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Research paper

Performance Enhancement of the Natural Draft Porous Surface Domestic Cooking Burner using Secondary Aeration

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Abstract

This paper presents the effect of secondary aeration on the performance of a novel natural draft porous surface burner for domestic cookstove applications. The burner is designed and developed in contrast to the principle adapted so far in bi-layer porous burners. Liquefied Petroleum Gas (LPG) is the only test fuel used in the experiment. The experimental results revealed that the thermal efficiency of the burner is 71.78% which is about 7% more efficient as compared to the best conventional free flame burner operating within the range of 0.55 to 2kW. CO and NOx emissions are significantly lower than the conventional free flame LPG burners. Provision for mixing of secondary air with preheated primary air-fuel mixture in the combustion chamber is made through the tubes attached to the body of the burner through natural drafting. Further reduction in CO values to 32ppm with an improvement in maximum thermal efficiency to 73.22% is also observed with secondary aeration by natural draft

Keywords: *emission; LPG; natural draft, Porous surface burner; secondary aeration; thermal efficiency;*

1. Introduction

The free flame LPG burner used for cooking purposes, gives a very low thermal efficiency. The maximum value of this thermal efficiency for a best conventional burner is around 65% which is due to small heat transfer coefficient, as convection is the only mode of heat transfer and it decreases with the further increase in power intensity. It produces high emissions due to incomplete combustion because of thin reaction zone and a sudden rise in peak flame temperature due to diffused reaction as the major part of the combustion takes place in the open atmosphere[1-4]. On the other hand porous burners have high thermal efficiency due to internal heat recirculation in the porous matrix and large heat transfer coefficient due to the presence of all the three modes of heat transfer. These porous burners are capable to reduce emissions due to uniform heating of the mixture within the porous matrix, improved combustion and high peak flame temperature [5-11].

Depending on the position of flame stability and combustion a Porous media burner (PMB) is classified into two groups. One is matrix stabilized and the other one is surface stabilized. In matrix stabilized porous burners, both the flame stability and combustion takes place completely within the porous matrix, while in surface stabilized porous burners both combustion and flame stability occurs downstream the porous surface. Higher radiation effect is felt and utilized in matrix stabilized PMBs[5-13]. Power intensities of these burners are above 400w/m2. Hence they have got diversified field of applications[14-16]. On the other hand, power intensities of the surface flame burners are limited to 400w/m2 and are suitable for domestic use [1,13].

Most commonly LPG is used as the conventional fuel for clean and efficient cooking applications in India[17]. Depletion of fossil fuel and stringent atmospheric conditions resulted from growing population, deforestation, rapid urbanization and higher rate of mortality demands for the development of an energy efficient conversion device for the sustainability of the mankind. Hence, lot of effort has been made by researchers for the last 2 decades, to design and develop fuel efficient and low emission burners. The intensive research work is resulted in the transformation of free flame burners to porous media surface flame burners.

From the extensive literature review, it is observed that porous media combustion technology is vividly used in industrial and commercial heating and manufacturing applications including household heating with different fuels due to the development in the morphological characteristics of different ceramics, metals and their foams and open cell structures. But the research in the field of cooking applications is very less[18].

Pantangi et.al.[1] investigated the thermal performance and emission characteristics of natural draft (self-aspirated) LPG cook stoves and then they converted it into porous media combustion using metal chips, pebbles and metal balls in the mixing chamber. The maximum thermal efficiency of this burner was about 73% for the best combination of porous media and the emissions of CO and NOX were in the ranging from 25–350 mg/m3 and 12–25 mg/m3, respectively. Then they diverted their research from natural draft to forced draft LPG (fuel rich to fuel lean) domestic burner using PMC technology. They developed different sizes of the bi-layered porous burners using 5mm alumina balls in the preheating zone (PZ) and SiC foam with a porosity of 90% in the combustion zone (CZ). They got an efficiency around 68%. Muthukumar et al. [19] extended Pantangi et al.'s work and used ceramic block of thickness10mm and 40% porosity instead of alumina balls in the PZ. They have tested the PRBs with different equivalence ratios and power intensities. They got a maximum thermal efficiency of about 71%. with very less amount of CO and

NOx emissions. These values were ranging from 9 to 16ppm and 0 to 0.2ppm respectively at an equivalence ratio of 0.68 and power intensity of 1.24kW. Further the same author and his co-workers [20] developed a novel porous radiant burner of 90mm diameter using LPG for cooking applications and reported a maximum thermal efficiency as high as 75% corresponding to an equivalence ratio of 0.54 with a firing rate of 1.3kW.They observed that the thermal efficiency of the burner decreased with the decrease in CZ porosity and an increase in equivalence ratio. Mishra et al. [4] further studied the performance of the PRBs with a firing rate of 5-10 kW with a diameter of 120 mm and observed that the thermal efficiencies of the PRBs were gradually decreasing with an increase in firing rate/power intensity.

Mujeebu et al. [5] developed two different bi-layered premixed forced draft LPG porous burners for household applications. One was matrix stabilized and the other one was surface stabilized. They have concluded that surface stabilized burners are suitable for cooking applications.

Some of the researchers studied the effect of different parameters such as loading height(height of the vessel above the burner port), energy input [21–23], flame impingement angle [24], combustion temperature on the primary aeration and flame structure [25], and the configuration of the flame ports [26-28] to improve the performance of natural draft conventional LPG burners and some others have done preliminary investigations using porous media.

Jugjai and Rungsimuntuchart [29] developed a novel semi-confined porous radiant recirculating burner (PRRB) and achieved an efficiency 12% more than a conventional burner within a power range of 5 to 30kW with compatible emission. The primary burner was a self-aspirated conventional free flame burner and porous media was used as medium of heat recirculation from exhaust gas to combustion air. Further improvement in thermal efficiency by 3% was obtained using central flame technique with heat recirculation by porous media.

W. Yoksenakul and Jugjai [30] designed and developed a self-aspirated porous medium burner within a power intensity of 23-61kW and obtained 4.58% more efficiency than the self-aspirated conventional free flame burner with an equal firing rate. They observed that thermal efficiencies of both the burners were decreasing with an increase in firing rate and also the distance between the burner port and the bottom of the loading vessel. They also found, that the NOx emission was as low as 98ppm, with the CO emission was around (200ppm) in the self-aspirated porous medium burner than the conventional burner due to the lack of secondary air entrainment and incomplete combustion. During the experiment secondary air was supplied to the burner by the process of natural draft due to the presence of negative pressure within the burner. It took around 1hour to reach at the steady state and hence was not suitable for domestic use.

From the literature, it is revealed that no more work on self aspirated LPG domestic burner has been done except the preliminary work done by Pantangi et.al.[1] using PMC technology. Recently, author of this paper, P.Pradhan et.al. [31] developed a self-aspirated porous burner for domestic cookstove application. They have tested the novel burners with two different geometries and compared the thermal performance of the burners with that of a conventional free flame burner within the domestic range of power intensities. They got an efficiency which is 7% more than the conventional free flame burner with compatible emissions.

This paper presents the effect of secondary aeration on the performance a novel self-aspirated porous surface burner developed by the author used for domestic cooking applications. Unlike W. Yoksenakul and Jugjai [10], provision for secondary air entrainment to the burner is made through natural drafting. But in this case secondary air is drawn into the interfacial gap between PZ and CZ.

2. Experimental setup and Procedure

2.1 Experimental Setup

A schematic of the experimental set-up used for testing the performance of the PSB is shown in Fig.1. The experimental setup consists of a digital weighing scale. A 14.2kg LPG cylinder supplied by HPCL is connected to the burner with a flexible hose of internal diameter 12.7mm.

The volume flow rate is measured by A acrylic body LPG rotameter (Make: FLOWPOINT, India) and a bourdon tube pressure gauge are fixed before the fuel ejector to measure volume flow rate of the fuel and pressure of the gas in the hose.

The transient temperatures at different locations of the PSB are measured by K-type thermocouples. The temperature data acquired by A data acquisition system (Make: CHINO, India, Model: KR2000) with K-type thermocouples is used for continuous displaying, recording and analyzing transient temperature data at different locations w.r.t the burner. A hot wire anemometer is used to fix different fuel flow velocities at the nozzle tip. The emission parameters from the flue are measured by using a flue gas analyzer (Make: AVL DITEST, India, Model: SCOPE 8400) that processed and analyzes data in SCOPE application software environments.

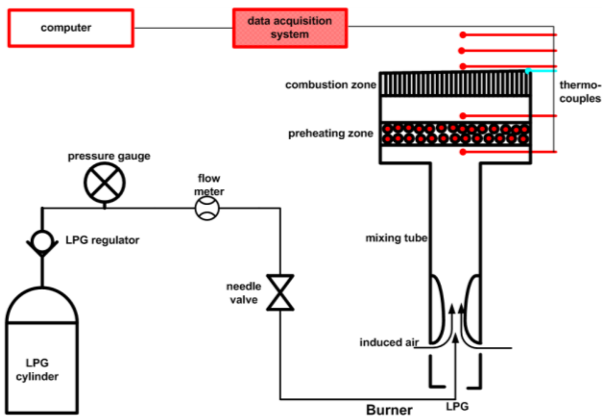

Fig.1: Schematic of the experimental setup

2.2 Experimental Procedure

BIS: 4246:2002 guidelines are strictly followed for conducting these experiments on domestic burners. five different fuel flow velocities i.e. 3.6m/s, 3.0m/s, 2m/s, 1m/s and 0.4m/s are selected as the input parameters within the operating of 0.55 - 2.0kW(domestic range of operation). A distance of 50mm is maintained between the burner top and bottom surface. At the beginning of the experiment, LPG cylinder is kept on the digital weighing scale to record the initial mass of the cylinder with the gas(W_1). Then opening the fuel regulating valve from the cylinder and second control valve LPG is allowed to flow through the ejector. Velocity of flow is adjusted with the help of second control valve by placing the hot wire anemometer close to the ejector tip. Corresponding to each fuel flow velocity (V), all the readings such as the gas pressure in the cylinder, initial weight of the cylinder with the gas (W_1) and volume flow rate from the rotameter are recorded. The weight of the test vessel (aluminium) is measured and then the test vessel with 5liters of water is kept on the burner for heating water.

Continuous stirring of water in the Vessel is done to maintain uniformity in temperature till it reached 90^0C. Finally, weight of the gas with cylinder (W_2) is noted once fuel supply to the burner is cut-off. A digital stopwatch is used to measure the time for each set of operation. For each input velocity, five set of observations are taken with emission data which helps in calculating thermal efficiency uncertainty analysis.

2.3 Instrumental and Experimental Uncertainty

2.3.1 Instrumental Uncertainty

LPG rotameter used in the experiment measures volume flow rate with an accuracy of ± 2% of full scale division (FSD) within the range of 0-12lpm with a resolution of 0.5lpm. The data acquisition system(DAS) is used to store, display and process transient temperature data with reference junction compensation accuracy of ± 0.5^0C and high speed of sampling accuracy of ± 0.1%. A hot wire anemometer measures the velocity of the flow of fuel within the range of 0.1 to 25.0m/s and resolution of 0.01m/s. It gives an accuracy of ± (5% + 1d) reading. It measures temperature within range of 0 - 50^0C with a resolution of 0.1^0C and an accuracy of $\pm 1^0$C. The mass flow rate of the fuel is measured with the help of a digital weighing scale with a resolution of 0.001kg and an accuracy of ±0.002kg. A flue gas analyzer (AVL DITEST) is used to measure emissions from the flue. For the measurement of the dimensions of the pores, a profile projector [Model: Metzer M, 806A, horizontal floor type] with magnifications ranges as 10X, 20X and 50X lens and an accuracy of ± 0.1% is used. Its surface illumination accuracy is ± 0.15%.

2.3.2 Experimental Uncertainty

Experiments are repeated for at least five times to standardize the results and to estimate uncertainty in experimental results. The same is calculated using Eq.1 proposed by Kline and McClintock [32].

$$W_r = \left[\sum \left(\frac{\partial R}{\partial X_i} \right)^2 \right]^{0.5} \quad (1)$$

Where *'R'* is a given function of the independent variables X_1, X_2……..X_n,
'W_r' the uncertainty in the result and *'W_i'* is the uncertainty in the independent variables [44].

3. Self-Aspirated/Natural Draft Porous Surface Burner (SAPSB)

The schematic of the self-aspirated/natural draft porous surface burner is depicted in Fig.2. The body of the burner as shown in the Fig.3b is made of mild steel. Wall thickness is kept at 3mm to provide stability to the burner. It is rapped with asbestos ropes to minimize heat losses from the burner to the atmosphere.

In designing such a new concept burner, parametric analysis of the conventional free flame burners and self-aspirated porous medium burners as well as the characteristics of porous medium burners from the literature were considered as the reference. The components of the burner are as shown in fig.3. Stainless steel balls (Fig.3a) of 5mm diameter is used in the PZ, a perforated fire brick ceramic block in the CZ (Fig.3c), wire mesh and supporting metal ring (Fig.3e), air-fuel mixing tube (Fig.3d) and the fuel ejector assembly (fig.3e) etc. The inner diameter of the burner is taken equal to 80mm with a height of 65mm.For the mixing tube diameter is taken as 40mm with a height of 110mm.

A wire mesh fixed in a metal ring is placed in the PZ to provide adequate support to the steel balls. Comparatively a better heat conducting material is used in the PZ than the material in the CZ. The minimum velocity of the flow of the mixture i.e. the lowest operating range of the burner is primarily dependent on upstream material properties (material used in the preheating zone). For the lowest flammability limit, the material used in the preheating zone should have low porosity, small pore size, low thermal conductivity [33-39]. The Peclet No., for this zone Pe < 65 for hydrocarbon fuels like LPG. It further indicates that the preheating zone should have low volumetric heat transfer coefficient [40]. Another criteria for lower flammability limit and flame stability is that the thickness of preheating zone in a bilayered porous burner should be less than the combustion zone [33-40]. It is due to the reason that increase in material thickness reduces the velocity of flow [36]. Small pore diameter needed because radiation heat transfer from this zone should be as small as possible [37-41]. Hence an interfacial gap is maintained in between the PZ and CZ. Due to this discontinuity there is no conduction and radiation effect on PZ. The rise in temperature of the preheating zone occurs due convection only.

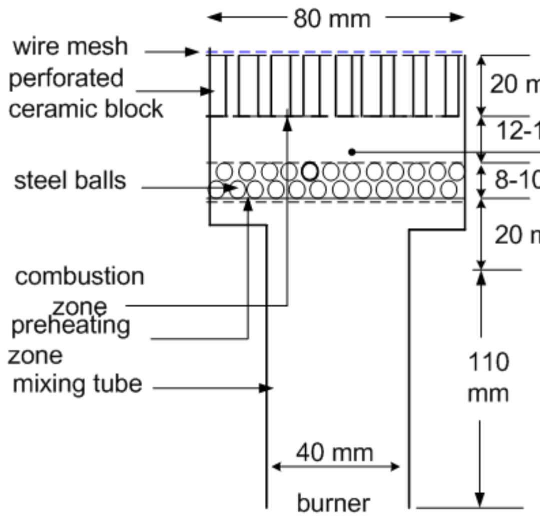

Fig.2: Schematic of the self-aspirated porous surface burner

Increase in temperature of the preheating zone decreases primary aeration in the mixture [25] and enhances rate of reaction. Flashback occurs when the rate of reaction is faster than velocity of flow of the mixture[36]. Hence two layers of 5mm steel balls is considered as optimal thickness of the PZ and optimal size of the steel ball to avoid flashback corresponding to minimum velocity of flow as 0.4m/s.

A fire brick ceramic block with a thickness of 20mm and 85% porosity is used in the CZ. Large pores with Pe > 65, high porosity, large heat transfer coefficient, high conductivity and low radiation extinction coefficient are the desirable characteristics of the materials generally used in the combustion zone for higher flammabil-

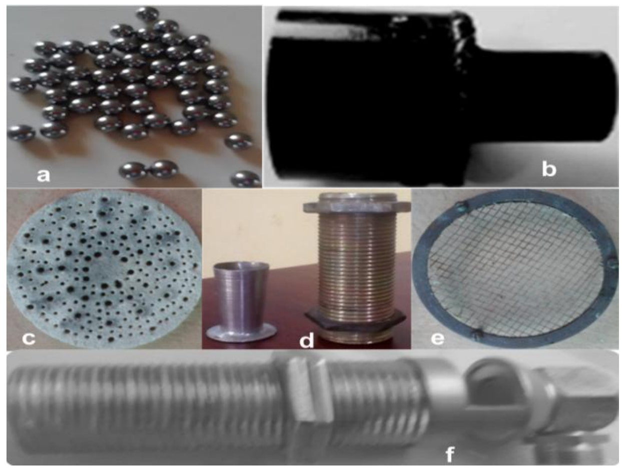

Fig.3: Components of the SAPSB (a) Stainless steel balls (b) burner body (c) perforated ceramic block (d) mixing tube with nuzzle (e) wire mesh with supporting frame (f) mixing tube with nuzzle and fuel ejector assembly.

ity limit. Mass flow rate increases with the increase in material thickness to produce excess enthalpy flame [36].
Thermal conductivity of the ceramic brick used in CZ varies from 0.2w/mK to 0.28w/mK within the temperature range of 300^0 to 750^0C. Increase in conduction and radiation modes of heat transfer increases with the increase in porosity of the material[7,33] and thereby overall heat transfer coefficient increases. Ceramic material used in CZ is made to a maximum porosity of 85%. Al though an increase in thermal efficiency is reported with the increase in porosity[2-8,33-35] but further increase in porosity may cause higher thermal stress and failure of the burner. Hence porosity is kept at 85%. Hence 85% porosity is taken as the maximum permissible porosity for the material used in the CZ. Thermal heat capacity of any material rises with the increase in porosity and thickness of the porous matrix [7,33 36]. Increase in thickness requires increased mass flow rate[36]. Increase in retaining time of the mixture within the reaction zone helps it for through heating and complete combustion[34-38]. Also for lower flammability limit and flame stability, thickness of preheating zone in a bilayered porous burner should be less than the combustion zone [33,35]. Considering the above data from the literature, three different thickness of the ceramic blocks are tested for their thermal performances and 20mm is considered as the optimal thickness corresponding to the maximum thermal efficiency of 71.78% at a fuel flow velocity of 2m/s. Thermo-physical properties and chemical composition of lightweight ceramic brick are as given below[43].

Thermo-physical properties of insulating firebricks[43]
Bulk Density : 604Kg/m3 Modulus of Rupture : 1.52MPa
Permanent Linear Change on reheating 24hrs. @ 1280°C : 1.95%
Cold Compressive Strength : 2.01 MPa
Thermal Conductivity 300°C : 0.2 W/m.°K
Thermal Conductivity 750°C : 0.28 W/m.°K
Thermal Conductivity 1000°C : 0.32 W/m.°K
Chemical composition of insulating fire bricks
Alumina : 37% Ferric Oxide : 1.6%
Silica : 61%

3.1 Design Modification to Supply Secondary Air to the Primary Air-Fuel Mixture by Natural Draft

While conducting experiment on the novel surface flame porous radiant burners, it was also observed that the length of the flame above the burner surface varies approximately from 35 to 65mm within the operating range from 0.4m/s to 3.6m/s and also stability of temperature below the preheating zone indicates that no flash back can occur within this operating range [2]. Generally, flash back occurs when velocity of the mixture is less than the velocity of propagation of the flame [2,33-35].
Instability in temperature of the surface(T_2) indicates the presence of incomplete and diffused combustion of fuel(combustion towards the downstream of the porous matrix). This fact represents that pressure in the combustion chamber is still lying below the atmospheric pressure. Hence it can be hypothecated that air can be naturally supplied to the combustion chamber. If so, CO emission can be reduced to the minimum due to the presence of excess air compared to primary aeration only. The second obvious reason is the slower reaction rate due to quenching of the flame as comparatively high temperature convection wave comes in contact with low temperature air. Hence, as shown in the fig.4, two numbers of 10mm long metal tubes, with 4mm internal diameter, are tightly inserted through the hole made in the burner body for secondary aeration. Use of metal tubes for natural aeration reduces the chance of high degree of quenching of mixture by ensuring air nearly at the same temperature of the preheated mixture which could otherwise resulted in flash back.

Fig.4: Photographic view of the burner showing the attachment of metal tubes for secondary aeration

4. Results and Discussion

4.1 Transient Temperature Analysis of the Burner

Arrangement of K-type thermocouples at different locations of the burner to measure transient temperature within a time period of 600 sec (10minutes) is as shown in fig.5.

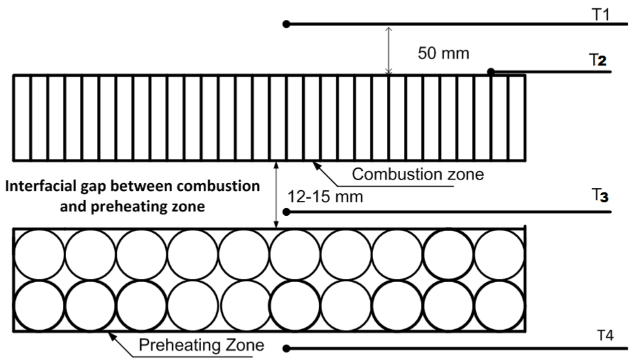

Fig.5: Arrangement of thermocouple to measure temperature at different locations of the burner

Although experiment is carried out for five different flow velocities, the transient temperature distribution corresponding to maximum efficiency at an optimal fuel flow velocity of 2m/s is represented in figs.6(a &b) to analyze the effect of temperature on thermal efficiency and emissions. From the experiment, it is revealed that the average surface temperature of the burner(T_2) is around 480.6^0C as shown in fig.6(a) measured over a time period of 600 sec before the supply of additional air to the burner and this value increases to 550^0C as shown in fig.6(b) when some amount air is being mixed with the preheated mixture in the interfacial gap by the process of natural drafting. Fuel reach mixture is always anticipated in self-aspirated burners as the primary mixing of fuel and air within the mixing chamber takes place due to momentum difference only[21-22]. Amount of primary aeration in fuel further decreases due to the rise in temperature of preheated zone as a result of expansion and torbulence of the mixture within the mixing chamber [21-22, 25-26].

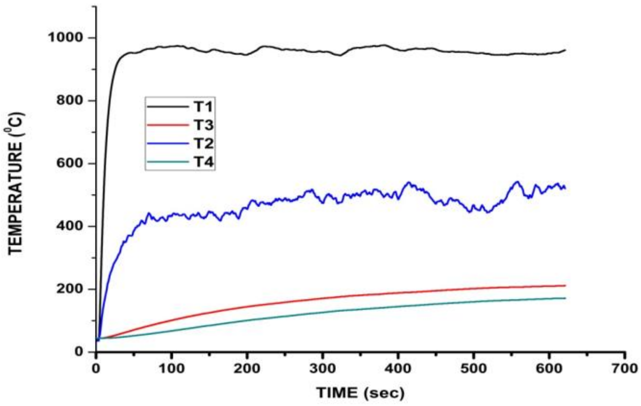

Fig.6(a): Transient temperature distribution at different locations of the burner without secondary aeration.

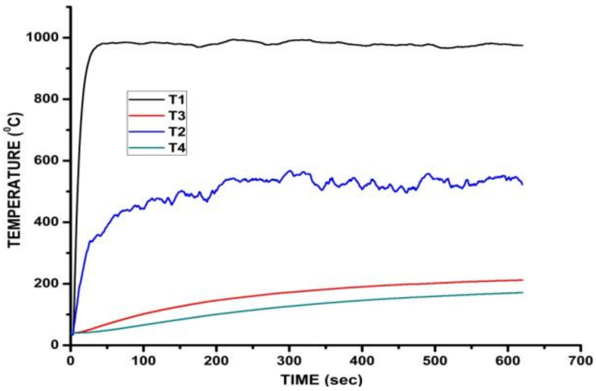

Fig6(b): Transient temperature distribution at different locations of the burner with secondary aeration

Comparing the two transient temperature graphs, a higher and more stable temperature of the flame is obtained at adistance of 50mm above the burner tip with secondary air entrainment. Also a comparision of temperature distribution in the interfacial gap between the two cases indicates that there is no quenching i.e. no reduction in temperature of the mixture due to secondary aeration to the burner by natural drafting and hence it is a possible means to improve thermal performance and emission from the burner.

4.2 Thermal Efficiency

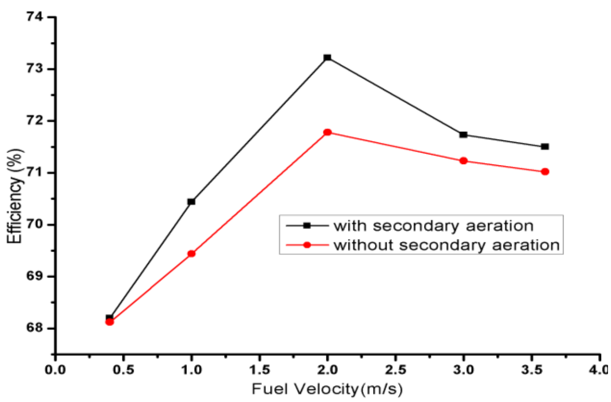

Fig.7: Comparison of thermal efficiency of the burner with and without secondary aeration.

The thermal efficiencies of the burner (SAPSB) are computed at different flow velocities and shown in Fig.7. As shown in the figure7 thermal efficiency of the burner is increasing continuously from 0.4m/s to 2m/s and then decreasing with the increase in fuel flow velocities or power input. The maximum efficiency of the burner is 71.78% which corresponds to the fuel flow velocity of 2m/s. These results are obtained in the absence of secondary aeration to the burner.

With secondary aeration, an improvement in thermal efficiency is observed corresponding to each fuel flow velocity and a maximum increase in thermal efficiency of 1.44% is obtained corresponding to a flow velocity of 2m/s. The estimated uncertainty in the calculation of overall thermal efficiency using Eqn.1 (described in section 2.3.2) for the burner at 2m/s is ± 2.34%.

4.3 Emission of CO and NOx

The emission of CO and NOx in the flue gas is measured with the help of digital flue gas analyzer. To measure emission from the flue the space around the burner is completely closed so that air from the atmosphere is not induced into the flue. The observed values of CO and NOx corresponding to different velocities with and without secondary aeration are depicted in the graph as shown in fig.8

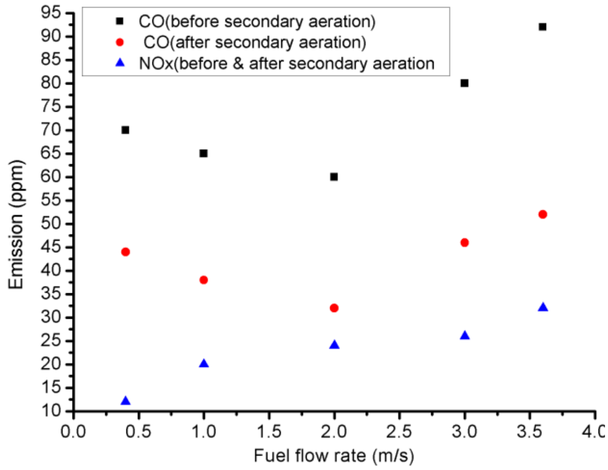

Fig.8: Emission of CO and NOx from the burner with and without secondary aeration

From the experiment, it is observed that CO emission from the porous surface burner lies between 70 to 92ppm within the fuel flow range from 0.4m/s to 3.6m/s and corresponding to the optimum velocity of 2m/s, it lies at 60 ppm. From the literature it is also revealed that in naturally aerated burners, CO emission decreases with stepped aeration [22,23]. As the burner is operated on natural air drafting mode, primary aeration of fuel reduces due to rise in temperature in the preheating zone [42]. From the transient temperature graph (Fig.6a& b), it is also observed that the temperature below the preheating zone rises from 135 to 153^{0}C within the operating range of velocities. Hence, a fuel rich mixture with faster rate of reaction is always anticipated in a self-aspirated burner [22]. No change in NOx emission is observed from the experiment but a significant reduction in CO emission is recorded. CO value corresponding to the optimum condition is observed to be 32ppm.

5. Conclusion

- The newly designed self-aspirated porous surface flame LPG burner has an efficiency of 71.78% at a power input of 1.75kW corresponding to a fuel flow velocity of 2m/s.
- It was about 7% more efficient compared to the conventional burners operating within the range of 0.55 to 2kW.
- A very low NOx of 12 to 42ppm and CO emission of 70 to 92ppm were measured without secondary aeration to the fuel. These emission values were much lower compared to that in case of conventional burners. Also these emission values were well within the WHO emission standards.

- Further modification in the design of the burner with secondary aeration to the primary air-fuel mixture before it entered into the combustion zone through natural draft, the efficiency of the burner is further increased by 1.44% with reduction in CO emission to 32ppm.
- There is no change in NOx emission before and after secondary aeration.

Hence, from the above experimental analysis it is observed that the proposed SAPSB would be a better replacement for CB and could be used for cooking applications.

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