

Effect of Burner Type on Thermal Efficiency and Emission of LPG Cookstoves

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Abstract

In this work, we investigated the thermal efficiency and emission of four types of LPG cookstove: conventional radial flow slotted burner (CB), new swirl flow burner (NB), radiant burner (RB) and swirling central flame burner (SB). The German Standards (DIN EN 203-2 and DIN EN 203-1) were used in this study. It was found that the maximum thermal efficiency of SB type was about 66%, and its value was the highest when compared to the conventional CB, NB and RB types, of which the values were 51%, 59% and 53%, respectively. This can be attributed to the swirl-enhancement of effective heat transfer and impinging resident time of hot flue gas onto the pot bottom. Simultaneously, we measured and estimated the emission of CO₂, CO and NO_x from these LPG cookstoves and the obtained concentrations were converted to Environmental Load Unit (ELU) per MJ of both input and useful energy, which can be used for comparing the detrimental impact of these stoves to the environment. It was found that the total emissions from the SB type were the lowest. The occupational and health aspects of these LPG cookstoves were also determined under conditions of with and without ventilation.

Keywords: cookstove; emission; LPG; gas burner; thermal efficiency

1. Introduction

The average daily production of Liquefied Petroleum Gas (LPG) in Thailand, mainly from petroleum refinery and natural gas separation plants, is about 89,000 bbl/d, and nearly half of which is used as fuel for cooking in the household and commercial sector [1]. It was found from various studies that the commercial LPG cookstoves available in Thailand, mostly utilizing a conventional radial flow slotted burner (CB), have relatively low average thermal efficiency [2-3]. For the purpose of this study, the thermal efficiency is defined as the ratio of absorbed heat by specific amount of water in the pot to the fuel heat input. An increase in stove thermal efficiency can save not only LPG for the same cooking purpose, but also reduce the pollutant emissions. New burners, such as swirl flow and heat recirculation types, with significant improvement in thermal efficiency have been developed [2-3]. However, the emission data from these cookstoves, which is important for in-door air quality control in residential buildings, are yet to be studied.

Stubington et al. [4] investigated the thermal efficiencies and emission rates of pollutants of Australian production cookers, and found that the thermal input and load height were shown to affect both the emissions and efficiencies. The ratio of NO₂/NO_x and the measured emission rate of CO were affected by the leakage of hydrocarbon from the stabilization ports into the secondary/dilution air at the base

of the burner and incomplete combustion of the fuel. The quantitative data obtained will provide a baseline to trade-off between the thermal efficiency and emissions in burner design. The emission of NO_x and CO from domestic cook top burners fuelled by natural gas at various load heights and thermal inputs were also studied by Ashman et al. [5]. The optimum load height was experimentally determined based on the proposed correlation of total emission with the emission rate and thermal efficiency.

The comparison of cooking stoves with different burner design based on emission and thermal efficiency is not a simple task, since the health effect and environmental impact of each pollutant is different. Kandpal et al. [6,7] reported the indoor air pollution caused by domestic cookstoves using various types of fuel, and addressed the health effects of accumulated pollutants in the unvented indoor environment. They, however, did not provide the results of emission per unit energy input and the total impact of all pollutants on both health and environment. Jones [8] reviewed the effects of combustion products on human health and pointed out that the use of gas for cooking and heating under unvented conditions or improper installation can generate severe problems.

The single environmental index, which is derived from the sum of all impact categories - the contribution of the category under study to national effects for that category - has been recently proposed by Golonka and Brennan [9] in their environmental life cycle assessment study. Although the index did not take into account the effect of concentration of pollutant species and allow for the different assimilative capacities of the environment for different locations, nonetheless it will be a useful aid to compare each option (process or product) on the environmental and health basis. The Swedish Environmental Institute and Volvo [10] proposed a system called the environmental priority strategies (EPS), which is determined by assigning an environmental index to each pollutant. These indices are expressed as

environmental load units (ELU) per kilogram of the pollutant. By summation of the ELU over all the pollutants concerned, a total environmental load associated with a process or product can be estimated. In developing the EPS system, the following qualitative and subjective factors: (i) scope (the general impression of the environmental impact), (ii) distribution (the extent of the affected area), (iii) frequency or intensity (the regularity and intensity of the problem in the affected area), (iv) durability (the permanence of the effect), (v) contribution (the significance of one kilogram of the emission of the substance in relation to the total effect), and (vi) remediability (the relative cost to reduce the emission by one kilogram) were considered. The environmental index of a pollutant is the product of the values assigned to these six factors. This system was used by Volvo to evaluate product designs and alternative materials.

For health effects, the permissible exposure level (PEL) for the mixture of gaseous pollutants, which is commonly used in the field of chemical process safety, can be estimated based on the OSHA standard [11]. The room or enclosure is considered to be safe for health, if the sum of all gaseous pollutant concentration in the ambient air is lower than this specified value. With these concepts, the total effects on health and environment of each process or product could be compared and linked to its performance.

This study reports the thermal performance and emission of pollutants from different type of cookstoves fuelled by LPG. The ELU and PEL concepts have been adopted to compare these stoves at various thermal outputs. Health hazards for the occupants in the kitchen were also evaluated with vented and unvented scenarios.

2. Experimental

Four cookstoves having different types of burner, as depicted in Fig. 1, were used in this study: conventional radial flow slotted burner

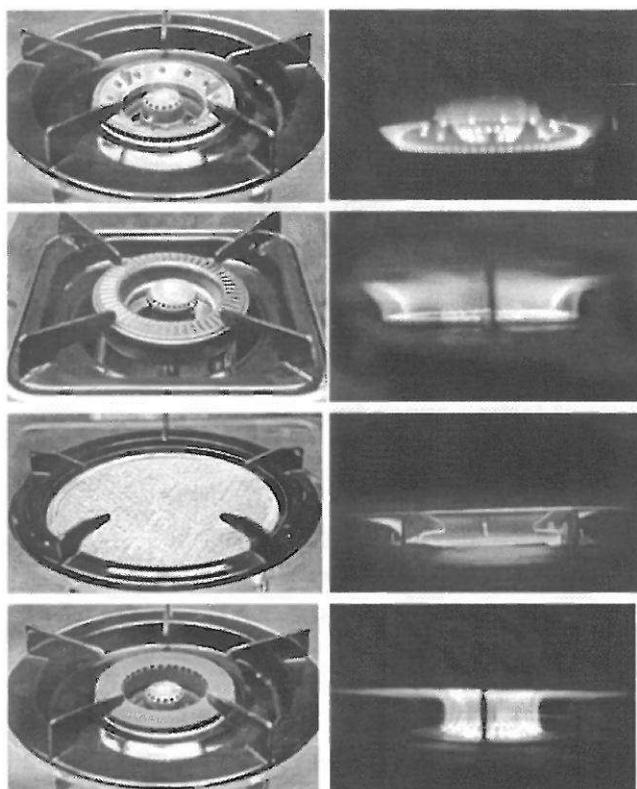


Figure 1 Cookstoves used in this study and their flame shapes when heating a standard pot filled with water placed on top. From the top down are shown CB, NB, RB, and SB type burners, respectively.

(CB), new swirl flow burner (NB), radiant burner (RB) and swirling central flame burner (SB). All of them are single cook top with the aspiration type pre-mixed nozzle. The first three are commercially available in the market, while the last one - whose performance test has been recently reported elsewhere [3] - was developed by our study group. The commercial cylinder LPG (15kg size), whose composition and properties were shown in Table 1, was used as fuel throughout this study.

The thermal performance test and emission measurement for each cookstove and thermal input or LPG flow rate were based on DIN EN 203-2 and 203-1 standard (1997), respectively. Figure 2 shows how the testing

apparatus was set up. The transient method was employed for the former test. Before a test run, all the components of the cookstove were preheated under preset values of thermal input by heating a specific amount of water in a standard pot placed on top of the burner to 70°C higher than the room temperature. Following this the gas valve was closed and the pot was replaced by a new one filled with the same amount of water. The gas valve was then turned on with the same thermal input load. A thermocouple (K-type) connected to a data logger (Yogokawa, NW 100), stopwatch, and wet gas meter (Shinagawa Model W-NK-1B) were used to record the water temperature, heating time, and fuel gas flow rate, respectively.

Table 1 Composition and Properties of LPG

| | |
|---|--------|
| Propane : Butane (mole basis) | 60:40 |
| Gas Density @ 25 °C, 1 atm (kg/m ³) | 1.6581 |
| Heating Value(MJ/kg) | 63.32 |

A steady state test was used in the pollutant emission measurement. For each type of stove, the test was performed at three different thermal inputs: minimum and maximum flow rates of LPG, and at maximum thermal efficiency. In brief, the stove with a standard pot filled with a specific amount of water placed on top was covered by a standard hood, with which the gas analyzer probe (Bacharach Model 300) was inserted into the outlet port for gas composition measurement. The system was allowed to reach a steady state for 15-20 minutes after the stove was ignited and adjusted to the desired thermal input, then the composition of CO, O₂, and NO_x was recorded. For each thermal input, the test was conducted in triplicate to ensure the data was reproducible.

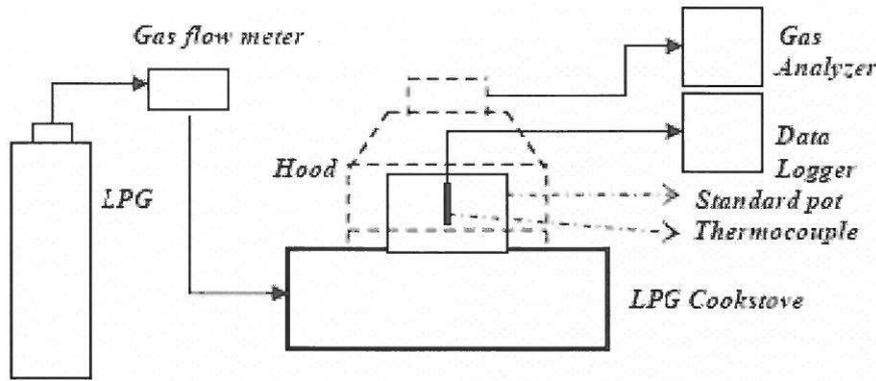


Figure 2 Schematic diagram of testing apparatus.

3. Results and Discussion

The thermal efficiency of each cookstove, as shown in Fig. 3, was calculated from the ratio of sensible heat absorbed by the water filling the standard pot to the fuel heat input. It was found that the maximum thermal efficiency of the SB type was about 66%, and its value was the highest when compared to the conventional CB, NB and RB types, of which the values were 51%, 59% and 53%, respectively. This can be attributed to the swirl-enhancement of effective heat transfer and impinging resident time of hot flue gas onto the pot bottom [3]. The lowest thermal efficiency found with the CB type stove is due to the inefficient convection heat transfer between hot combustion product gas and the pot, especially at the pot bottom. However, the radiation heat transfer employed by the RB type stove, whose thermal efficiency is slightly better than the CB type, is not as efficient as the convection mode that has been enhanced by swirling flow in the SB and NB types, and therefore needs to be improved.

The composition of CO, O₂, and NO_x was measured directly, while the concentration of CO₂ was estimated from the stoichiometry CO₂ and excess oxygen as recommended in the manual of the gas analyzer. Assuming that no

hydrocarbons are present in the combustion product and all of nitrogen oxides are in the form of NO₂, the stoichiometry equation for LPG combustion could then be written. Since the LPG flow rate is known, the emission of gas pollutants, in terms of g/MJ of energy input, for each stove type can be calculated, and the obtained results for three thermal inputs are shown in Fig. 4. It is clearly seen that each stove released different amounts of gas pollutants. The CB stove emitted low CO but high NO_x, while the RB stove gave high CO but low NO_x. In essence, a single environmental index is necessary to compare between stoves based on their thermal performance and emission. This study employed the ELU concept [10], as mentioned above, to normalize all of considered gas pollutants to a single index, and the estimated results for each stove were also illustrated in Fig. 4 together with their maximum thermal efficiency.

Since all studied cookstoves were an open-type burner, the measured composition of O₂ at the hood outlet (see Fig. 2), which was the mixing of the O₂ in the entrained air and the excess O₂ in the flue gas, was impractical to be used to observe their combustion efficiency, and thus the CO composition was used instead.

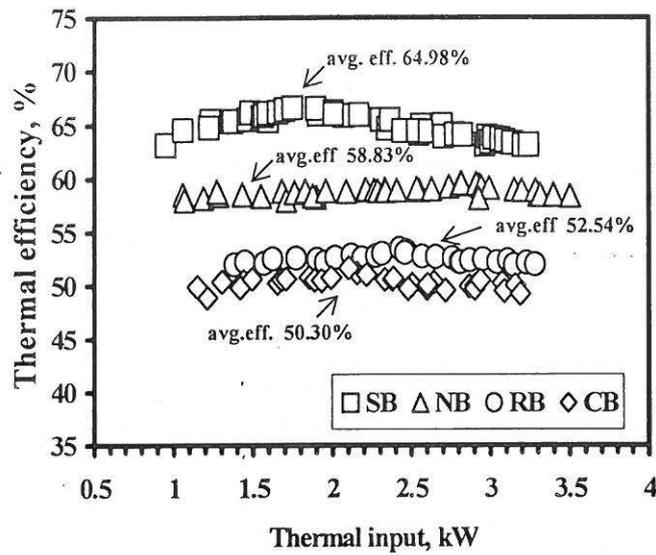


Figure 3. Thermal efficiency as a function of thermal input.

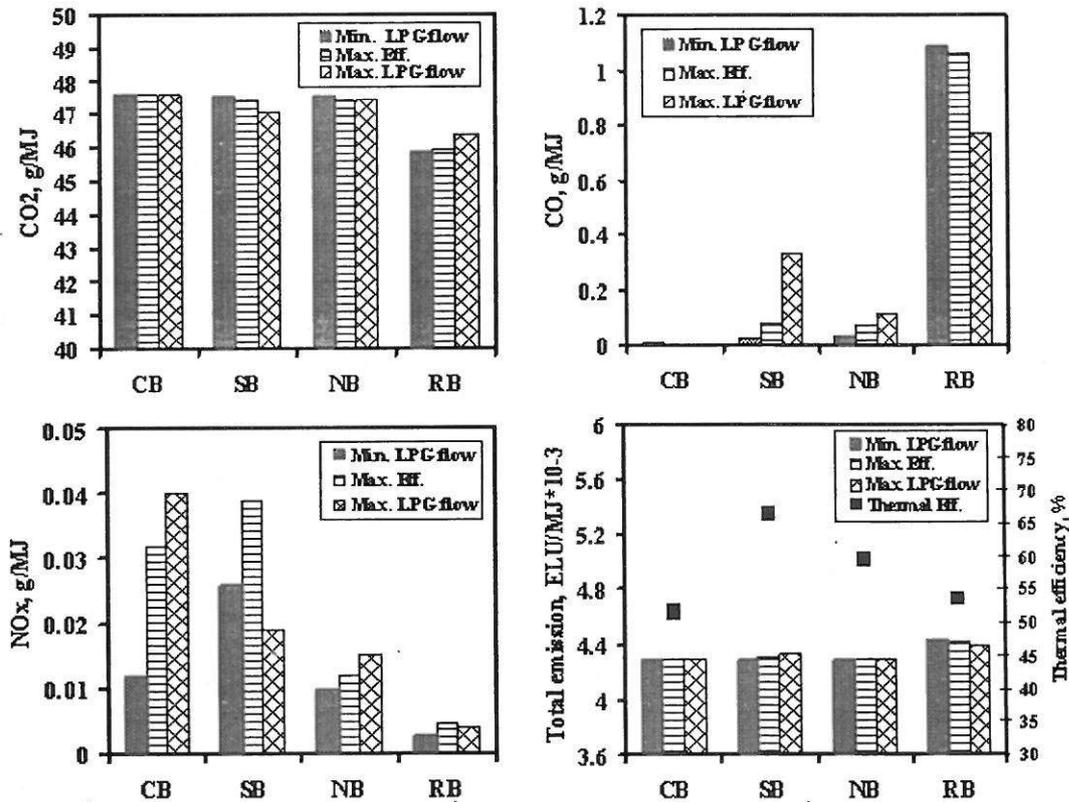


Figure 4. Emission of gaseous pollutants from cookstoves.

The CB stove gave lowest value of CO for all three thermal inputs, which confirms its better combustion efficiency (see Fig. 4). This will promote the NO_x generation as the LPG flow rate is increased due to the increase in flame temperature (Fig. 4). However, its thermal efficiency is lowest because of the inefficient transfer of heat as explained above. The relatively high level of CO emission, which also increased with the thermal input, of both SB and NB stoves when compared to the CB stove can be attributed to the increase in quenching effect of swirling flame impinging at the pot bottom, which thus reduces the post-flame combustion of CO. Not only heat transfer but also the fuel-air mixture is enhanced by the swirling flow, and this will result in high flame temperature and the corresponding NO_x emission. However, at high fuel flow rate the coalescence of inner and outer ring (Fig. 1) flame of the SB stove was observed during the experiment due to an increase in attached flame length on each burner port. Ineffective fuel-air mixing occurred as a result, and caused high emission of CO with the corresponding low emission of NO_x because of the low temperature flame. This effect was not observed in the NB type stove because of the difference in burner port design. For the RB stove, part of the combustion heat is used to increase the temperature of the porous ceramic plate, from which the heat is radiated back to the pot bottom (Fig. 1). This reduces the flame temperature, and hence significantly reduces the post-flame combustion of CO. The emission of CO and NO_x from the RB stove at all three thermal inputs, therefore, was highest and lowest, respectively. In addition, the CO emission gradually decreased as the thermal input was increased due to the increase in flame temperature, and thus the post-flame combustion.

The compensation between thermal efficiency and gaseous pollutant emission was clearly seen when the total emissions in term of ELU per MJ of energy input for all studied stoves were compared (Fig. 4). It was found

that the CB, SB, and NB stoves have nearly the same level of total emission, while the RB stove was slightly higher, and all of them showed an insensitivity of total emissions to the thermal input. Thus the SB stove, based on both thermal efficiency and emissions, gave best performance. This conclusion is easy to elucidate if the total emission per unit of useful energy is compared as depicted in Table 2, together with their maximum thermal efficiency. For the same amount of useful energy, the rank of minimum to maximum total emissions is as follows: SB, NB, RB, and CB; and it should be stressed that the increase in thermal efficiency of the stove significantly reduces the total emission of pollutants. This methodology enables us to trade-off between thermal efficiency and emission of different types of LPG cookstoves. Note that the data used in this study to calculate the ELU may not be specifically applied for Thailand since the impact of each pollutant is regionally and nationally dependent. However, the error is presumed to be less when it is applied for comparative study as was done in this work.

Table 2 Comparison of thermal efficiency and emissions of the studied stoves.

| Type | Thermal eff.,% | | | ELU/MJ | |
|------|----------------|-----------|-----------|---------------|----------------|
| | Max. | Min | Avg. | Energy input* | Useful energy* |
| CB | 51.6 9 | 48.9 4 | 50.3 0 | 4.29 | 8.30 |
| NB | 59.5 8 | 58.0 2 | 58.8 3 | 4.30 | 7.22 |
| RB | 53.4 6 | 51.9 5 | 52.5 4 | 4.44 | 8.26 |
| SB | 66.7 6 | 63.1 5 | 64.9 8 | 4.30 | 6.46 |

* at maximum efficiency condition

The assessment of health hazards within the kitchen when using these LPG cookstoves was also carried out. The permissible exposure level of gaseous pollutant mixture (PEL_{mix}), as suggested in Reference [11], was firstly estimated by using Eq. (1)

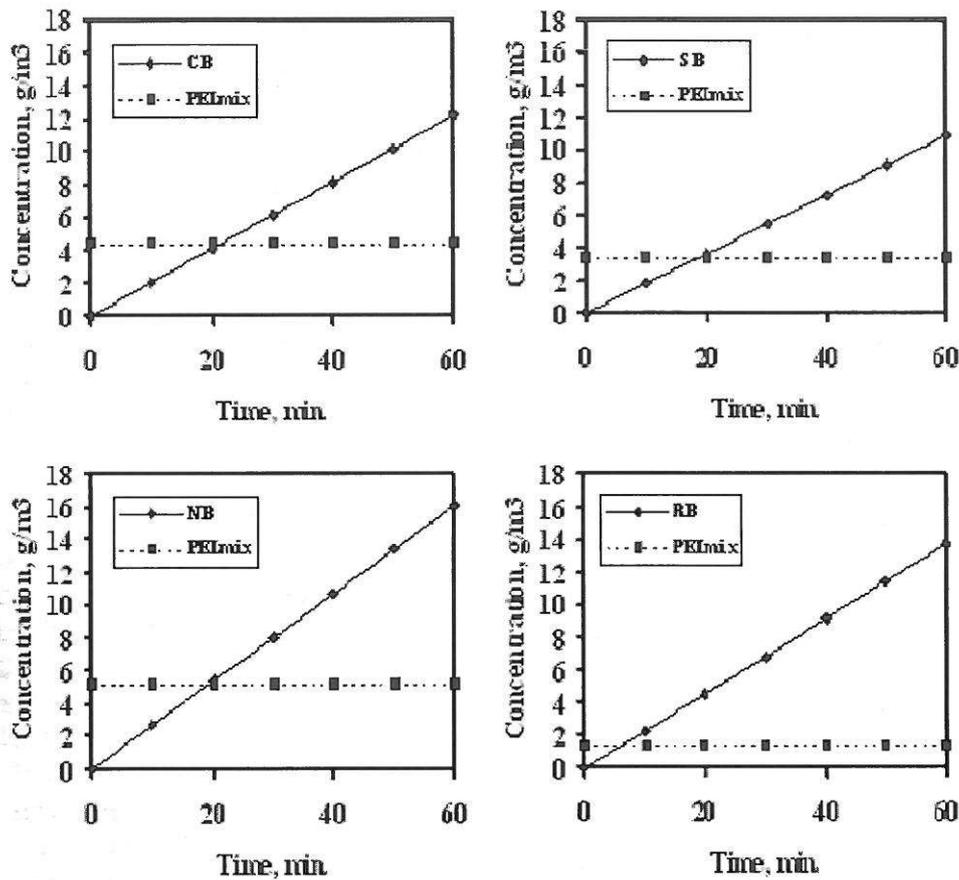


Figure 5 Accumulated emission of gaseous pollutants from the studied stoves as a function of time.

$$PEL_{mix} = \sum C_i / [\sum (C_i / PEL_i)]; \text{ for } i = 1 \text{ to } n \quad (1)$$

Where C_i is concentration of pollutant i and the subscript mix represents the gas mixture.

The unvented room or kitchen will be considered to be a risk for health when the summation of each accumulated pollutant within specific time intervals - evaluated from the total fuel energy input and the emission of pollutant (Fig. 4) - is higher than the estimated value of PEL_{mix} [11]. The comparison is presented in Fig. 5, and it was found that the CB, SB, and NB stoves showed health risks within 20 minutes of cooking, while it was only 10 minutes for the RB type stove.

For vented room or kitchen, the estimated PEL_{mix} for each stove were then used for minimum dilution ventilation rate (Q_v) calculation as a function of non-ideal mixing factor (k) by means of Eq. (2) [11]

$$Q_v = Q_m RT * 10^6 / [k(PEL_{mix})PM] \quad (2)$$

Where Q_m is generation rate of pollutant, R is universal gas constant, T is absolute temperature, P is ambient pressure, and M is molecular weight of gaseous mixture.

Figure 6 showed the minimum rate of dilution ventilation for each type of stove when k was varied from 1/7 to 1/2 [11]. The CB, SB, and NB type stoves needed nearly the same

ventilation rate to maintain the safe ambient during cooking. The RB type needed relatively high value due to the high emission of CO. The ventilation rate can be reduced significantly if the local ventilation technique is used such as a conventional hood. Using the recommended velocity (100-125 ft/min) [11] and cross-sectional area of commercial hood suitable for these stoves, it was found that the local ventilation rate is about 30% lower than the case of dilution ventilation with $k = 1/7$ (worst case), and hence reduces electrical energy consumption by fan.

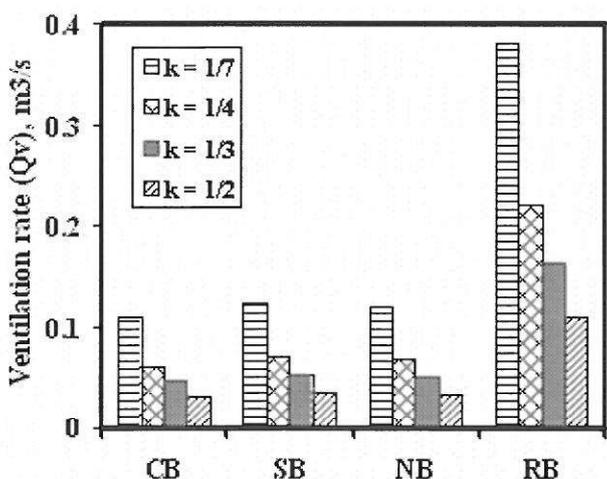


Figure 6. The effect of non-ideal mixing factor on minimum dilution ventilation rate of the studied stoves

4. Conclusion

1. The swirl flow flame burner (NB and SB) showed significant increase in thermal efficiency when compared with the conventional radial flow slotted burner (CB), while a radiant burner (RB) gave slightly higher efficiency.

2. The proposed method of using thermal efficiency in conjunction with single environmental index, ELU per MJ of energy input or useful energy, is successfully applied for comparison of different stove types, and the trade-off between thermal performance and emissions can be simply made. In this study, the SB type stove provided the best performance.

3. The health hazard during cooking can be simply estimated for both unvented and vented kitchens using the conventional method reported in the literature.

5. Acknowledgements

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