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Experimental Study on Temperature Distribution and Flame Length in a Narrow Channel Combustion Chamber

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Abstract

Temperature distribution and flame length in narrow channel combustion chamber are significant parameters in the design of narrow channels for safe combustion. Hence, the experimental study on effects of temperature distribution on flame length in narrow channel combustion as presented in this paper. The maximum temperature and flame length, for swirl angles 20°, 30°, 40°, 50° and 60°during combustion were measured respectively, using type K thermocouple and measuring rule. Temperature measurement for radial distance from the centre of the chamber towards the outer surface interacting directly with the environment was also taken for six points. Findings showed the maximum temperatures (930, 1065, 1101, 1139, 1185 and 1221) ^{o}C at flame length of (2100, 1500, 1450, 1200, 1050 and 920) mm for 0, 20, 30 40 50 and 60 degrees swirl angles respectively. As the swirl angle increased, the maximum temperature increased while the flame length decreased. The curve blade swirler aided proper mixing of the fuel and air by generating vortex yielded better combustion efficiency and characteristics in terms of temperature and flame length. Therefore, the relationship between temperature distribution, flame length and swirl cannot be exaggerated in safety. Furthermore, a prediction model equation was developed using the data collected for predicting the flame length for given swirl angle and maximum temperature to determine the possible flame length. The maximum deviation between the actual flame length and the predicted flame length was about 2.6%.

Keywords: *Combustion, temperature distribution, flame extension length, swirl angle, narrow channel, safety*

1. Introduction

In recent years, a large number of catastrophic tunnel fire accidents occurred worldwide, such as Mont-Blanc road tunnel fire, Funicular tunnel fire, Korea Daegu fire [1] which have a great impact on human life and tunnel infrastructure [2, 3]. As is well known, the fire-induced smoke along the tunnel ceiling should be determined to provide adequate fire protection for tunnel structure [4, 5]. Moreover, flame may directly impinge on the ceiling and extends along the tunnel ceiling, which will result in sinking or collapse of the tunnel structure [6]. It is worth noting that, the maximum smoke temperature [7, 8, 9, 5] and flame extension length [10, 6] along the tunnel ceiling are two important characteristic parameters for fire safety research. Also, in the past years, the key parameters of the temperature profile and flame length have been extensively studied under the influence of sidewall fire [11, 12, 13, 14] also observed and analysed the longitudinal temperature decay characteristics along the main tunnel and branch tunnel, they found out that the established correlation of thermal smoke temperature, as well as the flame length model of ceiling jet, can provide some guidance for the layout of the detectors and alarms system. Chen *et al* [15] investigated the maximum temperature under the ceiling with and without a branch tunnel and concluded that the maximum temperature with a branch tunnel is obviously larger than that without a branch tunnel, when the fire source is located in the bifurcated point. Therefore, exist of branch tunnel and sidewall will affect the flame behaviors and smoke movement in the tunnel fires [15, 3, 16]. Furthermore, Tao *et al* [16] investigated the flame extension length under the effect of a wall and a ceiling, a correlation of flame length with HRR and ceiling height was established. The effect of the distance between the carriage and the wall on the flame length was studied by Tang *et al* [6], by conducting a set of small-scale experiments; they however, provided new theoretical models for transverse and longitudinal flame extension length. Though, Vipul and Rupesh [17] reported that the length of flame is an important characteristic, which helps to qualitatively evaluate the effect of air-fuel mixing because the swirl helps to achieve low flame length and comparable emission with that of the non-swirling flame. However, swirling flow has a wide practical applications, this might be due to its attractive features. For example, swirling flows have been used to improve mixing and enhance the drying process in the chemical plants.

Moreover, swirling flames can be found in furnaces and gas turbines where combustion is improved by increasing its stability and reducing pollutant emissions. One of the most important characteristics of swirling flow is the production of an adverse pressure gradient in the direction of the flow. It was reported that the adverse pressure gradient promoted vortex breakdown, leading to the production of a recirculation zone which in turn improved flame stability while maintaining lower levels of emissions [18] and worked as a source of heat and chemical radicals [19]. According to Balakrishnan and Srinivasan [20], the main effect of swirl is to reduce combustion lengths by producing higher rates of entrainment of the ambient fluid and fast mixing close to the exit nozzle and on the boundaries of recirculation zones which also can contribute to flame stability and noise reduction. Moreover, Oyewola *et al*. [21] carried out a research on the temperature decay function of a liquid fuel swirl burner, the results showed that the highest axial temperature of combustion with and without swirler was 1121℃ and 930℃, respectively and the highest radial temperature of combustion with and without was 1130℃ and 942℃, respectively inferring that swirl has great potential to significantly affect the thermal profile of combustion. Furthermore, Oyewola *et al*. [22] investigated thermal characterization of straight and curve edge blade liquid fuel swirl burner, it was shown that 6 blades performed best with the highest temperature in all the ports, while 12 blades gave the least performance. Findings further showed that curve edge blade swirl generator gave better performance than straight edge blade swirl generator with highest temperature of 1065 °C and 1015 °C, respectively, due to the better mixing capability generated by the curve blade swirler [23]. Zhen *et al*. [24] reported the length of the swirling IDF is reduced with the increase of the angle of the vanes of the swirler. The flame length of the swirling IDF is comparable up to Φ=0.4. The effect of swirl on the flame length is considerable only after Φ=0.4. It was observed that the angle of vanes increases from 15° to 45°, the flame length decreases steadily after Φ=0.4. For the swirling IDF, the inner recirculation zone plays an important role in shortening the length of flame.

While, Vipul & Rupesh, [17] investigated flame appearance and emission characteristics of LPG inverse diffusion flame with swirl, they observed that the maximum centerline temperature reached in the swirling IDF is higher than that of the non-swirling IDF. It is seen that the occurrence of the maximum centerline temperature in the swirling IDF is closer to the burner outlet. This can be attributed to the IRZ, which is a characteristic structure of the swirling IDF in which the initial air flow is returned near the burner outlet. This leads to a better mixing between the fuel and air and thus to a rapid combustion with a drastic increase in the centerline temperature distribution. They therefore concluded that swirl helps to achieve low flame length and comparable emission with that of the non-swirling flame.

Furthermore, Fahmy, [25] investigated the combustion characteristic of inverse diffusion flame with elliptic swirls at different aspect ratio as compared with circular swirls. It was found that the elliptic swirls show lower emissions, shorter flame length and higher flame temperatures. Franziska *et al* [26] made a comparison between the turbulent non-premixed inverse oxy-fuel and a corresponding normal flame. The two flames are compared in terms of the local flame structure. Further, differences in the mixing field and especially in the location of turbulent/non-turbulent interface are studied. The IDF exhibited a longer flame than the NDF. The comparison of the NDF and the IDF suggests very similar flame structures. Other trends are taken in researches like mixing different type of fuel or different type of oxidizer. Escudero *et al*. [27] studied the effect of oxygen index (OI) on the flame height, soot volume fraction, soot temperature and radiant fraction. It has inferred that swirl has great potential to significantly affect the thermal profile of liquid fuel swirl burner by enhancing turbulence in the combustion chamber of a burner leading to higher temperature attainable and short flame length [28].

Regardless of the various researches in combustion, flame characterization, temperature distribution in combustion chamber, little has been done to study the temperature distribution and flame length in narrow channel combustion chamber which are significant parameters in the design of safe channel for combustion. In view of these, this study considered the need for an experimental study to investigate the effects of swirl angle and temperature distribution on flame length in a narrow channel combustion chamber.

2. Materials and methods

2.1 Experimental set-up

A locally fabricated liquid fuel swirl burner used for this research consists of a high pressure liquid pump atomizer operating at a pressure about10 bar. A single output centrifugal blower (powered by 2850 rpm, 0.5 hp, 3 phase electric motor) with a 2-inch gate valve for varying the air flow-rate was used. The burner is made of mild steel but the combustion chamber is made from stainless pipe steel type 304 of thickness 4 mm with dimension 108×420 mm per modular section for rigidity, corrosion resistance, heat resistance and probable thermal expansion when fired. It has five modules; each module has a flange machined with projection that exactly fits with the recess on the adjacent module to prevent leakages. The base module has a hinge which was fastened to the burner body by 1 M10-6H bolt and nut. Each module has ports for thermocouple measurement probes. The modular combustion chamber enables the monitoring and evaluation of the flame length and temperature profile. Having taken the following parameters into consideration (rigidity, corrosion resistance, heat resistance, thickness, length and breadth)**,** mild steel curve swirl vanes (2mm by 40mm by 20 mm) at swirl angles 20, 30, 40, 50 and 60 degrees were fabricated and welded to the centre core on a rod whose base has been threaded for fastening to the burner with M10-6H nut. Figure 1 pictorial drawing of the liquid fuel swirl burner (all dimensions in millimetre).

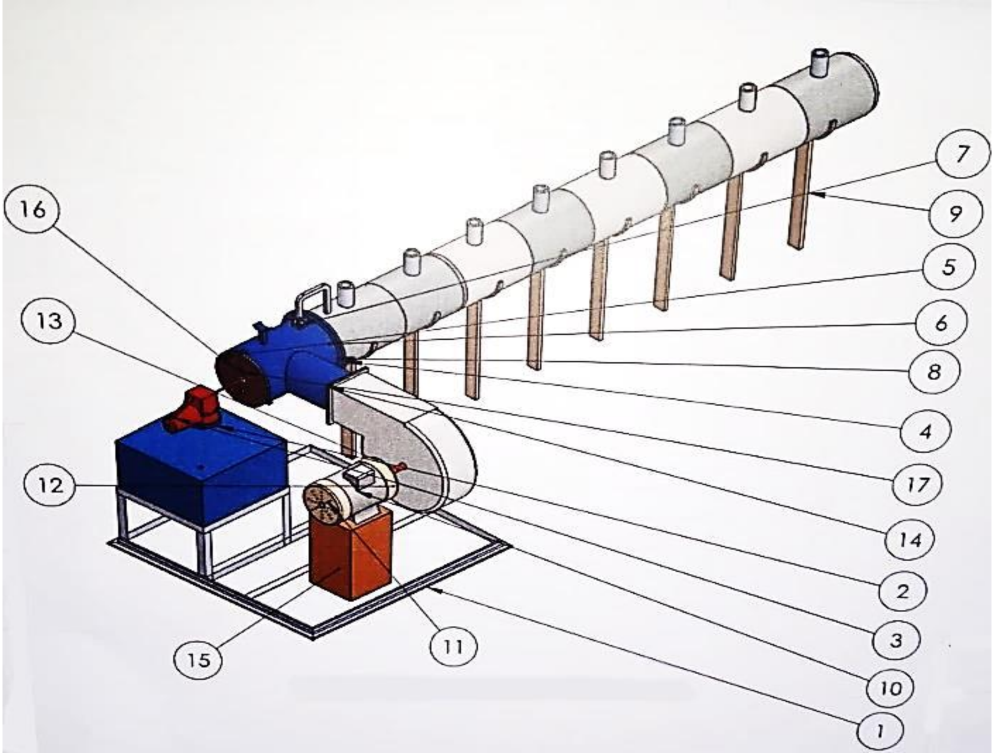

Figure 1 Pictorial view of the swirl burner

Table 1 Description of the parts in Figure 1

Part Number	Part Name	Material	Quantity
1	Base frame	Mild steel	1
2	Fuel tank	Mild steel	1
3	Atomizer	Plastic	1
4	Burner	Mild steel	1
5	Burner rear plate	Mild steel	1
6	Swirl plate	Mild steel	1
7	Pin	Mild steel	1
8	Combustion chamber	Stainless steel	8 modules
9	Combustion chamber stand	Mild steel	1
10	Motor body	Mild steel	1
11	Motor back cover	Mild steel	1
12	Motor front cover	Mild steel	1
13	Shaft	Mild steel	1
14	Blower	Mild steel	1
15	Base block	Mild steel	1
16	Screw	Mild steel	2
17	Nut M10	Mild steel	2

2.2 Operational procedure

With the control switch on, the centrifugal blower was put on first and set at a constant air flow rate, followed by the atomiser to supply diesel at a particular flow rate and fire was introduced in front of the burner for ignition till combustion took place and the first module of the combustion chamber was fixed followed by the rest. Measurements of temperature distribution and axial flame length were made using Type K thermocouple and a rule, for 6 curve edge blade swirl generator at swirl angles of 0^o, 20^o, 30^o, 40^o, 50^o and 60^o for axial port distance 150, 350, 550, 750, 950 and 1150 mm. Temperature measurement for radial distance from the centre of the chamber towards the outer surface interacting directly with the environment was also taken for six points.

3. Results and discussion

The results obtained from the experiments are illustrated graphically and presented as figures 2 and 3. Figure 2 presents the distribution of maximum temperature recorded for the for 6 curve edge blade swirl generator of swirl angles of 0^o, 20^o, 30^o, 40^o, 50^o and 60^o. As shown in the figure, at swirl angles of 0^o, maximum temperature recorded was 930 ^oC with flame length of 2100 mm. Interestingly, the maximum temperature recorded was the minimum when comparing it with the cases of increasing swirl generator angles. More so, the maximum temperature when comparing the angle of the swirl generator, was recorded for the largest angle of 60^o, and his also recorded the minimum flame length of 920 mm. Similar trend was observed in terms of maximum temperature recorded and flame length for each angle of swirl generator. This performance clearly indicates that the angle of swirl generator has effect on the temperature at the axial port of the combustion chamber and the flame length.

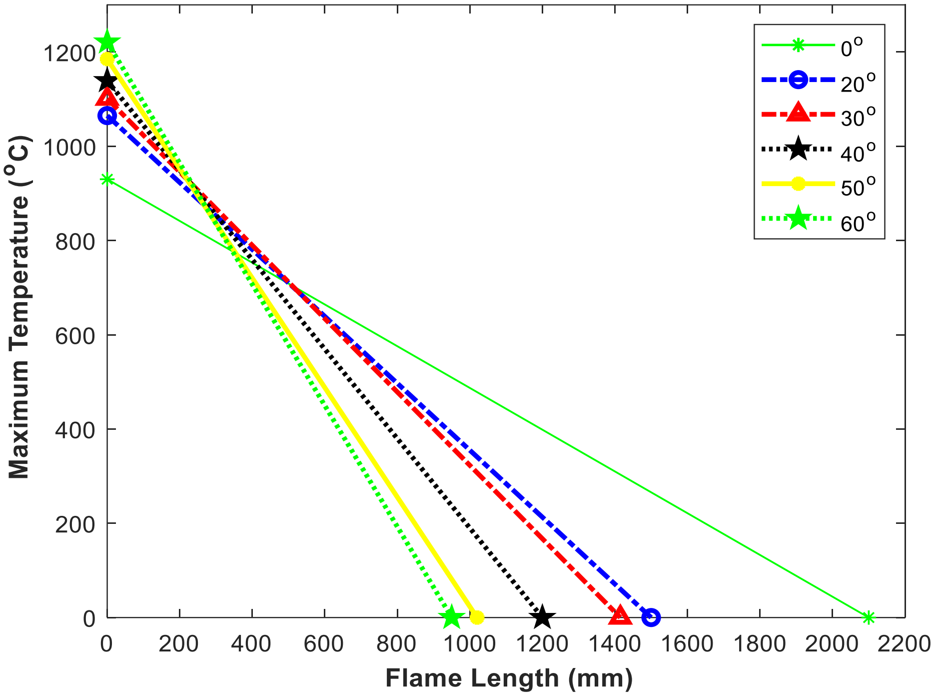

Figure 2 Maximum temperature distribution against flame length

Further observation of the performance trend as in seen in figure 2 shows that the temperature and flame length could be established to have very close or similar values for two or more distinct angle of swirl generator. In view of this, another graphical illustration showing the variation of maximum temperature and flame length with increase in swirl generator angle is presented as figure 3. The figure further displays the variation by indicating the continuous of increase in maximum temperature with increase in swirl generator angle and continuous decrease flame length also with increase in swirl generator angle.

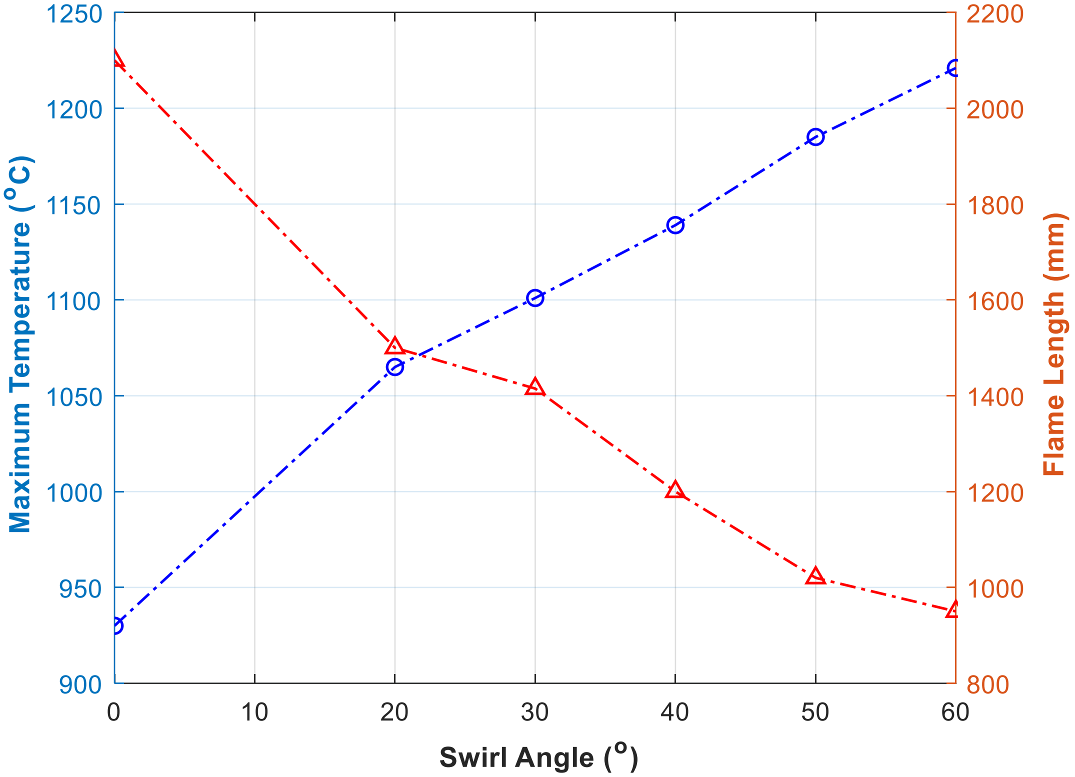

Figure 3 Variation of maximum temperature and Flame length with swirl angle

4. Predictive regression model

A regression equation which serves as a predictive model was developed using the data presented in Table 2 for predicting the flame length given the swirl angle and maximum temperature. The swirl angle, maximum temperature, flame length, predicted flame length and prediction deviation are also presented in Table 2.

Table 2 Shows error deviation between experimental and predicted data

Swirl angle (°)	Maximum Temperature (℃)	Flame Length (mm)	Predicted Flame Length (mm)	Error
0	930	2100	2099.009	0.988353
20	1065	1500	1506.605	6.60796
30	1101	1400	1373.894	26.10267
40	1139	1200	1230.803	30.8063
50	1185	1050	1046.19	3.806302
60	1221	920	913.4796	6.516933

The purpose of the prediction model is to determine the possible flame length for a given swirl angle and maximum temperature. The dependent variable is the flame length, while the independent variables are the swirl angle and maximum temperature. The regression equation was developed using excel and the equation is given as;

$$\gamma = 6925.895 + 5.413647\alpha \ - 5.1902\beta$$

Where: γ is the flame length (mm); α is the swirl angle in (°) and β is the maximum temperature (℃)

Based on the data presented in table 1 it can be said that the predictive model has satisfactory accuracy of predicting the flame length when maximum temperature and flame length is provided. The maximum deviation between the actual flame length and the predicted flame length is 30.81 which represent 2.6% error.

5. Conclusion

An experimental study was conducted in this study to investigate effects of temperature distribution on flame length in narrow channel combustion chamber. The experimental set up is locally fabricated liquid fuel swirl burner with a high pressure liquid pump atomizer operating at a pressure about10 bar. A single output centrifugal blower with a 2-inch gate valve for varying the air flow-rate was used. The modular combustion chamber enables the monitoring and evaluation of the flame length and temperature profile. Findings from the study revealed that as the angle of swirl increases, the maximum combustion temperature increased and the flame length decreased, this may be due to the inner recirculation zone created by the swirl which played an important role factor in reducing the length of flame. This is an indication that proper mixing of the fuel and air by the vortex generated by curve blade swirler for better combustion has a great influence on combustion efficiency and characteristics, especially temperature and flame length of a liquid fuel swirl burner. In addition, a prediction model equation was developed using the data collected for predicting the flame length for given swirl angle and maximum temperature to determine the possible flame length. The maximum deviation error between the actual flame length and the predicted flame length was about 2.6%.

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