Experimental Analysis of a Porous Radiant Pressurized Cook Stove by Using a Blend of Waste Cooking Oil (WCO) and Kerosene

Lav Kumar Kaushik and Prof. P. Muthukumar*
Department of Mechanical Engineering
Indian Institute of Technology Guwahati
Guwahati, India
pmkumar@iitg.ac.in

Abstract— A large number of populations in developing countries still continue to use various forms of solid fuels as the primary energy source for cooking. Maintaining uninterrupted availability of fuel at an affordable price demands them to achieve Sustainable Development Goals (SDGs). In this paper, a comparative thermal performance assessment of Porous Kerosene Pressure Cookstove (PKPs) and Conventional Kerosene Pressure Cookstove (CKPs) are presented. The experiments are conducted by using two different, Waste Cooking Oil (WCO) and kerosene blends (BS1, 10/90: WCO/Kerosene by % volume) and BS2 (50/50)). Also, the impact of firing power (1.5-3 kW) on burner characteristics are established and compared for both the stoves. With fuel sample BS1, the measured thermal efficiency is found in the range of 51.2-44.8% and 43-33.3% for PKPs and CKPs, respectively. Whereas, the same is in the range of 45.3-37.8% and 36.2-28.6%, respectively, in case of BS2. Due to improved combustion in case of porous media burner (i.e. PKPs), a large reduction is found for CO and NOx emissions. The overall performance of PKPs shows WCO as a potential alternative source for cooking.

Keywords— Conventional Kerosene Pressure Cookstove (CKPs), Porous Kerosene Pressure Cookstove (PKPs), Porous Media Combustion (PMC), Waste Cooking Oil (WCO).

I. INTRODUCTION

Developing countries, due to large population and energy deficiency [1], derive bulk of its cooking energy need from solid fuels. The poor economic condition of the people compels governments to provide a huge subsidy, e.g. in 2017-18, Indian government has allocated Rs. 16,051 crores for LPG and Rs. 8,664 crores for Kerosene subsidy [2]. Also, the inefficiency of cookstove negatively impacts human health and economy of every household [3]. In view of this problem, the search for a new and eco-friendly fuel has become extensively important. Waste Cooking Oil (WCO) generated from hotels and mass cooking appliances can provide one such alternate option. Research on plant oil as a cooking fuel [4-12] and cook stovе with porous media insert [13-17] provides encouraging results for developing energy efficient and easily adaptable cookstoves.

Early notable work on plant oil stove was carried out at Hohenheim University. Stumpf and Mühlbauer [4] and Kratzeisen et al. [5] made attempts to optimize the stove parameters viz., input power range, and thermal efficiency. In order to take care of the high viscosity of the plant oils, modification in the vaporizer tube has been the main focus of researchers [6-8]. Performance variation of Kerosene Pressure Cookstove (KPs) with vegetable oil, vegetable waste oil and a blend of these with kerosene were studied by many investigators [9-11] and maximum % of oil blends with kerosene were found for different plant oil (e.g. cottonseed oil, jatropha and WCO). The above works outline that the main reasons for lower performance are undesirable physical properties such as high auto-ignition temperature, density, and viscosity. Performance results show that by increasing incoming oil temperature, it is possible to reduce ignition time and incomplete combustion, thus to improve the combustion performance.

The Porous Media Combustion (PMC) operates on the novel concept of using a 3-D porous matrix in the combustion zone. In the literature, several articles provide a comprehensive overview of PMC [12,13]. Recently PMC has been used by several researchers to develop cookstove for domestic as well as commercial applications [14-18]. By inserting the porous matrix in the combustion zone of KPs, significant improvement in thermal efficiency and reduction in emissions have been achieved by some researchers [19-23]. Performances viz., thermal efficiency, kerosene consumption rate and emission of KPs with pottery clay, sodium silicate and saw dust porous inserts have been examined by Kakati et al. [19]. On the same stove, by using silicon carbide (SiC), zirconia (ZrO2), wire mesh roll filled with metal balls and alumina (Al2O3), Sharma et al. [20-23] showed a maximum
~10% improvement in thermal efficiency. Porous matrix enhances the heat transport from burned to an unburned portion and in turn improve combustion.

From above literature review, one can conclude that there is a clear void of work on using WCO as a cooking fuel in Porous Kerosene Pressure Stoves (PKPs). In this work, the authors focus on investigating the combustion characteristics of WCO and kerosene blend (% by volume) in CKPs and PKPs and compare their thermal performances.

II. EXPERIMENTAL SETUP AND PROCEDURE

The setup used for testing the performances of both CKPs and PKPs is shown in “Fig. 1”. Both KPs, consist of a hand pump and pressure gauge integrated fuel tank, one rising tube, two ascending and two descending fuel tubes. The main difference between them is in the vaporizer, the flat circular chamber in case of CKPs and two layered (SiC as combustion zone and mild steel perforated sheet as preheat zone) porous inserts in mild steel burner casing, in case of PKPs. The lighting up of a kerosene burner starts with pouring a small amount of kerosene into the spirit cup and then ignition with a burning wick. The working fuel is pressurized in the fuel tank by hand operated plunger to a desired pressure and passes to the burner through the main fuel supply pipe. The fuel flow rate is controlled by fuel control valve. After attainment of steady state, the burning wick is extinguished, and various measurements were taken.

A. Temperature mapping

The temperature distribution in burner plays a vital role in assessing the thermal performance. It gives the reason for the variation of thermal efficiency and emissions at different firing powers. In the PKPs, temperature was measured in both radial and axial directions. Radial temperature distribution gives understanding of the uniformity of the heat flux, whereas axial distribution gives stable flame position.

The radial and axial locations of the thermocouple’s positions are shown in “Fig. 2”. Temperature measurements for CKPs are also carried out, at which the first position shows the temperature of vaporizer plate, whereas others are within the flame with increasing distance from burner top.

B. Thermal efficiency and emission

Methods described in BIS (IS 10109:2002) are used to measure efficiency and emissions [24]. According to the Water Boiling Test (WBT), based on fuel consumption rate (g/hr), pan size and water mass have been selected for different firing power (Table 1). After KPs steady state, stove initial weight is measured and then recommended amount of water was kept above the stove. Heating the water up to 90°C gives time and fuel consumption. Thermal efficiency is calculated by using Eq. 1, and 2.
\[ \text{Thermal efficiency} = \frac{\text{Heat utilized}}{\text{Heat produced}} \] (1)

\[ \eta_{th} = \frac{(M \times C_p + m \times C_w) \times (t_2 - t_1)}{W \times LCV_{fuel}} \] (2)

Where, \( M \) is mass of the vessel with lid and stirrer (kg), \( m \) represents mass of water in the pan (kg), \( C \) is the specific heat (\( p: \) pan and \( w: \) water), \( t_2 \) and \( t_1 \) are the final and initial temperature of water. \( W \) and \( LCV_{fuel} \) are mass of fuel consumed (kg) and lower calorific value of fuel sample, respectively.

### TABLE I. ALUMINIUM VESSELS FOR THERMAL EFFICIENCY TEST [24].

<table>
<thead>
<tr>
<th>Consumption Rate g/hr</th>
<th>Pan Diameter (External), mm, ±5%</th>
<th>Pan Height (External), mm, ±5%</th>
<th>Total pan Mass with lid, g, ±10%</th>
<th>Mass of Water in Pan, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>151-180</td>
<td>245</td>
<td>130</td>
<td>632</td>
<td>4.8</td>
</tr>
<tr>
<td>201-240</td>
<td>285</td>
<td>155</td>
<td>853</td>
<td>7.7</td>
</tr>
<tr>
<td>241-270</td>
<td>295</td>
<td>165</td>
<td>920</td>
<td>9.4</td>
</tr>
</tbody>
</table>

The nature of the combustion can be estimated by exhaust emissions and it is done by flue gas sampling. The flue gases are isolated from the atmospheric air by using a hood and then emissions are recorded by the portable flue gas analyzer (Testo 340). In present work CO and NOX concentration refers to dry-basis measurements, with correction to a 3% fixed oxygen level.

C. Error Analysis

Uncertainty in measured quantities was estimated by using procedure described by Klein and McClintock [25]. If an estimated quantity \( R \) depends on the independent variables like \( X_1, X_2, X_3, \ldots, X_n \) then,

\[ R = R(X_1, X_2, X_3, \ldots, X_n) \] (3)

And the maximum value of uncertainty is given by:

\[ W_R = \sqrt{\left(\frac{\delta X_1}{X_1}\right)^2 + \left(\frac{\delta X_2}{X_2}\right)^2 + \ldots + \left(\frac{\delta X_n}{X_n}\right)^2} \] (4)

Formula for efficiency is given in Eq. 2 and the uncertainty is mainly due to the measured quantities of mass and temperature. After assuming, temperature rise of water and vessel are equal and, no error in values of specific heat of pan and water and calorific value, expression for error in thermal efficiency is given by:

\[ \delta \eta_{th} = \sqrt{\left(\frac{\delta \eta_{th}}{\delta M} \Delta M\right)^2 + \left(\frac{\delta \eta_{th}}{\delta m} \Delta m\right)^2 + \left(\frac{\delta \eta_{th}}{\delta W} \Delta W\right)^2} \] (5)

Where, \( \Delta M = \pm 0.1 \text{ g}, \Delta m = \pm 0.1 \text{ g}, \Delta(T) = \pm 0.5^\circ \text{C}, \) and \( \Delta W = \pm 0.1 \text{ g}. \) At the condition of maximum uncertainty in efficiency, \( M = 0.92 \text{ kg}, m = 9.4 \text{ kg}, \Delta T = 62^\circ \text{C} \) and \( W = 0.208 \text{ kg}, \) calculated value of uncertainty in efficiency is ± 0.23%.

III. RESULT AND DISCUSSION

The main objective of the presented work is to evaluate the maximum % of the WCO in the blend, which can be burned in CKPs and PKPs. Experiments were conducted with different % of the WCO, and it is found that the maximum 50% WCO blend in kerosene can be burnt in PKPs. For more than 50% WCO, both the stoves showed incomplete vaporization leading to unstable flame and finally shutdown of the burner. In order to compare the impact of WCO % on thermal performance viz., axial and radial temperature distribution, thermal efficiency and emissions (CO and NOx), results for 10% (BS1) and 50% (BS2) WCO blend with kerosene are presented for domestic cooking (1.5-3 kW) application and discussed in the following paragraphs.

A. Axial and Radial temperature distribution

The temperature mapping of the stove shows the physical symptoms and also, gives insights into the nature of combustion [19]. For proper understanding, the temperature was measured in axial and radial direction for PKPs and measurement was also taken in the axial direction for CKPs. With fuel samples, BS1 and BS2, the variation of temperature in the burner axial direction with increasing firing power for CKPs and both axial and radial direction for PKPs, are shown in “Fig. 3(a)-(b)” and Fig. “4(a)-(d)”, respectively. In the CKPs, the maximum flame temperature in the reaction zone was observed near to the evaporative head. In firing range, the temperature of the evaporative head ranges between 241-264°C for sample BS1, and similarly, 304-326°C for sample BS2. The high temperature in case of BS2 is because of the increase of viscosity, which in turn reduces flame height and more heat is transferred to the evaporator.

Increasing trend of the temperature with the firing power for both the samples is because of increase in fuel flow rate, which in turn increases the heat generation. For BS1, at close to burner surface, the temperature of the flame varies in the range of 754-784°C and, then a sharp increment in the range of 1108-1184°C is observed at a distance of 2.5 cm from the burner head.

The temperature rise is very sharp between, evaporative head and reaction zone, which is typical of Free Flame Combustion (FFC). A similar trend of temperature variation has been observed with sample BS2, for which temperatures are 665-698°C and 1019-1093°C, respectively.
Figure 3a: Axial temperatures of CKPs for BS\textsubscript{1} with firing power of 1.5-3 kW.

Lower temperatures for BS\textsubscript{2} sample are due to the combined effect of lower heating value and improper combustion, due to high % of WCO in the blend.

Figure 3b: Axial temperatures of CKPs for BS\textsubscript{2} with firing power of 1.5-3 kW.

Radiation and conduction in the PRB, in one hand, preheats the incoming air-fuel mixture, and on the other, helps in faster transfer of heat from the reaction zone in the downward direction, and as a result, the temperature rise is lower. With the increase in input power, reaction zone moves from the interface to the downstream of the burner, due to which higher temperature is attained on the surface of the porous matrix.

“Fig. 4(a)-(d)”, illustrates the heat circulation within the PKPs. Temperature in the axial direction (i.e. burner axis) shows the position of the stable combustion zone, which in turn explain the variation in thermal performance of the stove [21,22]. For fuel sample BS\textsubscript{1}, the temperature in axial position 1 is found in the range of 1039-1127°C, whereas for BS\textsubscript{2} same is 940-1036°C. The reason behind increment of temperature with increase in firing power is because of increased amount of the fuel, whereas decreasing calorific value with higher WCO % results in decrement of the same. But, the temperature rise is less sharp than that in the CKPs, because of the combustion inside the porous matrix.

Figure 4a: Axial temperatures of PKPs for BS\textsubscript{1} with firing power of 1.5-3 kW.

From radial temperature mapping (“Fig. 4(c)-(d)”), it is observed that a well-distributed temperature was achieved in the porous domain. At the lower firing power, the difference is little higher due to lower fuel rates which did not allow a uniform distribution of heat. This indicates non-uniform combustion, and hence the heat flux.

Figure 4b: Axial temperatures of PKPs for BS\textsubscript{2} with firing power of 1.5-3 kW.
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Figure 4c: Radial temperatures of PKPs for BS1 with firing power of 1.5-3 kW.

Figure 4d: Radial temperatures of PKPs for BS2 with firing power of 1.5-3 kW.

B. Thermal efficiency

In the input power (firing) range of 1.5-3 kW, a comparison of the thermal efficiency of test blends (BS1 and BS2) for CKPs and PKPs is presented in “Fig. 5”. For BS1, in case of the CKPs, it varies from 43-33.3%, whereas, for PKPs it ranges from 51.2-44.8%. Similarly, for BS2 these values are 36.2-28.6% and 45.3-37.8%, respectively. Due to the combined effects of radiative and convective heat transfer of the highly emissive porous material, for all the cases PKPs shows better efficiency than CKPs.

Within the firing range, lowest operating power yields a maximum efficiency and the decrement in thermal efficiency is higher in case of CKPs. The reason behind such behavior of CKPs is associated with the fact that, with increase in firing rate, the height of the flame increases which results in more convective heat loss [22,23]. With increase in % of the WCO, efficiency decreases for both the stoves. Such performance is because of increase in viscosity and decrease in energy content of the fuel. High viscosity results in poor fuel atomization and incomplete combustion [7-9], which in turn adversely affects burner performance. Efficiency reduction is lower in case of PKPs because of more preheating of fuel than CKPs and from literature [4,6], it has been concluded that heating the WCO would reduce the viscosity and improve the spray characteristics.

Figure 5: Comparative test results of thermal efficiency.

C. Emissions

“Fig. 6(a)-(b)”, shows the comparison of the amount of CO and NOx emissions between the tested samples. With BS1, measured values of CO and NOx are in the range of 268-484 ppm and 5.3-13.4 ppm, respectively, for PKPs (“Fig. 6(a)”). Whereas for CKPs, these values are 682-997 ppm and 36-59 ppm, respectively. Emissions from BS2 due to increase in % of WCO for PKPs (CO: 361-664 ppm and NOx: 13.8-47 ppm) and CKPs (CO: 905-1300 ppm and NOx: 84-180 ppm) are presented in the “Fig. 6(b)”.

Figure 6a: CO and NOx emission for BS1 with firing power of 1.5-3 kW.

It is observed that with increase in firing power, both the CO and NOx emissions increase for all the cases [24]. Also, in
case of BS$_2$, due to higher % of WCO, fuel mobility decreases, which in turn reduces mixing rate of air and fuel and causes higher emissions. Measured CO emissions of PKPs are lower than that of CKPs, because of better combustion and more residence time. Similarly, the NO$_x$ emission of PKPs is also found much lower than that of the CKPs. In the PKPs, lower global temperature (surface temperature of the burner) causes lower NO$_x$ emission. Whereas, high NO$_x$ from CKPs is because of the fuel-rich combustion, which in turn results in high temperature in the reaction zone.

![Figure 6b: CO and NOx emission for BS$_2$ with firing power of 1.5-3 kW.]

**IV. CONCLUSIONS**

As conventional cooking fuel sources are limited and not eco-friendly, in the present work, an attempt has been made to check the viability of WVO as cooking fuel. Comparative investigation on the performance of CKPs and PKPs focuses on the impact of the PKPs on energy saving and pollutant mitigation. Due to combustion in porous media, PKPs show improved performance with energy saving and less emission. For studied blend ratios, an average of 9 % surplus of thermal efficiency is seen with PKPs. With BS$_2$ sample, lower emissions from PKPs (CO: 361-664 ppm, NO$_x$: 13.8-47) as compared to CKPs (CO: 905-1300 ppm and NO$_x$: 84-180 ppm) shows its potential of emission reduction. PKPs can be operated with a maximum 50% WCO, thus directly reducing half of the kerosene usage and reducing the cooking cost to a great extent [26]. Investigation on vaporizing assembly is being further carried out in order to obtain an optimum burner geometry.

**REFERENCES**
