

Prediction of Total Equivalence Ratio for a Self-Aspirating Burner

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Abstract

A total air entrainment affects the burner performance in terms of completeness of combustion. In recent years, the prediction of a value of the air entrainment for a self-aspirating burner deals only with the primary air, and is also limited to the without preheat case. This study provides a combined theoretical and experimental investigation into the prediction of the total air entrainment for a self-aspirating burner, which is corresponding to the total equivalence ratio. Both with and without preheat of combustion air cases are carried out the primary air entrainment. The oxygen concentration in the mixture is measured by the oxygen sensor. It reveals the level of primary air within this mixture. Calculation method for predicting the total equivalence ratio was developed by using the momentum and energy conservation principles. It is observed that the levels of both primary and secondary air entrainment are increased with increasing the heat input due to the high momentum jet. The preheated case yields a lower primary and secondary air entrainment because of the preheating effect, the fluid in the mixing tube has more viscosity. The levels of total equivalence ratio are in the range of 0.5 to 6. The rich condition is occurred at lower heat input because of the low total air entrainment. At higher heat input, the high momentum jet entrains an excess air. Therefore, the total equivalence ratio becomes very low under lean conditions. The optimum operation of this burner occurs at heat input equals to 7.5 kW, in which the stoichiometric combustion is achieved. As a result, it may be helpful in predicting the thermal efficiency in the future especially in combustion with preheated air.

Keywords: Self-aspirating burner, Total equivalence ratio, Preheating effect, Air entrainment

1. Introduction

Self-aspirating burners designed to be fueled by liquefied petroleum gas (LPG) are widely used in households for cooking in Thailand. During recent decades, the total of LPG consumption is increasing continuously [1] due to rapid development and industrialization. It is found that, the cooking sector accounts for about 50% of the country's total LPG consumption, as shown in Fig. 1. Because the large number of self-aspirating burners involved in our daily life, even a slight improvement in

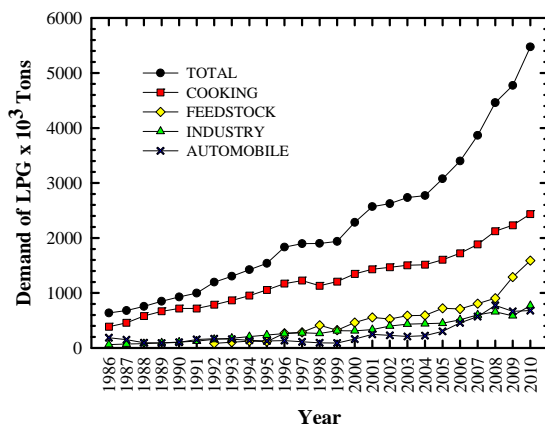


Fig. 1 Consumption of LPG in Thailand [1]

their thermal performance would result in a significant impact on the total energy consumption and the environment.

Much research on self-aspirating burners has been carried out to improve thermal performance and to reduce pollutant emissions by developing the burner port geometry and the combustion system [2-4]. The results showed that the thermal efficiency of the proposed burner is higher than that of a conventional burner. However, through the

preheating effect of the primary air [4], the amount of air entrainment is further reduced because of an increase in the flow resistance [5]. Therefore, incomplete combustion is taken place with a high level of CO emissions. The level of the primary air entrainment is of importance for more complete combustion of the self-aspirating burners. Many studies have been conducted with the self-aspirating burners to predict the level of the primary air entrainment [6-9]. They found that primary air entrainment is a function of fuel gas flow rate, type of fuel gas, injector geometry, mixing tube geometry, and burner port geometry. However, most of the studies mentioned above are limited to the cold test case (without combustion). In recent years, theoretical and experimental studies on primary air entrainment of a self-aspirating burner with hot test case (with combustion) were conducted. Its also performed for both without preheat [10,11] and preheat cases [12] to gain more understanding of primary air entrainment characteristics. A first correlation of primary air entrainment without preheated air is proposed. The results showed that the preheat case of $T_{pre} = 300^{\circ}\text{C}$ gives about a 14 percentage point (33% relative) lower primary aeration value than that of the without preheat case, because the preheating effect causes expansion of the mixture and an increase in its viscosity.

It is clear from the above review that the theoretical equations are not sufficient to use for the prediction of primary air entrainment with preheated air. Moreover, there is no information in the literature about the prediction of total equivalence ratio for a self-aspirating burner. Therefore, our present experimental work was devoted to study the prediction of primary air and secondary air entrainment with preheated air, which corresponds with the total equivalence ratio. It is importance and necessary to assess the behavior and performance of a given burners. This information may be helpful in calculating the adiabatic

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flame temperature and the thermal efficiency of burners in the future.

2. Methodology

Fig. 2 shows a schematic diagram of the primary aeration measurement using the oxygen sensor which is applied for both with and without preheat conditions. It is composed of a self-aspirating burner with cross-sectional area of injector $A_i = 0.64 \text{ mm}^2$, cross-sectional area of throat $A_t = 254.47 \text{ mm}^2$, and overall cross-sectional area of the burner port $A_p = 245.44 \text{ mm}^2$. Liquefied petroleum gas (LPG) is used as a fuel in the experiment, and the oxygen sensor is used to measure oxygen concentration with an accuracy of about 0.05%. An uncertainty analysis was carried out with the method proposed by Kline and McClintock [13]. Using a 95% confidence level, the maximum and minimum uncertainties in the presented primary aeration were found to be 3.3% relative and 1.6% relative, respectively.

In the without preheat case, the flow rates of LPG 1 are controlled by a pressure regulator ②. The flow meter ③ is installed downstream of a pressure regulator. The volume flow rates are measured in order to calculate the heat input (q) of the fuel gas. A mercury manometer ④ is used to measure the fuel pressure. Then, the fuel gas is injected by the injector orifice ⑤ into the mixing tube 6. Meanwhile, the primary air from the air compressor ⑦ is supplied to the air storage tank ⑧, which is provided to maintain the primary air temperature. The dimensions of the air storage tank are 40 x 40 x 40 cm. The air storage tank walls are covered with 4 cm thickness of ceramic fiber. The pressure within the air storage tank is maintained at an ambient condition, as measured by the water manometer ⑨. The primary air will be entrained into the mixing tube by a momentum-sharing process between the injected gas and the surrounding air. The mixture is distributed uniformly to the multiple port burner 10 with premixed flame.

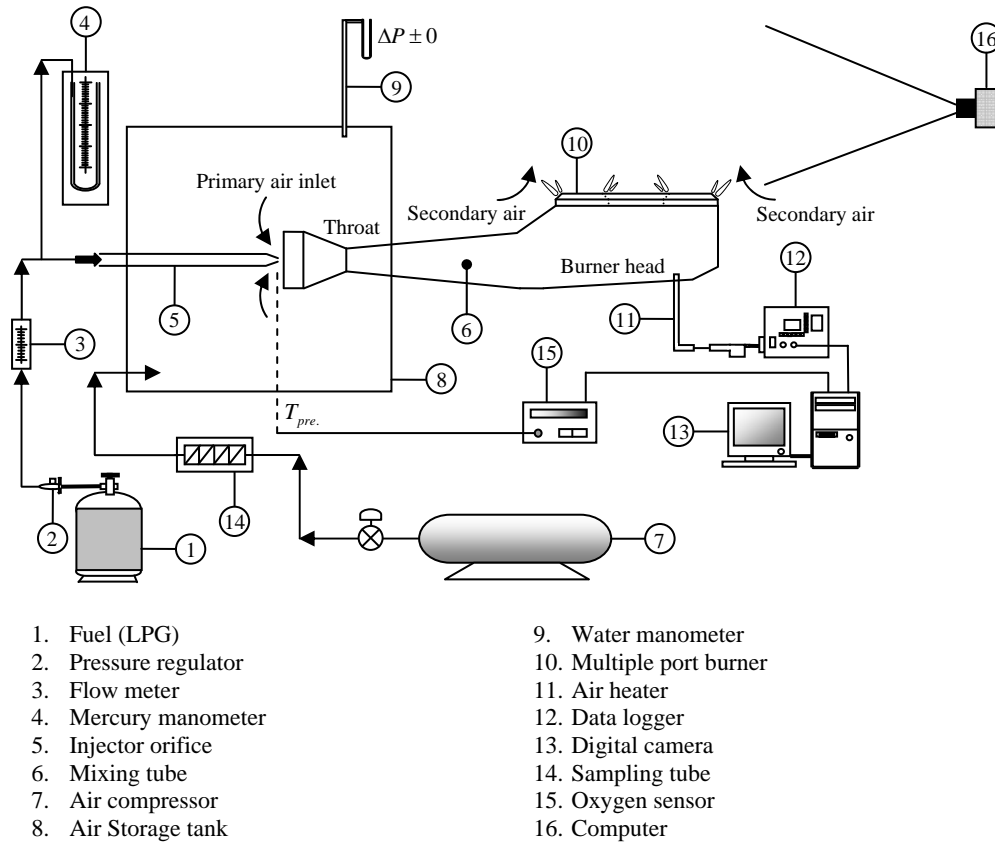


Fig. 2 Schematic diagram of primary aeration experiment

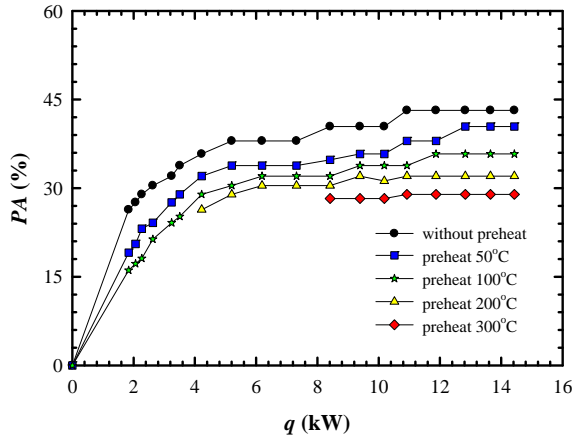


Fig. 3 Typical primary aeration of a self-aspirating burner

Meanwhile, the oxygen concentration in the mixture is measured by using a sampling gas line ⑪, which is located under the burner head, and then carried to the oxygen sensor ⑫ and is displayed by the computer ⑬. The primary aeration can be calculated from the following equation:

$$PA = \frac{\%O_2}{(A/F)_{stoi.} \times (21 - \%O_2)} \times 100 \quad (1)$$

For the preheat case, a similar experiment is performed using the same procedure as described for the without preheat case, but with a preheated primary air. The air heater ⑭ is installed downstream of the air compressor and provided to control preheated primary air temperatures. In this study, four preheated air temperatures ($T_{pre.}$) are selected for the experiments, i.e., 50°C, 100°C, 200°C, and 300°C. These temperatures are performed with N-type thermocouple, which is located at the primary air inlet, and then carried to the data logger ⑮. Meanwhile, the flame images are captured with a digital camera ⑯ to measure the height of the flame.

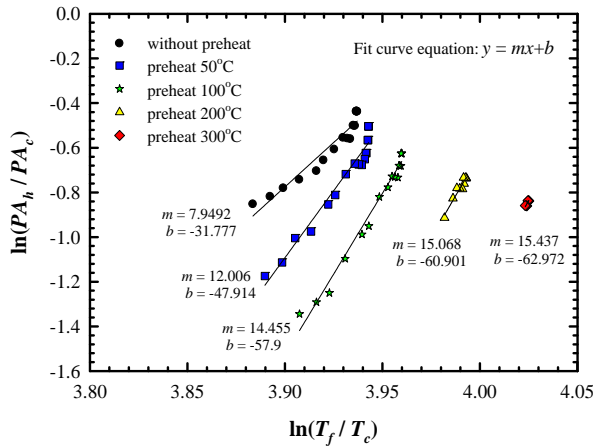


Fig. 4 Linearized plot of dimensionless PA with respect to dimensionless temperature

3. Results and discussion

3.1 Primary aeration and its variation with q

Fig. 3 shows typical primary aeration of a self-aspirating burner for both with and without preheated cases. It is clear that the primary aeration in both cases rapidly increases at the early stage with an increasing heat input (q). After that, the primary aeration is constant and no longer dependent on the heat input, due to limitations of mixing tube and burner port sizes. The primary aeration decreases with an increasing preheated air temperature ($T_{pre.}$).

It is interesting to note that, the preheated air temperature of $T_{pre.} = 300^\circ\text{C}$ gives about a 14 percentage point (33% relative) lower PA value than that of the without preheat case due to the preheating effect causes expansion of the mixture and an increase in its viscosity.

3.2 Correlation for primary aeration (PA)

To the authors' knowledge, earlier studies [6-8] pertaining to models and experiments predicting primary aeration for a self-aspirating burner were conducted only as cold tests (PA_c). Moreover, a preliminary experimental study [11] proposed a first correlation between the hot test and the cold one for primary air entrainment. However, the preheating effect caused by combustion with preheated air was overlooked. In this study, the general models or empirical correlations are revealed which are capable of predicting primary aeration as a function of preheated primary air temperature.

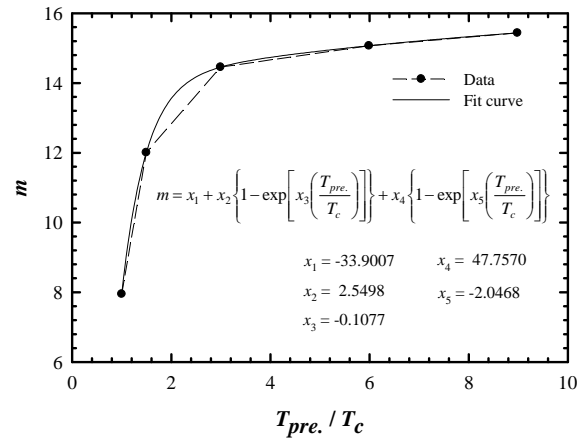


Fig. 5 Variation of the slope (m) with respect to $T_{pre.} / T_c$

The experimental data in the present study were used to develop an empirical expression for the primary aeration PA . The primary aeration for the hot test PA_h can be estimated from the cold test PA_c [11]. But, PA_h must be corrected to account for the effect of the temperature rise of the preheated primary air at the mixing tube inlet. The rising of temperature significantly affects the adiabatic flame temperature. Best-fit empirical correlation for PA_h as a function of PA_c and temperature has been determined and proposed with the formula:

$$PA_h = PA_c \left[\frac{T_f}{T_c} \right]^m e^{\lambda b} \quad (2)$$

where T_f and T_c respectively, are adiabatic flame temperature and ambient temperature.

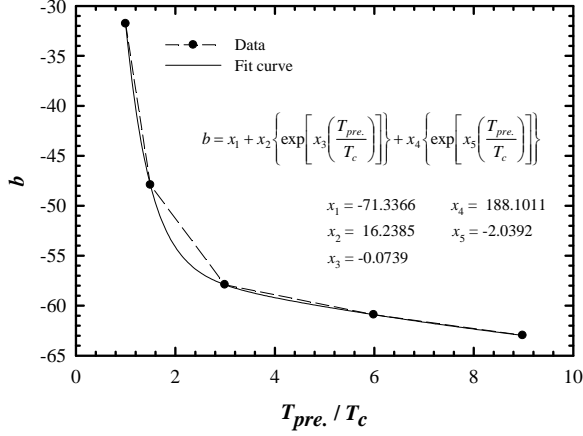


Fig. 6 Variation of the intercept (b) with respect to $T_{pre.} / T_c$

In addition, T_f is the flame temperature based on the primary equivalence ratio of the cold test with the primary air preheated. λ is a stage of completion. $\lambda = 0$ means without combustion, whilst with combustion referring $\lambda = 1$. The variable m and b in equation (2) are slope and intercept, respectively, as shown in Fig. 4. These variables also depend on the preheated primary air temperature and have been determined from Fig. 5 to 6 that can be expressed in the form

$$m = -33.9007 + 2.5498 \left[1 - e^{\left\{ -0.1077 \left(\frac{T_{pre.}}{T_c} \right) \right\}} \right] + 47.7570 \left[1 - e^{\left\{ -2.0468 \left(\frac{T_{pre.}}{T_c} \right) \right\}} \right]$$

$$b = -71.3366 + 16.2385 \left[e^{\left\{ -0.0739 \left(\frac{T_{pre.}}{T_c} \right) \right\}} \right] + 188.1011 \left[e^{\left\{ -2.0392 \left(\frac{T_{pre.}}{T_c} \right) \right\}} \right]$$

where $T_{pre.}$ is the preheated primary air temperature.

This correlation is valid for $30 < T_{pre.} < 300^\circ\text{C}$.

Equation (2) provides the best value in comparison with the experimental results. This is the first correlation obtained from this study. It can be concluded that when the mixing tube dimensions and the type of mixture are specified, the level of primary aeration will depend on the preheated primary air temperature ($T_{pre.}$). Fig. 7

shows a parity plot of PA_h obtained using equation (2) and by experimenting with a surface roughness of the mixing tube of $\mathcal{E} = 0.25$ mm. It was found that the maximum deviation between the correlation and the experiment is within $\pm 10\%$.

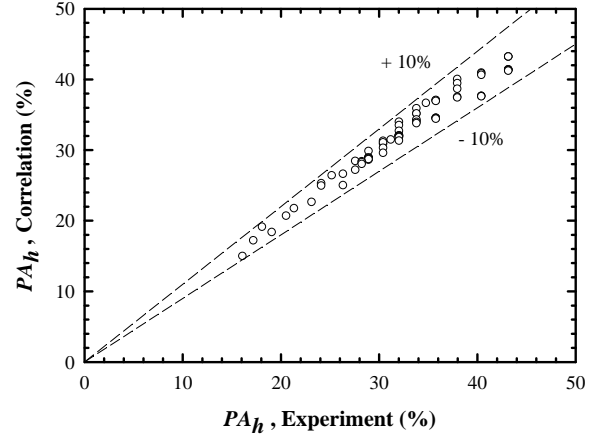


Fig. 7 Parity plot showing comparison between correlation and experimental data

3.3 Correlation for secondary aeration (SA)

The majority of the self-aspirating burners used in domestic LPG appliances are the blue flame. In this burner, the primary air will be entrained into the burner by the flow of a LPG jet through an orifice. The momentum force of this flow cannot normally entrain all the air needed to burn the mixture completely. The rest of the air required, called secondary air, comes from the air surrounding the flame as the mixture burns on the burner ports.

There is no information in the literature about the prediction of secondary air entrainment for a self-aspirating burner. However, previous study has been conducted with the free jets to achieve the desired objectives. Ricou and Spalding [14] presented an experimental technique for measuring the secondary air entrainment in the turbulent free jets. A correlation for secondary air entrainment has been determined and proposed with the formula:

$$\frac{\dot{m}_m + \dot{m}_{sa}}{\dot{m}_m} = 0.32 \left(\frac{\rho_{sa}}{\rho_m} \right)^{0.5} \frac{h_f}{D_p} \quad (3)$$

As shown in equation (3), the mass flow rate of secondary air \dot{m}_{sa} is a function of the mass flow rate of mixture (\dot{m}_m), density of secondary air (ρ_{sa}), density of mixture (ρ_m), flame height (h_f), and diameter of burner port (D_p).

Since $\dot{V}_{sa} = \dot{m}_{sa} / \rho_{sa}$, from equation (3), the volume flow rate of secondary air is given by

$$\dot{V}_{sa} = \frac{\dot{m}_m}{\rho_{sa}} \left[\left(0.32 \left(\frac{\rho_{sa}}{\rho_m} \right)^{0.5} \frac{h_f}{D_p} \right) - 1 \right] \quad (4)$$

As a result, the secondary air entrainment (or secondary aeration) is expressed in the form

$$SA = \frac{\dot{V}_{sa}/\dot{V}_g}{(A/F)_{stoi.}} \times 100 \quad (5)$$

where \dot{V}_g and $(A/F)_{stoi.}$ respectively, are the volume flow rate of gas fuel and stoichiometric air-fuel ratio.

Fig. 8 shows typical secondary aeration of a self-aspirating burner obtained using equation (5). It was found that the levels of SA for both with and without preheat cases increase with heat input q , because of a strong momentum effect caused by the high volume flow rate of the mixture as q increases. At $q < 6$ kW, the effect of higher buoyancy force is that there is more entrained secondary air, thus increasing the levels of SA for the preheat case. However, the higher q increases the effect of momentum force. As a result, the preheat case gives lower SA value than that of the without preheat case at $q > 6$ kW, because the preheating effect causes low primary aeration and a decrease in the momentum force of mixture.

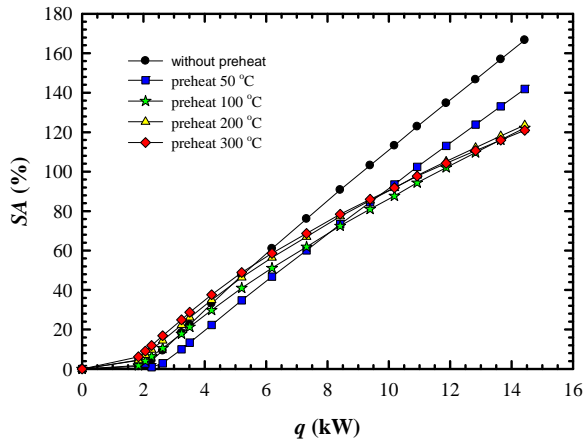


Fig. 8 Typical secondary aeration of a self-aspirating burner

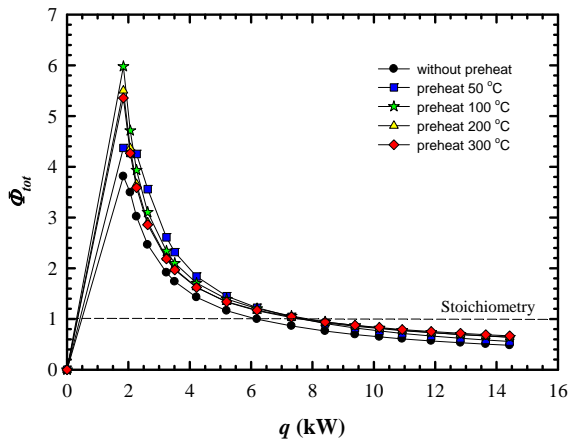


Fig. 9 Typical total equivalence ratio of a self-aspirating burner

3.4 Total equivalence ratio (ϕ_{tot})

The total equivalence ratio is commonly used to indicate quantitatively whether a fuel-oxidizer mixture is rich, lean, or stoichiometric. The total equivalence ratio is defined as

$$\phi_{tot} = \frac{100}{(PA + SA)} \quad (6)$$

In many combustion applications, the total equivalence ratio is the single most important factor in determining a system's performance [15]. Fig. 9 shows typical total equivalence ratio of a self-aspirating burner obtained using equation (6). It was found that the levels of total equivalence ratio are in the range between rich to lean conditions. The rich condition is occurred at lower heat input ($q < 7$ kW) because of the low total air entrainment. At higher heat input, the high momentum jet provides an excess air. Therefore, the total equivalence ratio becomes very low under lean conditions. The optimum operation of this burner occurs at heat input which is indicative of stoichiometric combustion.

4. Conclusions

1. The levels of both PA and SA are increased with increasing q due to the high momentum jet. Moreover, the preheated case gives a lower PA and SA values than that of the without preheat case, because the preheating effect causes expansion of the mixture and an increase in its viscosity.
2. The empirical formula for predicting PA_h in this study is accurate, finding the maximum deviation between the correlation and the experiment to be within $\pm 10\%$.
3. A first correlation for total equivalence ratio of a self-aspirating burner is proposed. The optimum operation of this burner occurs at q which is indicative of stoichiometric combustion.

5. Acknowledgement

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