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Optimizing Design and Process Parameters to Improve Thermal Efficiency and Emission Reduction of Domestic Gas Stove Burners

Hassan Zeb [1]

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Abstract

The purpose of this experimental study is to optimize the process and design parameter for burners commonly used in domestic gas stoves. We observed the effect of four parameters; design of burner (swirl or radial), loading height, primary aeration, and semi-confinement of combustion flame on the overall thermal efficiency and emissions from burner used in domestic gas stoves using natural gas as a fuel. Experimental results showed that swirling motion of the flame prolonged the residence time of the combustion products under loading vessel and hence increased the thermal efficiency with slight increase in CO emission. Additionally, swirl improved the mixing of fuel and air which facilitated the combustion reaction to completion. Flame confinement with a metallic shield was another factor which improved efficiency due to a delay in dispersion of flue gases into atmosphere. However, it might slightly increase CO emissions because of the limited supply of secondary air. Combined effect of both the swirling motion and flame confinement with a metallic shield decreased gas consumption up to 9%. Loading height was found to be an important factor for efficiency enhancement and emissions control but its value was very sensitive to change in burner diameter, amount of primary and secondary aeration, gas supply pressure and flow rate, velocity of fuel air mixture and loading vessel dimensions. Required amount of primary aeration decreased CO emissions through complete combustion and enhanced efficiency by producing strong blue flame. Without primary aeration, flame temperature was low as compared to the primary aeration flame indicated by the color of flame.

Keywords: Swirl Flow, Radial Flow Burner, Confinement of Flame, Primary Aeration, Loading Height, Thermal Efficiency Enhancement.

1. Introduction:

Energy security and demand of world is continuously growing due to rapid industrialization and urbanization. In current modern era, progress of any country majorly depends on its energy resources and energy security. Presently, about 54 % of total energy requirement is fulfilled by fossil fuel including coal (15 %) , gas (28 %) , and oil (11 %). Furthermore, nuclear and renewable energy contribute approximately 8 % and 38 % towards the total energy requirement [1]. Recent statistical analyses indicate that global energy demand is projected to increase substantially during the 21st century, with estimates ranging from 20 % to 50 % by 2050 under various policy scenarios [2]. Due to such high demand of energy, processes of utilization of energy either they are from hydral, solar or thermal sources should be efficient [1]. In recent research, great attention was paid to the efficient combustion processes at industrial and domestic levels to enhance the thermal efficiency and reduce the combustion emmisions [3, 4]. It was observed that combustion causes severe environmental impacts such as production of smog, acid rain, etc., which cause global warming and imbalance of global ecosystem [5]. Limited research work has been

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[1] Institute of Energy and Environmental Engineering, University of the Punjab, Lahore Pakistan
Corresponding author: Hassan Zeb (hassanzeb.ieee@pu.edu.pk)

done to improve the burner efficiency and decrease emission levels for both domestic and industrial processes [3, 6, 7]. For this purpose, advance combustion techniques such as heat recirculation, cyclone combustion chamber technique, swirl flow, and mild combustion processes need to be improved to enhance the thermal efficiency and to reduce the emissions from combustion processes [8-10].

Modern world is concerned regarding issues of environment, efficiency, and economics while utilizing the fossil fuel energy through combustion. Research studies must emphasize on the design and development of equipment which are not only efficient but also environmental friendly. Globally, indoor air pollution has been of a great concern in the past few decades due to its severe impact on human health and environment. In view of the energy conservation, conventional domestic burners are less attractive because of their low thermal efficiency. Thus, improvement in the thermal efficiency of the domestic burners and emission control is of great interest worldwide [4, 11-13].

Intensification of domestic gas burners covers two aspects of efficiency. One is the combustion efficiency and other is the thermal efficiency [14]. Combustion efficiency is the measure of ability of an instrument to covert the energy content of a specific fuel to resuable energy, given in percent. Complete combustion efficiency would extract all the energy available in the fuel. However, 100% combustion efficiency is realistically not achievable due to the heat loses and the limit of combustion.

Thermal efficiency is the measure of how effectively a system converts heat energy into useful work, or more specifically, the ratio of the output or work done by the working substance to the input or heat energy of the fuel supplied [15]. It can also be defined as the percentage of the thermal input transferred to the loading system [11]. Alternatively, it is the percentage of the energy transferred to the source once the flame is out of burner tip. So the overall efficiency of a burner is defined as the ratio of the useful heat absorbed by the working medium to the total heat input from the fuel, based on its calorific value [16].

This study focussed on enhancing thermal efficency for dosmetic gas burner to reduce the rapid depletion of local natural resources. During this experimental study different parameters were investigated such as design of burner (swirl/radial flow), loading height, primary aeration, and semi-confined combustion flame to anlyze their effect on thermal efficiency and pollution emissions from domestic gas burners by burning natural gas as a fuel.

1.1. Burner Design:

A significant amount of literature is available on the enhancement of thermal efficiency and reduction of emission from industrial and domestic gas [7, 17]. However, to the best of our knowledge, studies investigating the effect of flow in burners on thermal efficiency and reduction of emission in burners is still limited. Burner design is substantially influenced by nature of flow patterns such as swirl and radial flows [3, 11, 18]. Mass and heat transfer processes are greatly affected by swirl or turbulences in both domestic and industrial processes. Studies have shown that swirl flow enhances the residence time and mixing of components by affecting the field of flow [4, 6, 11, 19]. To attain the best performance of a gas burner, it is important for its design to yield maximum combustion efficiency. Additionally, the reduction of pollutant emissions from practical combustion devices is essential. Swirl significantly affects both pollutant emissions and thermal efficiency. Swirling motion of the flame increases the residence time of flue gases at the bottom of loading vessel which increases thermal efficiency. On the other hand, proper mixing of fuel with air, produced by the swirl, burns the fuel completely hence producing strong flame and reducing emissions such as CO and un-burnt hydrocarbons [20, 21].

1.2. Loading Height:

Loading height is the vertical distance from burner tip to the center of base of loading vessel. It is also an important parameter in terms of efficiency and pollution emissions and is dependent on several other factors. Optimum value of loading height changes with burner diameter, amount of primary air, thermal input, velocity of fuel air mixture, and loading vessel dimensions [10, 11, 22].

Generally, thermal efficiency first increases with loading height to an optimum value and then decreases [22, 23]. For a very small loading height, complete combustion is not possible to achieve, and the flame starts impinging on the bottom of the loading vessel decreasing thermal efficiency and increasing the amount of CO and un-burnt carbon. With an increase in loading height, combustion is shifted towards completion (all carbon converted to CO_2) and allows efficiency to reach its maximum value. Afterwards, it decreases as the flame and combustion gases are cooled to a greater extent by mixing with ambient air before contacting the loading vessel [11, 24].

1.3. Primary Aeration:

Theoretically, air required for complete combustion of natural gas is about 9 parts by volume per part of natural gas. Part of this air required is entrained by the flowing gas in the mixing tube, known as primary air, and other part of this theoretical air enters the flame from above the port to complete the combustion which is known as secondary air [25, 26].

Primary aeration produces blue flame which has higher temperature as compared to the yellow flame which is produced by the deficiency of the primary air. Not only does the blue flame have higher temperature but it also controls the emissions of CO by facilitating complete combustion to produce CO_2. On the other hand, yellow flame is lower in temperature and emits CO and un-burnt carbon due to incomplete combustion [25].

1.4. Shield Enclosing:

Most domestic gas burners designs rely on open combustion flame which loses a large amount of energy through the flue gas, leading to a relatively lower thermal efficiency. It is a well-known fact that if the dispersion of flue gas or flame to the surroundings is delayed then an improvement in thermal efficiency can be achieved. Also, enclosing the burner with a metallic shield does the same purpose and thus proposes a great potential to improve thermal efficiency [27, 28]. However, this shield restricts the flow of secondary air to come in contact with the flame immediately and can cause a slight increase in pollution emission [4, 11, 13].

Results obtained in this research will be helpful to understand the effect of parameters such as burner design, loading height, primary aeration, and shield enclosing on the thermal efficiency and emission of the pollutants. Furthermore, these results are of immense importance to provide design concepts in enhancing efficiency and reducing emissions for manufacturing domestic gas stoves which use natural gas as a fuel.

2. Experimental Setup and Method:

Schematic of experimental setup employed in this study is shown in Fig. 1. Natural gas was used a fuel which was supplied by Sui Northern Gas Pipeline Limited (SNGPL). Diaphragm gas meter (model ZT-G4A, **Zhejiang Chant Instrument & Meter Co. Ltd, China**) was used to measure the volume of natural gas in cubic meter (m^3) as shown in Fig. 2 (a). Pressure regulator (model R4408, VANAZ ENGINEERING LTD. India) for the adjustment of pressure. During this experiment Chinese National Standard CNS general no. 13605 was employed [6, 11, 18]. According to the standard, tests were conducted under following conditions; the pressure (P) of natural gas, water load (M), and temperature ramping was 28 mbar, 4.4 kg, and 50°C (from 30°C to 80°C), respectively. According to the procedure, 4.4 kg of water was taken in a vessel with a lid over it. A K- type thermo-couple with a range of -270°Cto 1260°C, coupled with a temperature recorder was used to measure the temperature of water load. Thermo-couple was inserted in water up to the middle of loading vessel through a hole in the lid. Volume of natural gas consumed in m^3 for 50°C rise in temperature from 30°C to 80°C of water load was measured using gas meter. Room temperature and pressure of the gas were also recorded for each experiment. Same procedure was adopted for swirl and radial burners shown in Fig. 2 (b) and (c), respectively. Stand used to vary loading height and experimental arrangements for burners with and without shield are shown in Fig. 3 (a), (b), and (c), respectively.

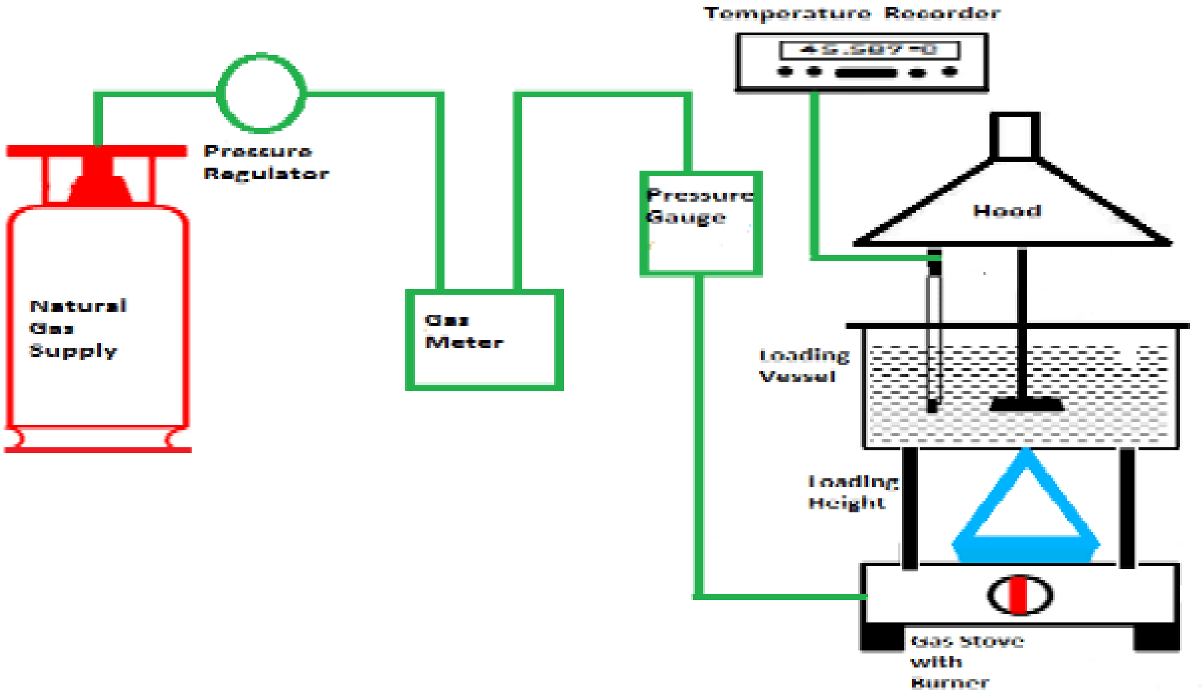

Figure 1: Schematic arrangement of experimental setup

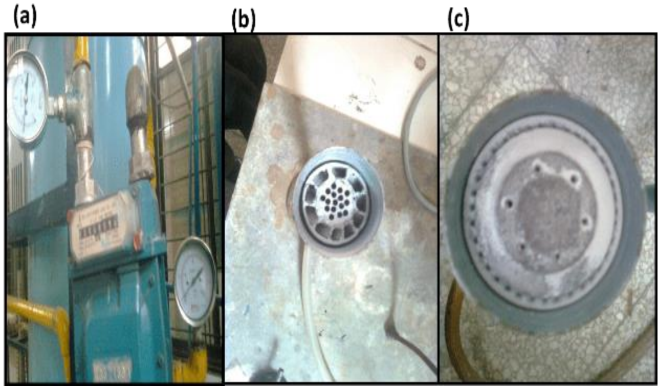

Figure 2: (a) Diaphragm gas meter with pressure gauges at the inlet and outlet, (b) Swirl burner, (c) Radial burner

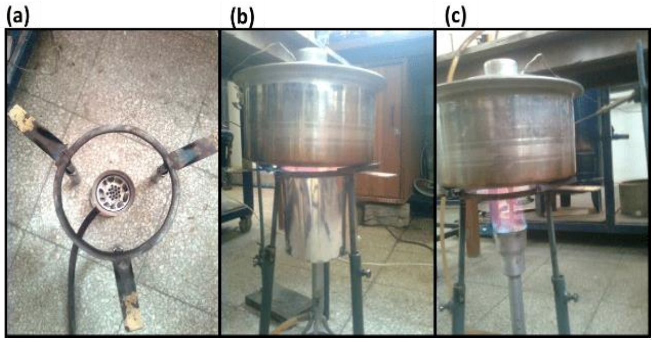

Figure 3: (a) Stand used to change loading height, (b) Burner with shield, (c) Burner without shield

Efficiency in percentage was determined by measuring the volume of the gas consumed in m^3 for a standard load of water which was heated through 50°C temperature rise from the initial temperature of 30°C to final temperature of 80°C. Efficiency is given as:

$$\eta = \frac{M \text{ x } C_p(T_f - T_i)}{Q \text{ x } HHV} \text{ x } 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where M, C_p, T_{fL}, T_i, Q, and HHV are standard load of water (4.4 kg), heat capacity of water (4.2 kJ kg^{-1}°C^{-1}), volume of gas consumed (m^3), and high heating value of natural gas (34726 kJm^{-3}), respectively.

Gas savings were determined by following equation:

Energy saving =

$$\frac{\eta_2 - \eta_1}{\eta_2} \text{ x } 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

η_2 represents thermal efficiency of the experiment with higher value and η_1 represents thermal efficiency of the experiment with lower value. All experiments were performed in triplicates and at a pressure and flow rate of 10 mbar and 0.000034 m^3s^{-1}, respectively.

3. Results and Discussion:

The effect of burner design (swirl/radial), loading height (defined as the vertical distance from the bottom of the loading vessel to the top of the burner tip), primary aeration and semi-confined combustion flame on emissions and thermal efficiency are discussed as follows:

3.1. Burner Design:

For the experiments conducted at a pressure and flow rate of 10 mbar and 0.000034 m^3s^{-1} respectively, the efficiency comparison of swirl and radial burners is shown in Fig. 4. Gas saving was 4.2%. As shown in Fig.4, the swirl flow burner exhibited higher efficiency than the radial flow burner at constant supply pressure, flow rate and loading height. This was due to increased heat transfer coefficient at the vessel bottom as a result of the swirling motion, resulting from the prolonged residence time of the combustion products in the vicinity of the vessel bottom. Moreover, improved mixing of gas and air was achieved due to swirling motion [4, 13]. In the temperature range between 40-80 °C, the average efficiency of swirl flow burner was 1.6% greater than radial flow burner. Although, in these experiments, the flue gas analysis was not performed but literature showed that for the case of swirl burner, the CO emissions were slightly higher than those observed in radial burner. Swirl burners possess elliptical design, whereas radial burners have circular design which results in slightly higher CO emissions from swirl burners as compared to radial burners. S. S. Hou and C. H. Chou work shows that as swirl angle was increased from 0° to 55° emission of CO increases from 450 ppm to 650 ppm [6, 29].

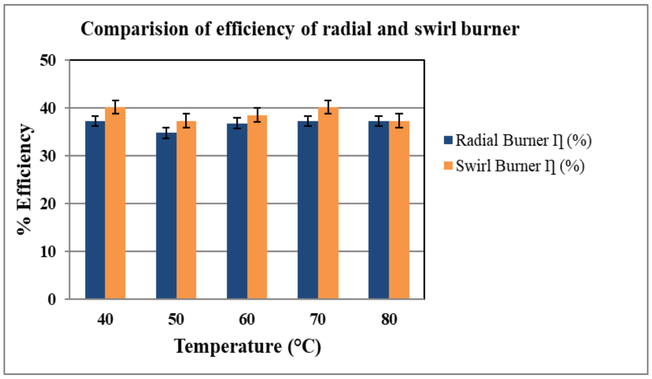

Figure 4: Comparison of thermal efficiency of swirl and radial burners

3.2. Effect of Shield Enclosing:

It is a well-known fact that delayed dispersion of the flame or flue gas to the surroundings resulted in improved thermal efficiency of the burner.

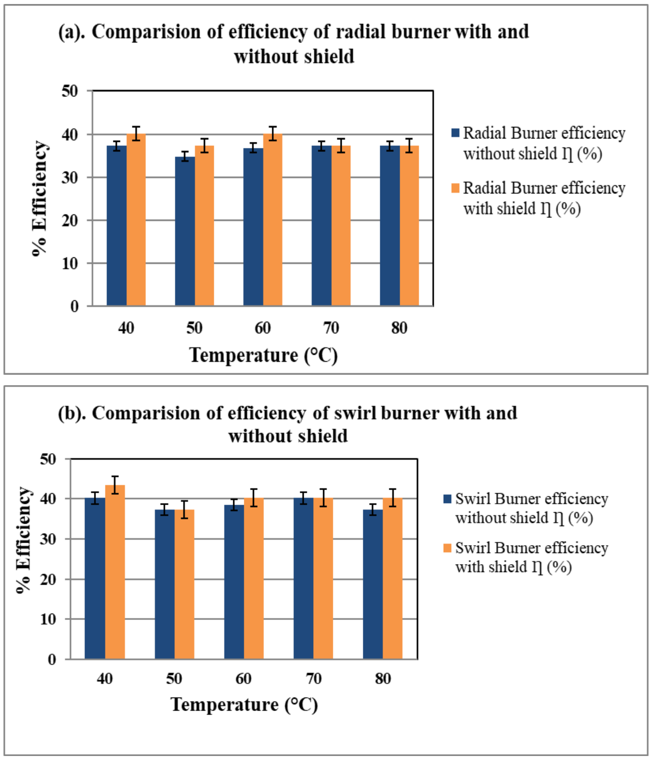

Figure 5: Comparison of thermal efficiency with and without shield for the case of (a) Radial burner, (b) Swirl burner

The comparison of thermal efficiency of radial and swirl burners with and without shield are shown in Fig. 5 (a) and (b), respectively. It is evident that the thermal efficiency of both swirl and radial burner increased significantly by 4-5% with metallic shield than without shield for the same level of heat input. Conversely, this might result in slight increase in CO emission as the secondary air supply could be slightly suppressed when the burner was enclosed in metallic shield [11].

Most commonly used domestic burners are operated on an open flame, which cause huge loss of energy to the atmosphere and consequently thermal efficiency decreases [4, 13]. Thus, thermal efficiency can be effectively increased by dispersion of flame or flue gas should be delayed which can be achieved by swirl motion and semi-confinement of flame. Previous research work on swirl motion and semi-confinement of flame showed that efficiency increased by 6-10% for all types of burner [11]. Commercialization of semi-confined combustion flame in domestic gas stoves is a milestone of this study. Easy fitted metallic shield in domestic gas stove was invented for commercialization as shown in Fig. 6.

Figure 6: Metallic shield designed for commercialization

3.3. Effect of Loading Height:

Effect of varying loading height on thermal efficiency and burner emissions is presented in Fig. 7.

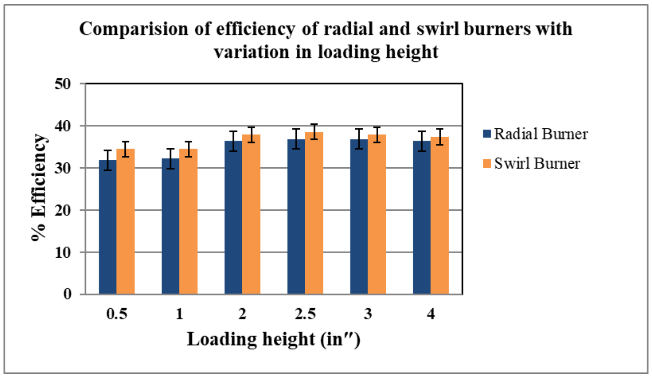

Figure 7: Comparison of overall efficiency with loading height for swirl and radial burner

In general, for the case of radial and swirl burners, initially the thermal efficiency increased from 34.4% and 31.8% to 38.4% and 36.8% with the increase in loading height from 0.5 inches to 2.5 inches, respectively. Afterwards, the efficiency decreased to 37.3% and 36.3% at the lading height of 4.0 inches, for swirl and radial burners, respectively. For small loading height (i.e., 0.5 inches), complete combustion cannot be achieved before the flame is impinging on the bottom of the loading vessel, which results in decreased thermal efficiency. With increase in loading height, combustion goes towards completion and allows efficiency to reach a maximum value. However, with the further increase in loading height (optimum value), the flame and combustion gases are cooled to a greater extent by mixing with ambient air before contacting the loading vessel. Thus, the temperature driving force for heat transfer is decreased which decreases the thermal efficiency.

At constant pressure and flow rate of gas, the increase of loading height reduces CO emissions as a result of complete combustion (all carbon to CO_2). On the other hand, the decrease in loading height leads to enhancement of flame impingement of the loading vessel. Consequently, incomplete combustion increases due to increased quenching by the load which increases emissions of CO and unburnt hydrocarbon. Incomplete combustion is an indication that either the primary or secondary air supply is insufficient, or the flame is being quenched by the impingement on a cool surface [3].

These emissions of CO and un-burnt carbon particles are also seen as a deposition on the bottom of loading vessel as shown in Fig. 8. The deposition of carbon particles on the surface of the vessel reduces the heat transfer coefficient, thereby decreasing the overall thermal efficiency of the system [30].

Figure 8: Deposition of carbon particles on the bottom of vessel when loading height is decreased

Loading height has an optimum value for both thermal efficiency and emissions. Low value of loading height causes the cooling of post-flame gases due to contact with loading vessel causing an increase in CO emissions. However, at high loading height, temperature gradient decreases which reduces thermal efficiency as reported by Hou [31] and Ko and Lin [18]. In this study, the optimum loading height was found to be 2.5 inches for both swirl and radial burners. It is worthwhile to mention that loading height is a tricky parameter and must be analyzed in view of other parameters such as burner diameter, amount of primary air, thermal input, velocity of fuel air mixture and loading vessel dimensions. Since, the optimum value of loading height is affected by aforementioned parameters [22].

3.4. Effect of Primary Air:

Amount of primary air injected into the burner tube to get it mixed with the fuel is a very important factor regarding emission control and efficiency of a burner. Primary air affects the heights of the cone and flame itself. The height of the cone decreases very rapidly as the amount of the primary air increases up to 75% of the theoretical air. Short flames are strong as the combustion reaction occurs in a confined space producing high temperature flame which increases the efficiency [25].

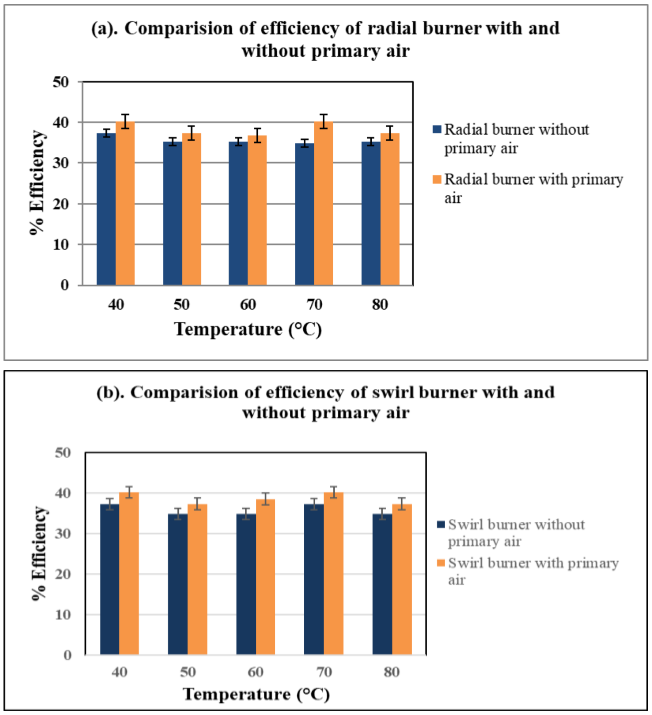

Figure 9: Comparison of thermal efficiency with and without primary aeration for (a) Radial burner and for (b) Swirl burner

Deficiency of primary air leads to incomplete combustion and produces yellow flame. Temperature of this yellow flame is lower than that of blue flame which consists of CO_2 and NO_x. Complete combustion of fuel provides large amount of energy because formation of each molecule of CO_2 generates almost 70% more energy than formation of CO molecule and hence efficiency is increased [25].

Fig. 9 shows the efficiencies of radial and swirl burners with and without primary air. It is clear that efficiency of the flame with primary air was higher than that of absence of primary air, which is in agreement with the previous study [22]. The deposition of un-burnt carbon and soot particles on the vessel bottom was observed as shown in Fig10 (a), which might decrease heat transfer coefficient affecting the efficiency of the flame burning without the supply of primary air.

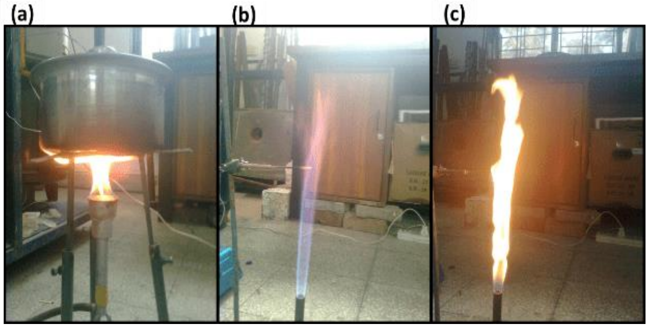

Figure 10: (a)Carbon deposition on the bottom of vessel without primary air, (b) Blue colored flame with fully opened valve of primary air (flame temperature was 897 °C), (c)Yellow colored flame with fully closed valve of primary air (flame temperature was 811 °C)

Interestingly, the optimum values of efficiency in the presence and absence of primary air vary with the loading height. In this study, the optimum value of efficiency in the presence of primary air was approximately 38.5 % at a loading height of 2.5 inches, whereas for the case when primary air was not being supplied, the optimum value of efficiency was neatly 36.5 % at a loading height of3.5 inches. The only possible reason for this finding could be the length of flame. When primary air was open, short flame appeared and the optimum value of efficiency was obtained at a loading height of 2.5 inches. However, for the other case when primary air was closed, long flame was observed and the optimum value of efficiency was obtained at higher loading height (i.e., 3.5 inches) compared to the case when primary air was open (i.e., 2.5 inches).

Measurements of flame temperature with and without primary air also confirmed the previously explained results. Fig.10 (b) and (c) show blue and yellow flames with average measured temperatures of 897 °C and 811

°C in the presence and absence of primary air, respectively. The temperature for the case of blue flame with primary air was approximately 10% higher than yellow flame without primary air. For both cases, the temperature readings were taken at a distance of 14 cm from the burner tip.

Conclusion:

Design modifications in the existing domestic gas burner regarding swirling motion, operating burner at an optimum loading height, provision of proper amount of primary air, and addition of a metallic shield enclosing the flame were investigated for overall efficiency and pollution emissions of a burner. Swirl flow in the burner design promoted mixing of fuel and air and thus contributed to increase in thermal efficiency by 1.6% than the conventional radial flow burner. The maximum thermal efficiency was found to be 38.4% and 36.8% for swirl and radial burners at optimum loading height of 2.5 inches, respectively. Delaying the dispersion of flue gas or the flame into atmosphere by enclosing the flame with a metallic shield increased the thermal efficiency by 4-5% for both swirl and radial burners. However, it could lead to a slight increase in CO emission due to limited secondary air. Primary aeration shortened the flame, increased its strength in terms of temperature, facilitated the completion of combustion reaction and hence improved the efficiency. Blue- and yellow-colored flames were observed in the presence and absence of primary aeration, respectively. The corresponding flame temperature of blue flame was approximately 10% higher than yellow flame. This study provides necessary framework regarding design modifications and optimization to achieve maximum efficiency for burners used in domestic stoves.

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