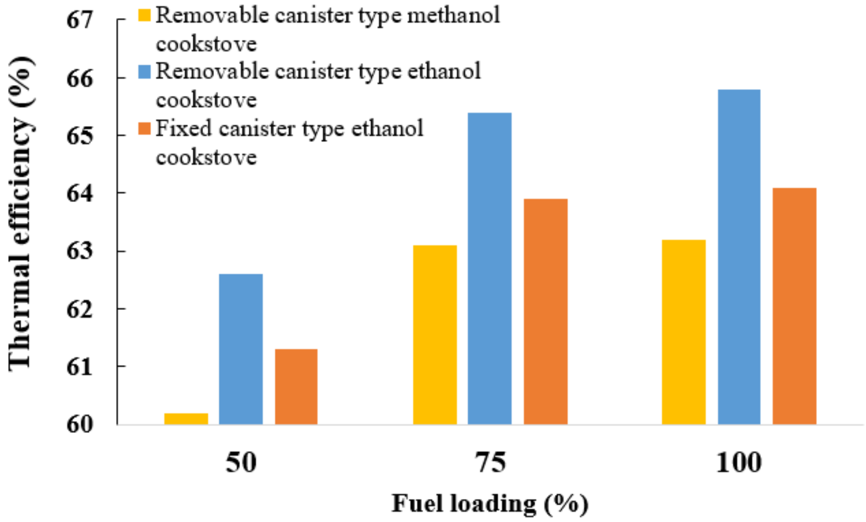


Figure 7.4 Effect of fuel loading on thermal efficiency

7.2.9 Vapour concentration test

All the tested cookstoves were allowed to burn for 4 h twice in a standard size kitchen. The amount of methanol and ethanol vapour in the confined space of a single unit of cookstove (consisting of two canisters) during burning conditions was found to be less than 5 ppm and 10 ppm, respectively. The Permissible Exposure Limit (PEL) for methanol and ethanol was taken as 200 ppm and 1000 ppm as per Occupational Safety and Health Administration (OSHA) guidelines and this exposure limit is calculated based on 8 h TWA (Time Weighted Average). The results showed that the obtained values are 97.5% and 99% lesser than the PEL which showed that the cookstove is safe for use. The lower concentration of unburnt vapour shows proper combustion of methanol and ethanol.

7.2.10 Allowable leakage test

The cookstove should be tested to know the leakage of fuel when it is not in operation to know the maximum allowable leakage in a room of standard size kitchen as per the LERC. As per the LERC, for any cookstove, the leakage should not go beyond the PEL. As per the method given by LERC, the allowable leakage rate of methanol and ethanol vapours from methanol and ethanol cookstoves in 24 h was found to be lower than 0.3 g/h and 2 g/h, respectively.

7.2.11 Emission test

When tested in accordance with the method described in section 7.1.11, the emission level of CO, CO_2, NO_x, and SO_x found is tabled below (Table 7.6).

Table 7.6 Limit values of emissions for tested cookstove

Emissions (ppm)	Methanol cookstove	Ethanol cookstove
CO	< 200 ppm	< 400 ppm
CO_2	> 10000 ppm	> 15000 ppm
NO_x	< 2 ppm	< 5 ppm
SO_x	-	< 10 ppm

Further, the carbon monoxide (CO) to carbon dioxide (CO_2) ratio of the exhaust gases of each canister of the tested cookstoves was found to be lower than 0.02.

7.3 Safety instruction

To operate the cookstove safely and smoothly, a safety instruction manual needs to be framed by conducting rigorous experiments under laboratory conditions. Operating the cookstove in a safe environment is an active component of cookstove technology that helps in avoiding the risk related to cookstove operations. Safety instructions for removable canister type methanol/ethanol cookstoves was given in three stages i.e., when cookstove is in operation, when canister is taken out from the cookstove body and storing of canister. However, in case of fixed canister type there is no need of taking the canister out from the cookstove body and storing the canister. Therefore, only first stage was required as the safety instructions. The formulated safety instructions are listed below:

Stage I: Safety instructions are to be followed when the cookstove is in operation

a) Do not breathe vapours (in case the flame goes off, during the lightening of the cookstove avoid breathing methanol vapour);

b) The cookstove should be placed on an even surface;

c) The cookstove should be operated in well ventilated space;

d) The standard kitchen volume should be between 25-35 m^3;

e) The standard air exchange rate in the kitchen should be 12-20 per h;

f) The maximum permitted continuous operation is for 4 h.

Stage II: Safety instructions are to be followed while taking out the canister from the cookstove's body

a) The canister should be left for a minimum of 10 min inside the body of the cookstove after switching off the cookstove i.e., closing the lever in the 'OFF' position. The canister should be removed only after the stipulated period;
b) In case the cookstove is not switched off by operating the lever in the 'OFF' position, operate the lever from 'ON' to 'OFF' position several times until the flame from the canister turns off;
c) If the lever is still not able to turn off the flame, it is required to remove the canister from the cookstove body by using protective gloves and turn off the flame by putting wet woolen clothes on the canister opening;
d) Avoid direct eye contact with the canister's opening while taking it out from the body.

Stage III: Safety instructions to be followed for storing/disposal of the canister

a) Handle empty canister with care because residual vapours are flammable;
b) Keep the canister (fresh / used) in a well-ventilated place;
c) Keep the canister away from heat, hot surfaces, sparks, open flames, and other ignition sources;
d) Do not store the canister with incompatible products such as strong oxidizers i.e. barium, perchlorate, bromine, chlorine, chloroform, or sodium methoxide. Diethyl zinc, Acetyl bromide, Sodium hypochlorite, etc., or metals such as Aluminium, Magnesium, and Potassium.
e) Keep/store away from direct sunlight, and extremely high or low temperatures;
f) The canister should not be racked at height to avoid any sudden fall;
g) Disposal of the used canister is the manufacturer's responsibility;
h) After every use of the cookstove detach the canister and close the cap/lid of the canister.

7.4 Summary

Various tests were conducted for the development of Indian standards for the FFC based methanol/ethanol cookstoves. Optimized water quantity for thermal efficiency evaluation, the allowable leakage rate of vapour during non-burning and burning conditions, and limiting emission values of CO, CO_2, NO_x, and SO_x helped in providing technical input for the standardization. With the help of all the mentioned tests, the final set of instructions for safety was developed for all the studied cookstoves.

Chapter 8 Conclusions and Future Scope

Preface

The conclusions referred to the important findings of the work presented in this thesis. The presented investigations added another dimension to the ongoing research work in the domain of methanol and ethanol for cooking applications. It was the first of its kind of research in the development of efficient and clean cookstoves based on PMC technology for methanol and ethanol fuels. This thesis work first focused on the performance evaluation of available FFC-based methanol and ethanol cookstoves and then on the development of energy-efficient and environmentally friendly PMC-based methanol and ethanol cookstoves applicable for household applications (1-3.5 kW). The performance evaluation included both laboratory and field studies. Thereafter, the research work was extended to assess the ability of PMC-based cookstoves to improve indoor air quality compared to their conventional counterparts. Furthermore, an Indian standard for FFC-based methanol/ethanol cookstoves was developed.

8.1 Conclusions from performance, usability, safety and sustainability studies on FFC based methanol cookstove

This study is an attempt to check the viability of methanol as an alternative for household cooking fuel in India. Performances of the LPG cookstove were compared with the methanol cookstove and the key observations are listed below:

- The methanol cookstove yielded a maximum thermal efficiency of 63.4%.
- Methanol cookstove gives cleaner combustion with comparable CO emissions of LPG cookstove.
- The Control Cooking Test (CCT) highlighted that the energy consumption of the methanol cookstove is comparable to that of the LPG cookstove.
- The methanol cookstove secures a similar score as LPG in terms of maintenance, comfort, and mechanical stability.
- Results of the user survey of methanol cookstove showed that the most widely reported favorable trait (over 90% of users) was safety and cleanliness.

- Users reported difficulty in frequent refilling of the canister (~30% of the users) and more time requirement for cooking as compared to LPG (16% of users).
- The foremost suggestion by the users (over 90%) was to increase the capacity or size of the canister to avoid frequent refilling.
- The fuel sustainability analysis revealed that with a 10% methanol penetration rate in India, 3.69 MMT of LPG import could be reduced by 2030.

Overall thermal, emission usability and sustainability studies put methanol cookstove as a viable alternative for household cooking.

8.2 Conclusions from development of PMC based methanol cookstoves

The improvement in the performance of canister based methanol cookstove was carried out by the development of the pressurized FFC and PMC based methanol cookstove. The FFC based pressurized methanol cookstove was not able to produce a sustainable flame with the available commercial burners (venus, silencer, and roarer). The shortcomings of conventional burners were overcome using PRB. The major observations are listed below:

- The developed PMC based methanol cookstove was operable in the range of 1.8-3.5 kW without any flashback.
- The optimized configurations were 65 mm porous matrix diameter, 0.8 mm orifice diameter, and vaporizer configuration of 2 ascending and 2 descending copper pipes (6 mm ID) which were interconnected at the top.
- The optimized distance between the orifice and PRB bottom surface was 55 mm. The maximum thermal efficiency of 66.6% was achieved with 4.8 kg of water.
- The developed cookstove gives a lower CO/CO_2 ratio which is 70% and 60% lower than the prescribed limit (0.02), for low FP (1.8 kW) and High FP (3.5 kW), respectively.
- A comparison study on FFC and PMC based methanol cookstoves showed that there was an increase in thermal efficiency and a decrease in CO/CO_2 ratio by 4.8% and 33.3% respectively, due to the use of PMC based cookstoves.

The valuable insights from the above study suggest that the developed cookstove can be operated at high FP with the use of PRB, which is required for the commercialization of methanol/ethanol cookstoves.

8.3 Conclusions from feasibility studies on ethanol as cooking fuel

The feasibility study of ethanol as cooking fuel consists of comparison of FFC based fixed and removable canister type ethanol cookstove with PMC based ethanol cookstove. The key observations are listed below:

- The optimum fuel storage capacity was 1 litre for fixed canister type ethanol cookstove with minimum fuel residual capacity of 0.034 litre and the corresponding value for removable canister type cookstove were 1.98 litre and 0.41 litre, respectively.
- The optimized blend percentage with a maximum visible reduction in soot formation was found to be 93% ethanol and 7% water (E93W7).
- The PMC based ethanol cookstove yields a maximum efficiency of 60.3%, which is the highest among all compared cookstoves at low FP settings.
- The advantage of using PMC based ethanol cookstove from a user perspective is its higher FP of 3.5 kW which was limited to 2 kW for FFC based cookstoves.
- The CCT highlights that the PMC based ethanol cookstove requires 7.2% and 9.7% lower cooking time and 4.5% and 2.9% lower fuel consumption than fixed and removable canister type FFC based ethanol cookstoves, respectively.

Overall thermal and emission performances and CCT analysis showed that PMC based ethanol cookstoves put ethanol as a viable alternative for household cooking.

8.4 Conclusions from IAQ assessment

A study was conducted which includes the monitoring of pollutants in a developed kitchen room with four different fuels i.e., ethanol, methanol, kerosene, and LPG. This is the first of its kind study, which comprehensively monitored the emission values of $PM_{2.5}$, PM_{10} and CO from CS_{PMC} and compared it with the conventional CS_{FFC}. The 2 h real time concentration monitoring during cooking hours established that CS_{PMC} shows a significant reduction ($p < 0.05$) in pollutants emission. Further, the 24 h average concentration of the studied pollutants and its comparison with WHO guidelines is also a major contribution of the study. The major observations from the study are highlighted below:

- The maximum reduction of 55.3%, 62.6% and 66.6% were found due to the usage of $CS_{PMC}^{Kerosene}$ for PM_{10}, $PM_{2.5}$ and CO, respectively as compared to $CS_{FFC}^{Kerosene\ pressure}$.
- All the developed CS_{PMC}, showed a significantly lower value of pollutants.
- The $CS_{FFC}^{Kerosene\ pressure}$ and $CS_{FFC}^{Kerosene\ wick}$ wick are emitting higher emissions than WHO guidelines for $PM_{2.5}$ and PM_{10} by 32.4% and 27%; and 22% and 11.6%, respectively.
- The $CS_{PMC}^{Kerosene}$ showed a reduction of 4% and 10.8% for $PM_{2.5}$ and PM_{10}, respectively to WHO guidelines.
- The maximum reduction due to the use of CS_{PMC} was found in the case of CS_{PMC}^{LPG} and there was a reduction of 17.6%, 37.4% and 85.1% for the $PM_{2.5}$, PM_{10} and CO, respectively, to the prescribed WHO values.

Hence, the present study established that the emissions of pollutants from household cooking fuels in CS_{FFC} have higher emissions compared to CS_{PMC}. Therefore, cookstoves based on PMC technology can be a plausible solution to achieve better IAQ and health benefits.

8.5 Indian standard for FFC based methanol and ethanol cookstove

All the important inputs which require for the formation of a standard of FFC based methanol and ethanol cookstoves are evaluated through various tests. There are 11 tests conducted to evaluate the cookstove's performance namely, resistance to draught test, resistance to heating test, shutting off the cookstove test, durability test, normal evaporation test, fuel consumption test, thermal efficiency test, fuel loading capacity test, vapour concentration test, allowable leakage test and emission test. The key observations are listed below:

- Maximum thermal efficiency of 63.2% for FFC based methanol cookstoves and 65.8% for ethanol cookstoves were obtained with the use of 6 kg and 8 kg water, respectively.
- The allowable leakage rate of methanol and ethanol vapour which are fixed as 0.3 g/h and 2 g/h, respectively for the safe usage of cookstove. As these values are lower than the prescribed limit of OSHA guidelines for safe usage i.e., 200 ppm and 1000 ppm for methanol and ethanol, respectively.

In conclusion, the studies conducted on FFC-based methanol and ethanol cookstoves, as well as the comparison with conventional cookstoves such as LPG and kerosene, provide valuable insights into their performance, usability, safety, and sustainability. The methanol cookstove shows promising results with a maximum thermal efficiency of 63.4% and cleaner combustion with comparable CO emissions to LPG. User surveys indicate high satisfaction in terms of safety and cleanliness, although some users expressed concerns about frequent refilling and longer cooking times compared to LPG. The development of PMC-based methanol cookstoves demonstrates improved performance, with higher thermal efficiency, lower CO/CO2 ratios, and increased stability. Feasibility studies on ethanol as a cooking fuel highlight its potential as a viable alternative, with optimized fuel storage capacities and higher efficiencies achieved in PMC-based ethanol cookstoves. Furthermore, IAQ assessments reveal significant reductions in pollutant emissions from PMC-based cookstoves compared to FFC-based ones, contributing to improved indoor air quality and health benefits. Finally, the establishment of Indian standards for FFC-based methanol and ethanol cookstoves ensures performance, safety, and emission compliance. Overall, these findings suggest that FFC and PMC-based methanol and ethanol cookstoves offer viable alternatives for household cooking, providing enhanced performance, usability, safety, and sustainability.

8.6 Future scope

The major findings observed from the present thesis work contribute to the knowledge of the design of new burners and pave paths for further investigations in similar areas. The research work can be extended to the following –

- The comparison of methanol and ethanol based cookstoves with biomass based cookstoves from the Indian perspective
- Evaluation of optimal fuel/air mixture for methanol and ethanol based cookstove
- Study of formaldehyde emission from methanol cookstove
- Development of commercial scale (5-10 kW) methanol and ethanol cookstoves
- Optimization of blending percentage of ethanol and methanol for better output of cookstove
- Pilot study on ethanol based cookstove in Indian scenario

References

Adeniji, B., Ana, G., Ige, O., Oluwole, O., Olopade, C., 2015. Exposure to Emissions from Kerosene Cooking Stoves and the Pulmonary Health Status of Women in Olorunda Community, Ibadan, Nigeria. Air Qual. Atmos. Heal. 6, 435–445. https://doi.org/10.1007/s11869-012-0183-6

Adjei-Mantey, K., Takeuchi, K., 2022. Supply-side factors of LPG adoption and usage frequency in Ghana: Assessing the validity of subjective distance to refill. Energy Sustain. Dev. 70, 475–481. https://doi.org/10.1016/j.esd.2022.08.021

Ahmad, M., Khan, I., Shahzad Khan, M.Q., Jabeen, G., Jabeen, H.S., Işık, C., 2023. Households' perception-based factors influencing biogas adoption: Innovation diffusion framework. Energy 263. https://doi.org/10.1016/j.energy.2022.126155

Bailis, R., 2004. Controlled Cooking Test (CCT) Version 2. Househ. Energy Heal. Program. Shell Found. 1–8.

Bailis, R., Broekhoff, D., Lee, C.M., 2016. Supply and sustainability of carbon credits and alternative fuels for international aviation.

Bailis, R., Thompson, R., Lam, N., Berrueta, V., Muhwezi, G., Adams, E., 2018. Kitchen Performance Test (KPT) Overview: Household Surveys and Fuel Consumption Measurements.

Balakrishnan, K., Mehta, S., Kumar, P., Ramaswamy, P., 2004. Indoor Air Pollution Associated with Household Fuel Use in India. An Exposure Assessment and Modeling Exercise in Rural Districts of Andhra Pradesh, India 114.

Benka-Coker, M.L., Tadele, W., Milano, A., Getaneh, D., Stokes, H., 2018. A case study of the ethanol CleanCook stove intervention and potential scale-up in Ethiopia. Energy Sustain. Dev. 46, 53–64. https://doi.org/10.1016/j.esd.2018.06.009

Bhojvaid, V., Jeuland, M., Kar, A., Lewis, J.J., Pattanayak, S.K., Ramanathan, N., Ramanathan, V., Rehman, I.H., 2014. How do people in rural india perceive improved stoves and clean fuel? evidence from Uttar Pradesh and Uttarakhand. Int. J. Environ. Res. Public Health 11, 1341–1358. https://doi.org/10.3390/ijerph110201341

BIS, 1986. IS 11760 (1986): Specification for Gravity-fed Kerosene Wick Stove [MED 26: Oil Burning Appliances].

Bloomfield, E., 2014. Gender and Livelihoods Impacts of Clean Cookstoves in South Asia 102.

Charron, D., Lam, N., Pennise, D., Wofchuck, T., 2011. Ethanol as a Household Fuel in Madagascar: Health Benefits, Economic Assessment and Review of African Lessons for Scaling up.

Chemanalyst, 2020. Methanol Market Pricing, Demand, Market Analysis 2030 | ChemAnalyst [WWW Document]. URL https://www.chemanalyst.com/industry-report/methanol-market-63 (accessed 9.29.20).

Dai, H., Lin, B., Zhai, C., Hong, Y., Li, Q., 2015. Subadiabatic combustion of premixed gas in ceramic foam burner. Int. J. Heat Mass Transf. 91, 318–329. https://doi.org/10.1016/j.ijheatmasstransfer.2015.07.122

Deb, S., Kaushik, L.K., Kumar, M.A., Satish, S.H.V., Muthukumar, P., 2021. Clustered Porous Radiant Burner: A cleaner alternative for cooking systems in small and medium scale applications. J. Clean. Prod. 308, 127276. https://doi.org/10.1016/j.jclepro.2021.127276

Deb, S., Muthukumar, P., 2021. Development and performance assessment of LPG operated cluster Porous Radiant Burner for commercial cooking and industrial applications. Energy 219, 119581. https://doi.org/10.1016/j.energy.2020.119581

Devi, S., Sahoo, N., Muthukumar, P., 2019. Combustion of biogas in Porous Radiant Burner: Low emission combustion. Energy Procedia 158, 1116–1121. https://doi.org/10.1016/j.egypro.2019.01.276

Dinesh, M.H., Pandey, J.K., Kumar, G.N., 2022. Effect of parallel LPG fuelling in a methanol fuelled SI engine under variable compression ratio. Energy 239, 122134. https://doi.org/10.1016/j.energy.2021.122134

Ernstgard, L., Shibata, E., Johanson, G., 2005. Uptake and disposition of inhaled methanol vapor in humans. Toxicol. Sci. 88, 30–38. https://doi.org/10.1093/toxsci/kfi281

Gautam, S.K., Suresh, R., Sharma, V.P., Sehgal, M., 2013. Indoor air quality in the rural Indiatle 24, 2013.

Gould, C.F., Urpelainen, J., 2018. LPG as a clean cooking fuel: Adoption, use, and impact in rural India. Energy Policy 122, 395–408. https://doi.org/10.1016/j.enpol.2018.07.042

Hajamalala, A.M., 2014. Thermal performance of a low-concentration ethanol stove without pressure system. Curr. Sci. 107, 289–296. https://doi.org/10.1007/s

Hazra, S., Lewis, J.J., Das, I., Singha, A.K., 2014. Adoption and use of improved stoves and biogas plants in rural India. https://doi.org/10.13140/RG.2.2.30398.28481

IEA, 2022. The Energy Progress Report 2022, IEA.

Indian Oil Corporation, 2021. Indian Oil Product Prices [WWW Document]. URL https://iocl.com/TotalProductList.aspx (accessed 9.28.20).

IRENA, 2014. REmap 2030 - A Renewable Energy Roadmap. /publications/2014/Jun/REmap-2030-Full-Report 188.

IS:4246, 2002. IS 4246 (2002): Domestic Gas Stoves for use with Liquefied Petroleum Gases.

Jetter, J.J., Ebersviller, S.M., 2015. Test Report - CleanCook Model A1 Stove with Alcohol Fuel,2015.

Jugjai, S., Rungsimuntuchart, N., 2002. High efficiency heat-recirculating domestic gas burners.pdf 26, 581–592.

Kakati, S., Mahanta, P., Kakoty, S.K., 2007. Performance analysis of pressurized kerosene stove with porous medium inserts. J. Sci. Ind. Res. (India). 66, 565–569.

Kandpal, J.B., Maheshwari, R.C., Kandpal, T.C., 1995. Indoor air pollution from domestic cookstoves using coal, kerosene and LPG. Energy Convers. Manag. 36, 1067–1072. https://doi.org/10.1016/0196-8904(94)00087-G

Kaushik, L.K., Muthukumar, P., 2020. Thermal and economic performance assessments of waste cooking oil /kerosene blend operated pressure cook-stove with porous radiant burner. Energy 206, 118102. https://doi.org/10.1016/j.energy.2020.118102

Kaushik, L.K., Muthukumar, P., 2019. Performance assessment of a porous radiant cook stove fueled with blend of waste vegetable oil (WVO) and kerosene. Energy Procedia 158, 2391–2396. https://doi.org/10.1016/j.egypro.2019.01.289

Kimemia, D., Van Niekerk, A., 2017. Cookstove options for safety and health: Comparative analysis of technological and usability attributes. Energy Policy 105, 451–457. https://doi.org/10.1016/j.enpol.2017.03.022

Kline and Mcclintok, 1953., 1953. Describing uncertainties in single sample experiments. Mechanical Enginnering.

Lask, K., Booker, K., Han, T., Granderson, J., Yang, N., Ceballos, C., Gadgil, A., 2015. Performance comparison of charcoal cookstoves for Haiti: Laboratory testing with Water Boiling and Controlled Cooking Tests. Energy Sustain. Dev. 26, 79–86. https://doi.org/10.1016/j.esd.2015.02.002

Liao, J., Kirby, M.A., Pillarisetti, A., Piedrahita, R., Balakrishnan, K., Sambandam, S., Mukhopadhyay, K., Ye, W., Rosa, G., Majorin, F., Dusabimana, E., Ndagijimana, F., McCracken, J.P., Mollinedo, E., de Leon, O., Díaz-Artiga, A., Thompson, L.M., Kearns, K.A., Naeher, L., Rosenthal, J., Clark, M.L., Steenland, K., Waller, L.A., Checkley, W., Peel, J.L., Clasen, T., Johnson, M., Aravindalochanan, V., Bankundiye, G., Barr, D.B., Bussalleu, A., Canuz, E., Castañaza, A., Chen, Y., Chiang, M., Craik, R., Davila-Roman, V.G., de las Fuentes, L., Elon, L., Espinoza, J.G., Garg, S., Hamid, S., Hartinger, S., Harvey, S.A., Hengstermann, M., Hennessee, I., Herrera, P.M., Hossen, S., Howards, P.P., Jaacks, L., Jabbarzadeh, S., Lenzen, P., Lovvorn, A.E., Mbabazi, J., McCollum, E., Meyers, R., Moulton, L., Mukeshimana, A., Mutariyani, B., Natesan, D., Nizam, A., Ntivuguruzwa, J. de D., Papageorghiou, A., Puttaswamy, N., Puzzolo, E., Quinn, A., Rajamani, K.D., Ramakrishnan, U., Ramasami, R., Ramirez, A., Ryan, P.B., Saidam, S., Sarnat, J.A., Simkovich, S., Sinharoy, S.S., Smith, K.R., Swearing, D., Thangavel, G., Toenjes, A., Valdes, V., Williams, K.N., Young, B.N., 2021. LPG stove and fuel intervention among pregnant women reduce fine particle air pollution exposures in three countries: Pilot results from the HAPIN trial. Environ. Pollut. 291. https://doi.org/10.1016/j.envpol.2021.118198

Makonese, T., Annegarn, H.J., Meyer, J., 2020. Performance evaluation of three methanol stoves using a contextual testing approach. Energy Sustain. Dev. 55, 13–23. https://doi.org/10.1016/j.esd.2019.12.002

Masekameni, M.D., Makonese, T., Annegarn, H.J., 2015. A comparison of emissions and thermal efficiency of three improved liquid fuel stoves. Proc. 23rd Conf. Domest. Use Energy, DUE 2015 71–76. https://doi.org/10.1109/DUE.2015.7102965

Maurya, P., Palanisamy, M., Mahalingam, A.K., Kaushik, L.K., Ramalingam, A., 2022. Performance, economic and pilot studies on canister-based methanol stove for household cooking application. Energy Sustain. Dev. 66, 117–124. https://doi.org/10.1016/j.esd.2021.11.006

Methanol Economy [WWW Document], 2018. URL https://www.niti.gov.in/methanol-economy (accessed 1.17.23).

Methanol Institute, 2020, 2020. The Methanol Industry|Methanol Institute|www.methanol.org [WWW Document]. URL https://www.methanol.org/the-methanol-industry/ (accessed 9.27.20).

Ministry of Coal, 2018. Coal Mining Block | Ministry of Coal, Government of India [WWW Document]. URL https://coal.nic.in/coal-mining-block (accessed 9.29.20).

Moses, N., Maccarty, N., 2018. Cookstove Usability Testing Protocol.

Mudombi, S., Nyambane, A., Von Maltitz, G.P., Gasparatos, A., Johnson, F.X., Chenene, M.L., Attanassov, B., 2018. User perceptions about the adoption and use of ethanol fuel and cookstoves in Maputo, Mozambique. Energy Sustain. Dev. 44, 97–108. https://doi.org/10.1016/j.esd.2018.03.004

Murren, J., 2006. User Responses-the Ethanol-fueled CleanCook Stove's Safety, Fuel Consumption & Efficiency Addis Ababa, Ethiopia.

Muthukumar, P., Maurya, P., 2021. Self-aspirated pressurized methanol cookstove with a porous radiant burner.

Muthukumar, P., Shyamkumar, P.I., 2013. Development of novel porous radiant burners for LPG cooking applications. Fuel 112, 562–566. https://doi.org/10.1016/j.fuel.2011.09.006

Natarajan, R., 2018. Methanol as an alternative fuel?, Motor Ship.

Obueh, J., 2008. Project Gaia Nigeria Pilot Study Final Report Results of Project Gaia ' s CleanCook Methanol Stove Pilot Study in Delta State , Nigeria Sponsors Delta State Government.

Oketch, P., 2013. Optimization of Performance of Bio-ethanol gel cookstove.

Oluoch, D.O., Nyamasyo, G., 2020. Indoor Air Pollution from Cooking and its Effects on Households in Low Income Urban Areas in Developing Countries 1–8. https://doi.org/10.35248/2375-4397.20.8.260.Copyright

PCIA & Global Alliance, 2013. The Water Boiling Test Version 4.2.3; Cookstove Emissions and Efficiency in a Controlled Laboratory Setting. Glob. Alliances clean cookstoves 2, 52.

Petroleum Planning & Analysis Cell, 2020. Petroleum Planning & Analysis Cell.

Pizarro-Loaiza, C.A., Antón, A., Torrellas, M., Torres-Lozada, P., Palatsi, J., Bonmatí, A., 2021. Environmental, social and health benefits of alternative renewable energy sources. Case study for household biogas digesters in rural areas. J. Clean. Prod. 297. https://doi.org/10.1016/j.jclepro.2021.126722

PPAC, 2020. PPAC [WWW Document]. URL https://www.ppac.gov.in/content/146_1_ProductionPetroleum.aspx (accessed 9.29.20).

Puzzolo, E., 2014. Cooking with ethanol : a stakeholders ' perspective Dissertation submitted in accordance with the requirements of the University of Liverpool for the degree of Master or Public Health.

Rajvanshi, A.K., Patil, S.M., Mendonca, B., 2007. Low-concentration ethanol stove for rural areas in India. Energy Sustain. Dev. 11, 94–99. https://doi.org/10.1016/S0973-0826(08)60568-2

Robinson, J., 2006. Bio-Ethanol as a Household Cooking Fuel : A Mini Pilot Study of the SuperBlu Stove in Peri-Urban Malawi.

Saraswat, V.K., Bansal, R., 2017. India's Leapfrog to Methanol Economy. Niti Ayog.

Sharma, M., Mahanta, P., Mishra, S.C., 2016a. Usability of porous burner in kerosene pressure stove: An experimental investigation aided by energy and exergy analyses. Energy 103, 251–260. https://doi.org/10.1016/j.energy.2016.02.100

Sharma, M., Mishra, S.C., Acharjee, P., 2009. Thermal efficiency study of conventional kerosene pressure stoves equipped with porous radiant inserts. Int. Energy J. 10, 247–254.

Sharma, Monikankana, Mishra, S.C., Acharjee, P., 2009. Thermal efficiency study of conventional kerosene pressure stoves equipped with porous radiant inserts. Int. Energy J. 10, 247–254.

Sharma, M., Mishra, S.C., Mahanta, P., 2016b. Effect of burner configuration and operating parameters on the performance of kerosene pressure stove with submerged porous medium combustion. Appl. Therm. Eng. 107, 516–523. https://doi.org/10.1016/j.applthermaleng.2016.07.016

Sharma, M., Mishra, S.C., Mahanta, P., 2011. An experimental investigation on efficiency improvement of a conventional kerosene pressure stove. Int. J. Energy a Clean Environ. 12, 79–93. https://doi.org/10.1615/InterJEnerCleanEnv.2012005580

Sidhu, M.K., Ravindra, K., Mor, S., John, S., 2017. Household air pollution from various types of rural kitchens and its exposure assessment. Sci. Total Environ. 586, 419–429. https://doi.org/10.1016/j.scitotenv.2017.01.051

Sinha, G.S., 2017. Development and Performance Analysis of Self-Aspirated Porous Radiant Burners for Kerosene Pressure Stove, 2012-2017 (Doctoral dissertation). Guwahati.

Sinha, G.S., Muthukumar, P., 2019. Study of effects of various parameter on thermal efficiency of porous burner with kerosene pressure stove, in: Journal of Physics: Conference Series. p. 012136. https://doi.org/10.1088/1742-6596/1240/1/012136

Sinha, Gyan Sagar, Muthukumar, P., 2019. Material characterization role in porous media combustion stability and performance. Mater. Today Proc. 18, 5063–5068. https://doi.org/10.1016/j.matpr.2019.07.501

Statista, 2018. Methanol production capacity globally 2030 | Statista [WWW Document]. URL https://www.statista.com/statistics/1065891/global-methanol-production-capacity/ (accessed 9.30.20).

Stokes, H., 2005. Commercialization of a New Stove and Fuel System for Household

Energy in Ethiopia Using Ethanol from Sugar Cane Residues and Methanol from Natural Gas Project Overview Presented to the Ethiopian Society of Chemical Engineers ESChE At the Forum on " Alcoho 1–16.

Stokes, H., Ebbeson, B., 2005. Project Gaia: Commercializing a new stove and new fuel in Africa. Boil. Point 50, 31–33.

Stokes, H.C., Crocco, J.R., 2005. the Reality of Methanol Use As a Cooking Fuel in Developing Countries.

Swanepoel, S., Niekerk, V., 2001. Nova Report on reseach into domestic stove requirements and the desirability of Methanol as fuel on behalf of ORIGO-ELECTROLUX.

Tagle, M., Pillarisetti, A., Hernandez, M.T., Troncoso, K., Soares, A., Torres, R., Galeano, A., Oyola, P., Balmes, J., Smith, K.R., 2019. Monitoring and modeling of household air quality related to use of different Cookfuels in Paraguay. Indoor Air 29, 252–262. https://doi.org/10.1111/ina.12513

University of California-Berkeley, 2005. Installing Indoor Air Pollution Instruments in a Home, Version 5.1.

WHO, 2022. Increasing Access to Clean Cooking through Subsidies. Polcy Brief, WHO, Geneva.

Appendix I

1. **Calorific value of Fuels (IITG – Laboratory)**

Fuel	**Lower calorific value (MJ/kg)**
Kerosene	: 43.9
Methanol	: 18.5
Ethanol	: 26.7
LPG	: 45.6

2. **Fire Power (FP)**

To find the FP of burner, kW = Mass flow rate of the fuel × calorific value of the fuel

For example:

FP of cookstove, if the flow rate is 150 g/h =0.150 kg/h × 43900 kJ/kg = 1.8 kW

3. **Pressure gauge**

Make	: Waree instruments
Dial size	: 100 mm
Range	: 0-2 bar
Housing Materials	: 0.05 bar
Accuracy	: ±0.05% full scale
Temperature Limits	: 0 °C to 120 °C

4. **Weighing balance**

Make	: Saffron
Model	: SES 20 TH
Capacity	: 2 g to 20 kg
Accuracy	: ±0.1 g full scale

5. **Thermocouple**

Type	: K

Range	: 20 °C to 1350 °C
Accuracy	: ±0.1 g full scale

6. **Data acquisition unit (DAQ)**

Make	: Agilent Technologies
Model	: 34970A
Scan rate	: 60 to 250 channels/second
Scan Intervals	: 0 to 99 hours; 1 ms time step
Accuracy	: 6 digits of resolution with 0.004%

7. **Portable gas analyser**

Make	: Testo
Model	: 340
O_2	: 0-25 Vol%
Resolution	: 0.01 Vol%
Accuracy	: ±0.2Vol.%
CO	: 0-10000ppm
Accuracy	: ±10ppm (0-200 ppm)
Resolution	: 1 ppm
NO	: 0-3000 ppm
Accuracy	: ±5ppm (0-99 ppm)
Resolution	: 1 ppm
NO_2	: 0-500ppm
Accuracy	: ± 10ppm (0-199)
Resolution	: 0.1 ppm

8. **Bomb calorimeter**

Make	: Anton Parr
Model	: 1341

9. **Indoor Air Quality (IAQ) meter**

Make	: Temptop
Model	: M -2000
PM2.5	: 0-999 $\mu g/m^3$
Accuracy	: ±10 $\mu g/m^3$ (0-10 $\mu g/m^3$) ±10% (> 100 $\mu g/m^3$)
Resolution	0.1 $\mu g/m^3$
PM10	: 0-999 $\mu g/m^3$
Accuracy	: ±15 $\mu g/m^3$ (0-10 $\mu g/m^3$) ±15% (> 100 $\mu g/m^3$)
Resolution	0.1 $\mu g/m^3$

10. **Methanol and ethanol vapour concentration measurement device**

Make	: ATS
Model	: 101 M
Methanol vapour	: 0-500 ppm
Accuracy	: ±10 ppm
Resolution	: 1 ppm
Ethanol vapour	: 0-500 ppm
Accuracy	: ±10 ppm
Resolution	: 1 ppm

Appendix II

A -Usability attributes and scoring criteria

Fuel convenience

The fuel convenience signifies the time spend for purchase and preparation of the cookstove. The ranks for this aspect are calculated based on two sub criteria i.e., fuel availability and fuel preparation as shown in Table A1. Fuel availability is time spend in collecting or buying the fuel. In the case of LPG, refilled fuel cylinder is home-delivered and is streamlined by an online booking system launched by the Ministry of Petroleum and Natural Gas, India. In the case of methanol, the government is planning to provide the methanol filled canister through refilling station. Fuel preparation is the time spend for preparing the fuel before lighting the cookstove. Methanol cookstove needs insertion of the canister to the stove body from the respective location of canister whereas LPG cookstove needs switching the regulator in ON mode for fuel supply.

Table A1: Rank scoring criteria for fuel convenience

Attributes	**Rank scoring**				
	0 *(Very Poor)*	1 *(Poor)*	2 *(Fair)*	3 *(Good)*	4 *(Best)*
Fuel availability	Fuel is not available	>1h	15-60 min	5-15 min	< 5 min
Fuel preparation	More than 5 min/meal	2-5 min/meal	1-2 min/meal	30-60 sec/meal	No time

Cooking performance

The cooking performance of a tested cookstove is evaluated based on cooking speed, FP range, FP control, and versatility. Cooking speed is determined by the cooking time for a particular dish. FP range refers to the easiness of keeping low heat and FP control refers to ease in adjusting the heat requirement of the cookstove. Versatility refers to the compatibility with common meals and existing vessels and pans. The rank is provided based on the question as given in Table A2.

Table A2: Rank scoring criteria for cooking performance

Attributes	Rank scoring				
	0 *(Very Poor)*	1 *(Poor)*	2 *(Fair)*	3 *(Good)*	4 *(Best)*
Cooking speed "Does your stove cook quickly or slowly?"	Very slowly	Slowly	Neither quickly nor slowly	Quickly	Very quickly
FP range "Is it hard or easy to keep the fire small and cook at a low heat on your stove?"	Very hard	Hard	Neither easy nor hard	Easy	Very easy
FP control "Is it hard or easy to control the size of the fire in your stove?"	Very hard	Hard	Neither easy nor hard	Easy	Very easy
Versatility "How many of the different sizes of vessels and pans you cook with fit on your stove?"	Very un-important	Unimportant	Somewhat important	Important	Very important

Operability

Operability refers to the degree of ease to which a cook can operate the cookstove. For gaseous and alcohol based stoves, it depends on refuelling time, visibility of fire, ease of lighting and fire start-up delay. For methanol refuelling time depend on canister capacity, numbers of family member and cooking frequency. The scoring criteria for the operability are shown in Table A3.

Table A3: Rank scoring criteria for operability

Attributes	**Rank scoring**				
	0 *(Very Poor)*	1 *(Poor)*	2 *(Fair)*	3 *(Good)*	4 *(Best)*
Refuelling time	< 3 day	3-10 day	10-20 day	20-30 day	>60 day
Visibility of fire	-	Never visible	Minimally visible	Moderately visible	Highly visible
Ease of lighting	> 30 sec	15-30 sec	10-15 sec	5-10 sec	No time

Fire start-up delay	5-2 min	1-2 min	10-5 sec	2-5sec	No time

Maintenance

Maintenance refers to the longevity of the cookstove which is based on the expense and effort required for short and long term maintenance (Table A4). Therefore, the longer the period of maintenance higher the score will be for the given cookstove. The period for short or routine maintenance lies from never to more than 6 times per year. Long-term maintenance depends upon the time required for the replacement of cookstove or cookstove parts.

Table A4: Rank scoring criteria for maintenance

Attributes	**Rank scoring**				
	0 *(Very Poor)*	1 *(Poor)*	2 *(Fair)*	3 *(Good)*	4 *(Best)*
Routine maintenance	> 6 times per year	4-6 times per year	2-3 times per year	1 time per year	Never
Long term maintenance	Necessary replacement parts are too expensive	Necessary replacement parts are not available or hard to find	-	Replacements of parts at least annually	-

Comfort

The comfort related to working on the cookstove is an important consideration decides the selection of cookstoves. Comfort for the cookstove depends on sub-criteria i.e., safety feature, smoke exposure, soot deposits, cookstoves height and cookstoves aesthetics, durability, value and taste. The rank scores are derived from the existing sub-criterion score as given in Table A5. Cookstoves which create no trouble during operation are assigned the best rank.

Table A5: Rank scoring criteria for comfort

Attributes	**Rank scoring**				
	0 *(Very Poor)*	1 *(Poor)*	2 *(Fair)*	3 *(Good)*	4 *(Best)*
Vessel soot deposit	-	Soot covers bottom and more than ½ sides	Soot covers bottom and less than ½ sides	Soot covers bottom of vessel	No soot

Perceived safety "How you feel about the safety of your stove?"	It is so unsafe that I do not want to use it	It is not very safe to use	It is neither safe nor unsafe"	It generally feels safe to use, but sometimes feels unsafe"	It feels very safe to use
Perceived smoke "Which of the following best describes the amount of smoke your stove creates in the area where you cook?"	There is so much smoke that I don't like to use this stove"	I don't like the amount of smoke	I am neutral	There is less amount of smoke	The stove produces no smoke
Cooking height "How important is the height of a stove?"	Not suitable for cooking	Cooking height need to modified	I am neutral	Suitable for cooking	Highly suitable for cooking
Stove aesthetics "Which of the following best describes how you feel about the appearance of this stove?"	It is so ugly that I do not like having it in my house	It does not look very attractive. I wish it was different	I am neutral	It looks good, but could look better"	I really like the way it looks. I would not change it
Durability "Which of the following best describes how you feel about the durability of this stove?"	The durability is so poor that it is not worth using"	It is not very durable	I am neutral	It is somewhat durable	It is very durable
Value "Which of the following best describes how you feel about the value of this stove?"	It is a bad value for the cost	It is not a very good value for the cost	I am neutral	It is a good value for the cost	It is a very good value for the cost
Taste "Does this stove make the flavour or taste of your food better or worse than other stoves?"	Much worse	A little worse	Neither better nor worse	A little better	Much better

Location-specific needs

Cookstove needs other than cooking refers to location-specific needs. It depends on other applications i.e., space heating, insect repellent, lighting, portability, water heating, and food drying needs. In the present study, cooking is considered as the only need provided by the cookstove. Therefore, no score is assigned for this criterion.

Interview Analysis

Q.1 Can you list a few of your favourite things about your stove?

Q.2 Can you list a few of your least favourite things about your stove?

Q.3 Is there anything you would like to change about your stove?

Q.4 Is there anything else you would like to tell me about your stove or cooking in general?

B- *Safety attributes and scoring criteria*

Surface temperature of touchable parts

In this study, the lever/fuel regulating knob is the only touchable parts considered for study. In the present investigation, the surface temperature of touchable parts is measured with a T-type thermocouple. The highest temperature recorded during the 2 h burn cycle for evaluating the score and assigned the corresponding rank score (Table B1). A temperature of 40 °C and below is assigned the best rating.

Table B1: Rank scoring criteria for the surface temperature of touchable parts

Attributes	**Rank scoring**				
	0(*Very Poor)*	1 *(Poor)*	2 *(Fair)*	3 *(Good)*	4 *(Best)*
Temperature of touchable-parts (°C)	>50	≤50	≤45	≤42	≤40

Mechanical stability (assessment of overturning)

A cookstove should not topple or slide easily when in use. A higher tilt angle indicates that the cookstove is more mechanically stable than the one with a lower value. The rank score for stability attribute is shown in Table B2 for evaluating the score.

Table B2: Rank scoring criteria for the mechanical stability (Kimemia and Van Niekerk, 2017)

Attributes	**Rank scoring**				
	0(*Very Poor)*	1 *(Poor)*	2 *(Fair)*	3 *(Good)*	4 *(Best)*
Mechanical stability (tilt angle°)	<10	≥10	≥13	≥16	≥20

Appendix III

Uncertainty analysis

Estimation of uncertainty in the estimated quantities thermal efficiency (η_{th}), combustion efficiency (η_{comb}) and CO/CO_2 ratio have performed according to the sequential perturbation technique (Kline and Mcclintok, 1953). A sample calculation for the uncertainty in η_{th} is shown below. The expression for error ($\delta(\eta_{th})$) associated with the calculation of η_{th} (1) is found from the following:

$$\eta_{th}(\%) = \frac{(\mathrm{m_w c_w} + \mathrm{m_p c_p}) \times \Delta\mathrm{T}}{\mathrm{m_f} \times \mathrm{LCV}} \times 100 \tag{1}$$

$$\delta(\eta_{th}) = \left(+ \left(\frac{\partial\eta_{th}}{\partial \mathrm{m_p}}\right)^2 \times (\delta \mathrm{m_p})^2 + \left(\frac{\partial\eta_{th}}{\partial \mathrm{m_w}}\right)^2 \times (\delta \mathrm{m_w})^2 + \left(\frac{\partial\eta_{th}}{\partial \mathrm{m_f}}\right)^2 \times (\delta \mathrm{m_f})^2 + \left(\frac{\partial\eta_{th}}{\partial \Delta\mathrm{T}}\right)^2 \times (\delta\Delta\mathrm{T})^2 \right)^{\frac{1}{2}} \tag{2}$$

$$\delta(\eta_{th}) = \sqrt{(\mathrm{E_1} + \mathrm{E_2} + \mathrm{E_3} + \mathrm{E_4}} \tag{3}$$

Appendix IV

Development of numerical model

A numerical model was developed to study the combustion of methanol in PRB and to predict the radial temperature variation and equivalence ratio. As equivalence ratio was not measured experimentally due to higher temperature near the orifice and unavailability of experimental measuring instruments.

Model geometry

A schematic of the developed PRB is shown in Figure 1. The PRB domain consists of two regions characterized as porous and air inlet regions. The air inlet region is a cylindrical section of 55 mm height and 35 mm radius. The porous region consists of SiC matrix of 90% porosity with dimensions of 32.5 mm radius and 20 mm height. In the present study the fuel inlet is represented by the orifice diameter which varies as 0.8 mm, 1mm and 1.2 mm.

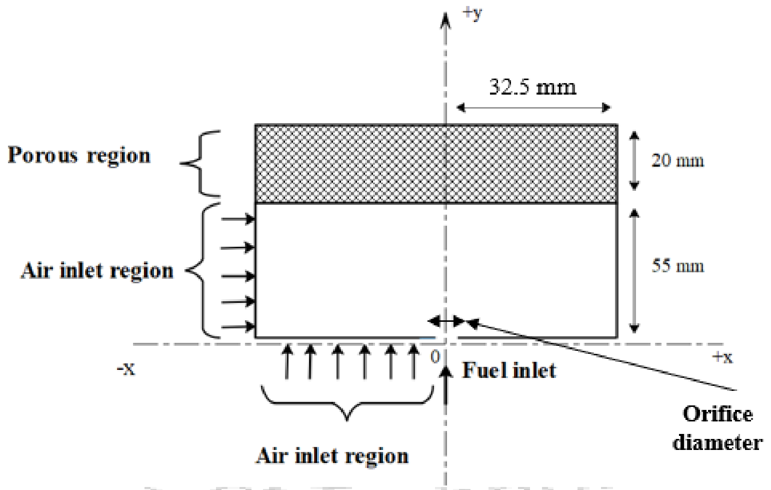


Figure 1. Schematic of computational domain of the PRB

Assumptions

Modelling liquid fuel spray evaporation in PRB involves the phase change of a liquid under complex heat transfer and the subsequent mixing of vapours inside a solid medium. The following assumptions were made in the present study to reduce the complexities involved in the problem:

1. The computational domain is assumed to be symmetric about the nozzle axis.
2. The heat feedback from the combustion zone is simulated by a volumetric heat source in the porous region.
3. The porous medium is treated as inert, homogeneous, and isotropic and is assumed to have constant porosity.
4. The flow is steady, incompressible, turbulent and non-isothermal
5. The fuel combustion happens in a single step reaction.

Governing equation

To simulate the mentioned geometry in Figure A1, the governing equations include the conservation equation of mass, momentum, energy in the gas and solid phase, and species transport. In the momentum equation, an additional term representing pressure drop within the porous medium was considered. The energy equations take into account conduction in both phases, radiation from the solid phase, as well as heat transferring between the two phases.

Governing equations are written as follows:

Continuity equation:

$$\nabla.\left(\rho_g \varphi \vec{V}\right) = 0 \tag{A}$$

where ρ_g, φ and $\vec{V}$ are density of gas, porosity of the medium and velocity of the gas, respectively.

Momentum equation:

$$\rho_g \varphi \vec{V}.\nabla \vec{V} = -\varphi \nabla \mathrm{p} + \mu_g \varphi \nabla.\left(\nabla \vec{V}\right) - (\nabla \mathrm{p})_{Porous} \tag{B}$$

where $(\nabla \mathrm{p})_{Porous}$ is the pressure drop due to the existence of the porous medium. It is evaluated by the modified Ergun equation, given below:

$$(\nabla \mathrm{p})_{Porous} = \frac{180(1-\varphi)^2 \mu_g}{\varphi^3 {d_h}^2} \vec{V} + \frac{1.8(1-\varphi)\rho}{\varphi^3 d_h} \vec{V}\vec{V} \tag{C}$$

Energy equation in gas phase:

$$\rho_g C_g \, \varphi \vec{V}.\nabla T_g = \varphi \nabla.\left(\nabla T_g\right) - \varphi \sum_{i=1}^{N} h_i \, \dot{\omega}_i + H_\text{v}(T_s - T_g) \quad \text{(D)}$$

Energy equation in solid phase:

$$(1 - \varphi)\nabla.(k_s \nabla T_s) + H_\text{v}\left(T_g - T_s\right) = 0 \quad \text{(E)}$$

Species conservation equation:

$$\rho_g \varphi \vec{V} \nabla. Y_i = \varphi \rho_g \nabla.(D_i \nabla Y_i) + \varphi \dot{\omega} \quad \text{(F)}$$

In Eq. (F) $\varphi\dot{\omega}$ represents the species production/destruction rate of the chemical reactions.

The combustion of methanol is represented by the single step chemical reaction shown in Eq. J. The rate of reaction is calculated by the eddy-dissipation model.

$$CH_3OH + 3O_2 \rightarrow 2CO_2 + 4H_2O \quad \text{(G)}$$

Energy equations for two phases are coupled through convective heat transfer. The volumetric heat transfer coefficient is calculated by using the following equation:

$$H_\text{v} = \frac{Nu_\text{v} k_g}{{d_p}^2} \quad \text{(H)}$$

where Nu_v is the Nusselt number and used to evaluate the volumetric heat transfer coefficient by using the correlation which is given below:

$$Nu_\text{v} = 0.95 Re^{0.35} Pr \quad \text{(I)}$$

where Pr is the Prandtl number and Re is the Reynold number, which is evaluated based on the mean pore diameter of the porous medium, d_p:

$$Re = \frac{\rho_g d_p V}{\mu} \quad \text{(J)}$$

Solution procedure

The simulations are carried out using the commercial code Ansys Fluent 20. The finite volume method was used to solve the governing equations. The second order upwind style is adopted for discretization. The SIMPLE algorithm was used to solve the pressure-velocity coupling. The discrete grid solution was used to ensure the accuracy of the calculations. When the residual error of the energy equation was less than 10^{-6} and other equations are less than 10^{-4}, convergence was achieved.

Grid independence studies

A grid sensitivity analysis is carried out to capture the maximum temperature at the outlet of the porous surface with the optimum minimum number of meshed elements. In order to achieve this, computational analysis is performed with various mesh elements for nozzle diameter of 0.8 mm and power input of 1.8 kW. Convergence criteria are based on scaled residuals, and the order of residue is 10^{-6}. Firstly, the coarse mesh is provided and then the mesh is refined. Further refinement is done by increasing the mesh elements. The result of grid independence studies is presented in Table 1. It is evident that the static temperature changes by only 0.2% after 359992 elements. So, all the calculations were carried out by adopting this optimum mesh, which saves computational time with minimum variations in result.

Table 1. Grid independence test

Local Thermal non-equilibrium model	
Mesh elements	**Temperature (°C)**
788846	784
359992	783
200401	756

Variation of equivalence ratio with radial distance

The effect of variation of equivalence ratio with radial distance for different orifice diameters and input power is shown in Figure 2. The variation of equivalence ratio with radial distance w.r.t. center shows that from 32.5 mm to 10 mm, equivalence ratio decrease and then from 10 mm to 0 mm it increases. The decrease in equivalence ratio shows that there is more air entrainment beneath the porous matrix. Whereas, the increase in equivalence ratio was mainly due to the formation of conical jet through orifice which leads to more fuel entrainment.

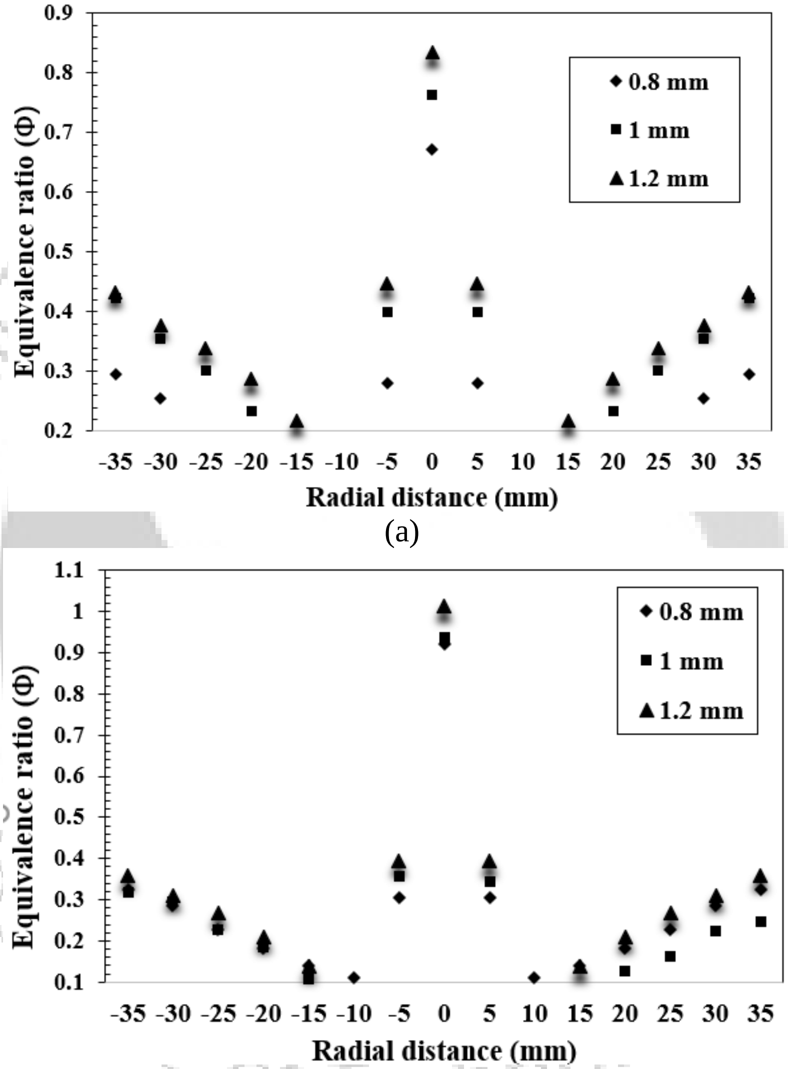
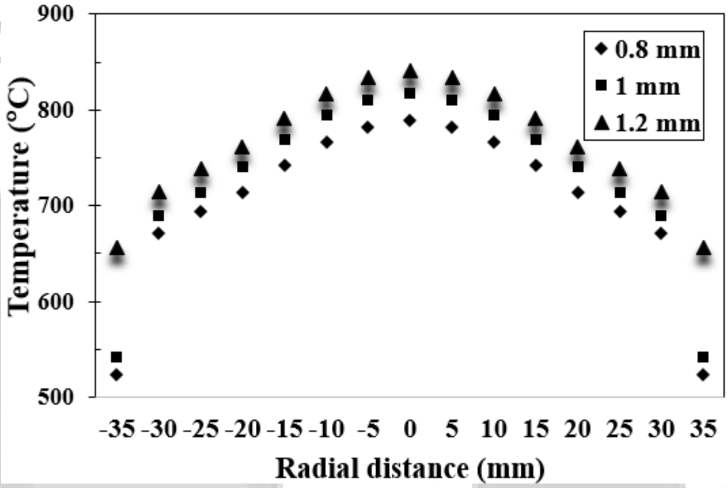


Figure 2. Effect of orifice diameter on equivalence ratio for FP (a)1.8 kW and (b) 3.5 kW

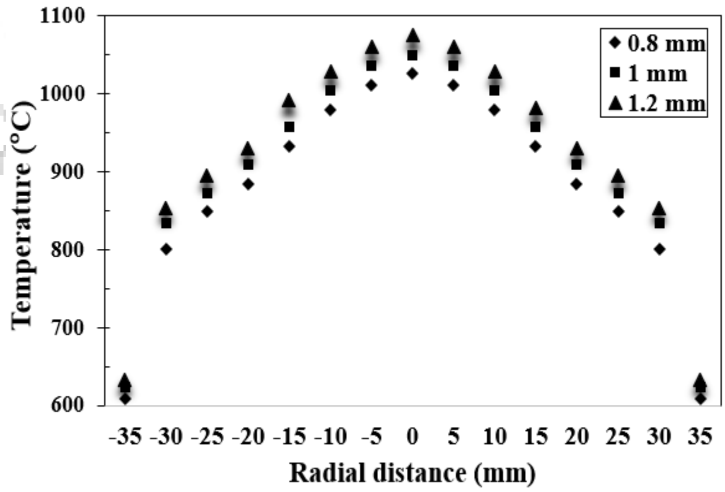
It was also observed that with the increase in orifice diameter from 0.8 to 1.2 mm, the equivalence ratio increases which indicates the formation of rich mixture. The range of equivalence ratio obtained for orifice diameters of 0.8 mm, 1mm and 1.2 mm were 0.29-0.67, 0.43-0.76 and 0.44-0.82, respectively, for input power of 1.8 kW. Similarly, for input power of 3.5 kW, the same was found in the range of 0.32-0.92, 0.34-0.94 and 0.36-1.101, respectively.

Variation of radial temperature with orifice diameter

Figure 3 shows the variation of radial temperature with orifice diameter and radial distance from the center. It was observed that with the increase in orifice diameter, there was increase in radial temperature. The maximum radial temperature of 8401 °C and 1060 °C were found at the center of porous matrix for FP of 1.8 kW and 3.5 kW, respectively, for orifice diameter of 1.2 mm. There was increase of 4.7% in maximum radial temperature as the diameter increases from 0.8 mm to 1.2 mm for FP of 3.5 kW. Whereas in the case of lower FP i.e., 1.8 kW, the corresponding value was found to be 6.5%.



(a)



(b)

Figure 3. Effect of orifice diameter on radial temperature for FP of (a) 1.8 kW and (b) 3.5 kW

Validation of numerical model with experimental results

The result obtained from the numerical model was also validated with the experimental results. The experiments were conducted with orifice diameter of 0.8 mm and the variation in radial temperature was measured for different radial locations. The results are given in Table 2 for FP of 3.5 kW. It was observed that the maximum temperature predicted by the numerical model was only 2.4% higher than the experimental temperature. The higher temperature predicted by the model is mainly due to the assumption of constant specific heat capacity, which affects the prediction of the rise in the system temperature (Dai et al., 2015). Furthermore, the computational domain and numerical models were simplified based on assumptions, resulting in an inaccurate prediction of heat loss from the outlet and walls.

Table 2. Validation of numerical model with experimental results

Radial location (mm)	T_{model} (°C)	$T_{experimental}$ (°C)
-32.5	607	584
-17.5	900	849
0	1012	988
17.5	900	850
32.5	608	590

Publications

1. Patent

[1] Muthukumar P., **Maurya, P.,** Self-aspirated pressurized methanol cook stove with porous radiant burner. **Indian Patent No. 202131051305,** Indian Institute of Technology, Guwahati, India. **Patent Granted**.

2. BIS Standard

[1] "Domestic Methanol Cookstove - Canister Type – Specification- IS 17907: 2022"- **Published.**

[2] "Domestic Ethanol Cookstove - Canister Type" **–Final draft is Published.**

3. Journals

[1] **Maurya, P.,** Muthukumar, P., Mahalingam, A. K., Kaushik, L. K., & Ramalingam, A. 2022. Performance, economic and pilot studies on canister based methanol stove for household cooking application. ***Energy for Sustainable Development*, *66*, 117-124.**

[2] **Maurya, P.,** Muthukumar, P., and Anandalakshmi, R., 2022. Methanol cookstove a potential alternative to LPG cookstove: Usability, safety and sustainability studies. ***Sustainable Energy Technologies and Assessments*, *53*, p.102508.**

[3] Muthukumar, P., Kaushik, L. K., Mahalingam, A. K., Deb, S., **Maurya, P.,** Shaik, S. R., & Mujeebu, M. A. (2023). Evolutions in Gaseous and Liquid Fuel Cook-Stove Technologies. ***Energies*, *16*(2), 763.**

[5] **Maurya, P.,** Muthukumar, P., Anandalakshmi, R., 2023. Assessment of Indoor Air Quality of Porous Media Combustion Based Cookstoves. ***Environmental Science and Pollution Research- (accepted for publication)***

Book Chapter

[1] **Maurya, P.,** Arun Kumar, M., Kaushik, L.K., Muthukumar, P. and Anandalakshmi, R., 2022. Comparison of Thermal and Emission Performance of Canister Based Methanol Cookstove with Kerosene Wick Cookstove**.** ***Innovations in Energy, Power and Thermal Engineering*** **(pp. 159-167). Springer, Singapore.**

Conferences

[1] **Maurya, P.,** Arun Kumar, M., Kaushik, L.K., Muthukumar, P. and Anandalakshmi, R., 2022. Comparative Performance Assessments of Canister based Methanol Cookstove with Kerosene Wick Cookstove for Domestic Cooking Application**.** ***International Conference on Innovations in Thermo-Fluid Engineering and Sciences [ICITFES - 2020]*** NIT Rourkela, India, 10-12 February 2019.

[2] **Maurya, P.,** Muthukumar, P., and Anandalakshmi, R., 2022. Adoption of methanol cookstove- usability, safety and sustainability studies. ***International Conference on Water, Energy & Environment (WEECON-2021),*** ISET Research in association with IEI Vietnam.

[3] **Maurya, P.,** Muthukumar, P., and Anandalakshmi, R., 2022. A comparative analysis of porous radiant burner cookstove on indoor air quality with available household cookstove., ***International Conference on Renewable Energy (ICRE-2022)*** organized by Centre for Non-Conventional Energy Resources (CNCER), University of Rajasthan, Jaipur, India in association with International Association for Hydrogen Energy (IAHE), USA & MRSI, Rajasthan Chapter held on February 25-27, 2022**.**

[4] **Maurya, P.,** Muthukumar, P., and Anandalakshmi, R., Combustion characteristics of methanol vapour-air in porous media burner for cooking application, ***Energy Summit, 2022,*** IIT Madras, 7-9 December, 2022**.**