AN EXPERIMENTAL STUDY ON THE EFFECTS OF SWIRLING OXIDIZER FLOW AND DIAMETER OF FUEL NOZZLE ON BEHAVIOUR AND LIGHT EMITTANCE OF PROPANE-OXYGEN NON-PREMIXED FLAME

By

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In this study, the stability and the light emittance of non-premixed propane-oxygen flames have been experimentally evaluated with respect to swirling oxidizer flow and variations in fuel nozzle diameter. Hence, three types of the vanes with the swirl angles of 30°, 45° and 60° have been chosen for producing the desired swirling flows. The main aims of this study are to determine the flame behavior, light emittance, and also considering the effect of variation in fuel nozzle diameter on combustion phenomena such as flame length, flame shape, and soot free length parameter. The investigation into the flame phenomenology was comprised of variations of the oxidizer and fuel flow velocities (respective Reynolds numbers) and the fuel nozzle diameter. The results showed that the swirl effect could change the flame luminosity and this way could reduce or increase the maximum value of the flame light emittance in the combustion zone. Therefore, investigation into the flame light emittance can give a good clue for studying the mixing quality of reactants, the flame phenomenology (blue flame or sooty flame, localized extinction), and the combustion intensity in non-premixed flames.

Keywords: *Swirl effect, Propane, Oxygen, fuel nozzle, non-premixed flame, light emittance*

1. Introduction

According to the effect of swirling flows on increasing the flame stability, applying the swirling flow to the commercial combustion systems has been attractive for many years. Nowadays, the concept of swirling flow as a flame stabilization method has been extensively using in the power plants, refinery

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burners and also internal combustion engines. The effects of this type of flame stabilization methods on improving the flame stability in premixed and non-premixed combustion systems have been perfectly recognized [1, 2]. The behavior of this type of flows can usually be described by using Reynolds number and a dimensionless number known as the swirl number (SN). The swirl number is defined as a ratio between the axial flux of swirling momentum to the axial flux of axial momentum [3, 4]. In this regard, Beer and Chigier [5] divided the swirling flows into two main groups of low ($SN<0.6$) and high swirling flows. Under such flows, the relation between the quantity of radial velocity component and the quantity of mean axial velocity depends on the swirl number. Therefore, increasing the swirl intensity increases the quantity of radial component of the velocity. For high swirl numbers, the reverse flow can be created due to the presence of reverse pressure difference in the axial direction. The reverse flow is one of the factors which can stabilize flame by creating a central recirculation zone.

In this regard, Al-Abdeli and Masri [1, 2] and Gupta et al. [6] conducted extensive studies on the swirling flows. They showed that the flame stability and length was increased and decreased respectively by creating recirculation zones in the combustion chamber. Also, they maintained that creating the recirculation zones in the combustion chamber could intensify the mixing process of the flows, especially in the shear layer zone. Moreover, the effect of swirl number on increasing the flame stability was studied by Feikema et al. [7]. They showed that compared to non-swirling flows, the swirl of flow can dramatically increase flame stability (based on maximum fuel velocity). In another research, Kerr et al. [8] showed that imposing the swirl caused decreasing effect on the axial velocity. Thus, the flame front approached the head of burner and this way increased the flame stability. Also, Mathur et al. [9] investigated the stability of diffusion flames subject to various swirl intensities. They maintained that a strong enough swirling flow could create a central recirculation zone at the center of combustion chamber, so that this zone was proportional to the diameter of combustion chamber. Moreover, the effect of various swirling flows on the efficiency of a combustion chamber and air pollutant emissions were studied by Buckley et al. [10]. They asserted that applying the swirling flow concept could reduce NO_x and CO emissions and simultaneously increase the combustion efficiency. Also, the simultaneous effects of swirling air and fuel on the stability limits of non-premixed propane and hydrogen flames were studied by Yuasa et al. [11]. They observed that the results of low swirl cases were very similar to the results of no swirl cases. In spite of this similarity, for higher swirl cases and similar to the previous works, the flame stability limits increased due to creating the recirculation zone near the fuel nozzle outlet. Also, they showed that simultaneous usage of the swirling air and fuel flows could increase the flame stability more than just the swirling air case.

During the last decades, various methods, such as visual, laser base, and electrical methods, have been developed for investigating the behavior of reactive flows [12, 13]. Due to this fact that a flame is a luminous object, it can be evaluated using visual methods and techniques. For instance, Brisley et al. [14] decomposed the flame luminosity using a camera and a proper filter. Also, Gilabert et al. [15] captured images of flames using three cameras.

In the laser-based methods, the distribution and phenomenology of radical species in combustion field can be investigated. Mohamad et al. [16] showed the distribution of radical species in a gaseous flame using a light source of laser.

Moreover, in the electrical methods, the flame characteristics can be determined using the intrinsic properties of some electrical devices, such as capacitor, impedance, and resistor. For instance, Rahim et al. [17] could determine the general distribution of a flame using electrical capacitor.

Furthermore, the light emittance (Lux) is a parameter which has already been using for various applications and targets such as the lighting system design and professional preparation of a place for scientific and commercial imaging. In all applications of this parameter, the main target is to compare between the available conditions and the reference condition which is acceptable for user. Depending on the various conditions, the illuminance of a certain place can be different. This parameter and the related devices can play an important role for detecting small changes in the illuminance due to user's inability to detect the small variations in light emittance visually [15, 18, and 19].

Therefore, in addition to the measurement methods mentioned above, the light emittance index can be introduced as a criterion for determining the combustion and flame zones. The active zones in combustion field are brighter than the other zones due to presence of the active radicals in the main flame zone and consequently their respective chemiluminescence signals. In photometry, light emittance is defined as the luminous flux per unit area emitted from an object. This parameter can be converted to a quantitative factor using measurement devices such as lux-meter.

According to the literature reviewed above, it can be concluded that there is not clear and convincing evidence in the literature about applying the light emittance index (Lux) as a diagnostic parameter for studying the flame characteristics. Therefore, according to the earlier works e.g. [20], one of the main targets of this study is focused on presenting practical and low cost method for detecting the flame behavior under various conditions. Thus, in the present study an experimental test bench has been developed for investigating various effects of the swirling oxygen flow and the diameter of fuel nozzle on the stability and light emittance of propane-oxygen flame. In this regard, some characteristics of the flame such as the mixing quality of propane-oxygen, the effect of the swirling flow level on the flame stability, and the illuminance of swirling flames were studied by introducing the light emittance index (Lux) as a parameter for considering the combustion phenomena.

2. Experimental setup and method

As shown in fig. 1, a non-premixed swirl burner was developed to investigate the effect of swirling flow on combustion phenomena [3]. In this burner, the swirling oxygen and non-swirling fuel as coaxial flows were entered into the combustion chamber. The gaseous fuel was injected into the combustion chamber via a fuel nozzle located at the center of the burner. The required oxygen was delivered to the combustion chamber axially after passing through the swirler vanes (fig. 1, down) located around the fuel nozzle. As seen in figs. 1 and 2, a metallic cylinder which its frontal section was replaced with Pyrex glasses was used for viewing the flame inside the combustion chamber. Moreover, this configuration could prevent the surrounding air from taking part in the combustion process. The inner diameter and length of metallic cylinder were 13 and 90 cm, respectively. The inlet oxygen into the combustion chamber was rotated by the swirler vanes with the swirl angles of 30°, 45° and 60°. A schematic view of the applied swirl burner with its details is shown in figs. 1 and 2. A similar swirl burner was previously used by Rowhani and Tabejamaat [3]. In order to study the effect of variation of the fuel nozzle diameter on the combustion process and the flame behavior, the inner diameter of fuel nozzles were chosen 1, 1.5 and 3 mm. Furthermore, as known, the Oxy-fuel combustion has been proposed as a remedy for increasing the flame temperature, combustion efficiency and, simultaneously, significant reduction in NO_x emission as compared to conventional air-fuel combustion [21]. This technique has been extensively using as an efficient method in some metal melting and high temperature processes. Therefore, pure propane and oxygen (99.99%) (Which they were reserved in high pressure tanks) were used in order to provide the required fuel and oxidizer. Here, it should be noted that based on the conducted measurements, the fuel and oxidizer temperature at the fuel nozzle and the swirler outlet was 25 °C. This was due to this fact that the consumed fuel and oxidizer were small as compared to the amount of reserved gases in the tanks. The flow rates of fuel and oxidizer were measured by rotameters (with an accuracy of ±3% in full capacity).These rotameters were installed on the measurement board which controlled the swirl burner. The flame pictures were recorded by a digital camera (Canon Power Shot G6). During the experiments, the temperature of the laboratory was 25 °C.

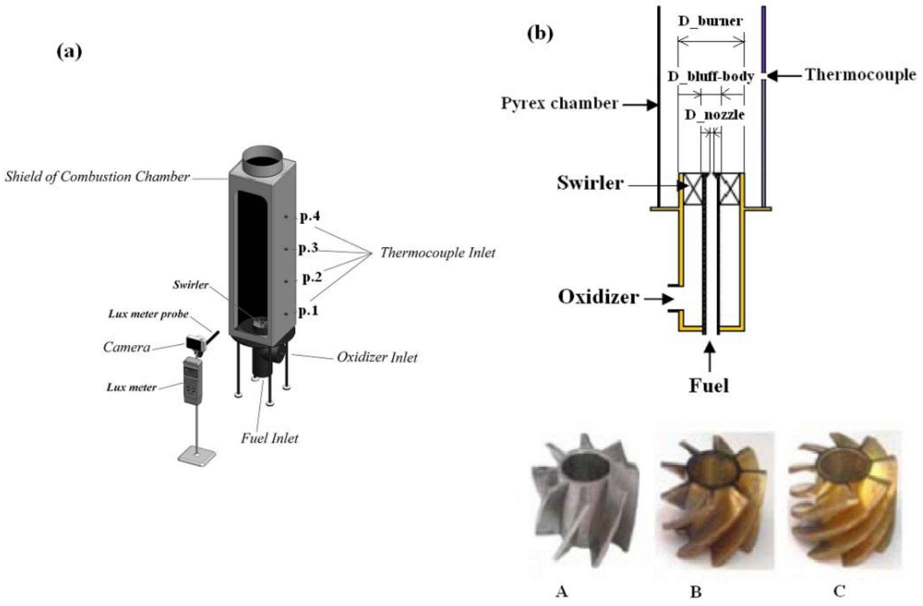


Figure 1. (a) A schematic view of the applied burner with the related swirler vanes (b) (A: 30^0, B: 45^0 and C: 60^0) (D_{nozzle} and $D_{bluff\ body}$ are the fuel nozzle and the bluff-body diameters, respectively)

To evaluate the swirling effect on the variation of flame luminosity, a digital luxmeter (Lutron YK-10LX) was applied. Also, for increasing the accuracy, all the tests were conducted at the room temperature of 25 ^{0}C. Moreover, the Sensor of the luxmeter was located 1.5 m away from the flame. This sensor was isolated from the ambient lights by a tube with 11.5 cm in length and 2.5 cm in diameter. Furthermore, a Testo 350 XL gas analyzer was applied for analyzing the exhaust gas compositions and measuring the flue gas temperature at the end of the combustion chamber. In this regard, the probe of the gas analyzer was mounted at the center of the outlet of the combustion chamber. Also, for determining the temperature at various locations along the chamber axis, one B-type (the maximum operating temperature 1700 °C) and three K-type thermocouples (the maximum operating temperature 1260 °C) were used. As seen in fig.1 a, four locations (p.1 to p.4) were provided for measuring the temperature along the axis of the chamber. The first measuring location (p.1) was located 15 cm away from the fuel nozzle. Also, the measuring locations (p.1 to p.4) were spaced apart 15 cm the longitudinal direction of the combustion chamber in order to cover the possible influences of variations in the swirl angle, the flow rate, and the equivalence ratio. According to the expected temperature distribution along the chamber axis, the B-type thermocouple was located in p.1 port (with the highest temperature level along the flame) and the other thermocouples were located in p.2 to p.4 ports, respectively. Here, it should be mentioned that the tips of all thermocouples were located at the center of the combustion chamber. All the measurement instruments including the luxmeter, the gas analyzer, and the thermocouples were calibrated before conducting the experiments.

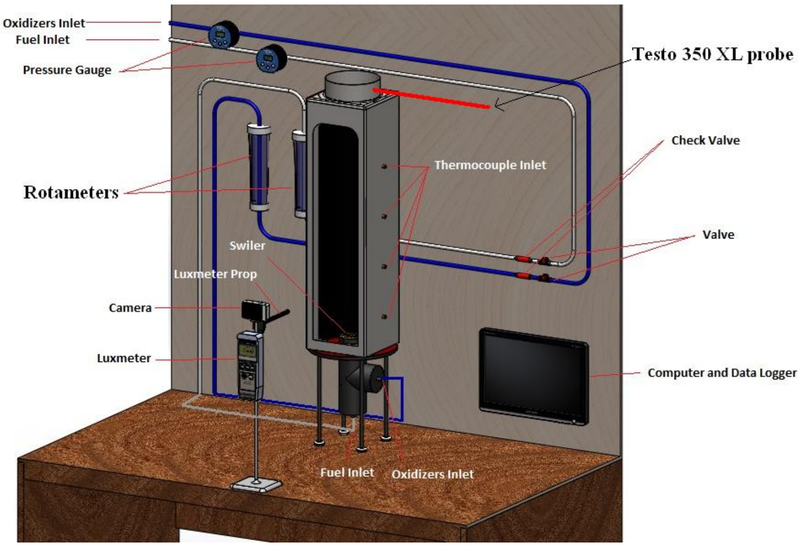


Figure 2. A view of the applied test bench with the instruments on the fuel and oxidizer lines

2.1. Calculation of the swirl number

For a swirler vane with inner diameter of d_i and outer diameter of d_o, the swirl number can be calculated as follows [4, 5]:

$$SN = \frac{2}{3}\tan(\theta)\left(\frac{1-\left(\frac{d_i}{d_o}\right)^2}{1+\left(\frac{d_i}{d_o}\right)^2}\right) \tag{1}$$

Where, d_i, d_o, SN and θ are the internal diameter of the vane (mm), the external diameter of the vane (mm), the swirl number, and the vane angle, respectively. According to the above equation, the swirl number can be determined just by knowing the geometrical variables of the vane such as inner and outer diameters and the vane angle. Therefore, the calculated swirl number is called as the geometric swirl number [5]. In this study, regarding eq. (1), the calculated swirl numbers for the vanes with swirl angles of 30°, 45° and 60° are 0.46, 0.8 and 1.41, respectively.

3. Results and discussion

The results of this study are presented in three sections. At the first, the effects of the swirling oxidizer flow and also the fuel nozzle diameter on the combustion process and the flame stability in the combustion chamber are considered. Then, the effects of these parameters on the flame light emittance index and the soot free length fraction are investigated. The soot free length fraction (SFLF) is defined as a ratio between the visible premixing length and the visible flame length [22].

3.1 Phenomenology of swirling flames

To investigate the effect of variation of the fuel nozzle diameter on the combustion characteristics, three different diameters of the fuel nozzles were chosen individually for every swirler. The results for various fuel nozzles at equal swirl angle and fuel flow rate (Reynolds number) are pictured in fig. 3. According to fig. 3, decreasing the fuel nozzle diameter can shorten the flame length and increase its integrity against the fluctuations in the combustion field. Moreover, as shown in fig. 4, the flame can be stabilized at a restricted range of equivalence ratio by decreasing the fuel nozzle diameter. However, the flame is established within the more extended and higher range of velocities. Thus, it can be seen in fig. 5 that although decreasing the fuel nozzle diameter restricts the range of equivalence ratios for stable flame, the optimum condition for the flame stabilization occurs in the fuel nozzle with 1.5 mm in diameter. In this diameter, the flame can be stabilized in an acceptable range of equivalence ratios and higher velocities (Reynolds numbers).

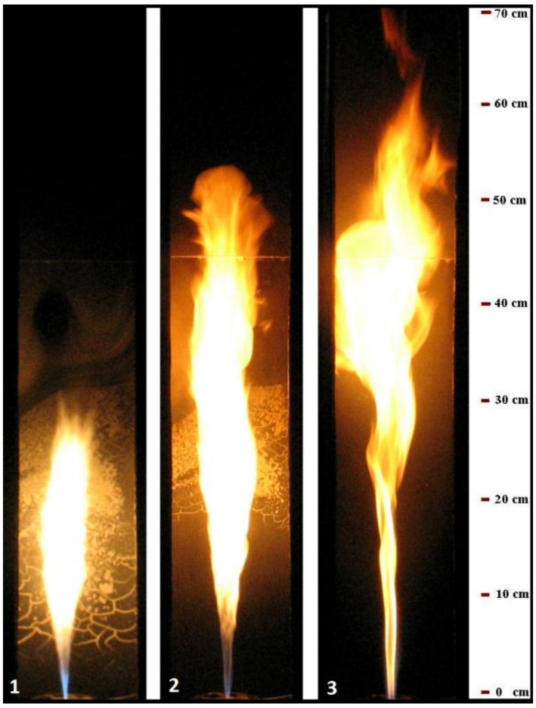


Figure 3. Swirling propane-oxygen flame with the swirl angle of 60°. Oxygen flow rate: 15 lit/min, Propane flow rate: 4 lit/min; the fuel nozzle diameters; 1: 1 mm, 2: 1.5 mm, 3: 3 mm

This shows that there are optimum values for the diameter ratio, fuel velocity and swirling angle in which the flame can be stabilized in an extended range of equivalence ratios and velocities. Also, it is seen that decreasing the fuel nozzle diameter at a constant fuel flow rate can dramatically shorten the flame length. One of the main reasons for occurrence of this phenomenon can be related to increasing the flow turbulence and consequently better mixing between the fuel and oxidizer flows. For a fuel nozzle with 1 mm in diameter, the effect of turbulence is certainly more intense than the other fuel nozzles. The occurrence of the phenomenon may be due to constant Reynolds number in all three fuel nozzles, lower diametrical ratio $\left(\frac{D_{nozzle}}{D_{Bluff-body}}\right)$ and also increasing the spatial rim $\left(D_{Bluff-body}-D_{nozzle}\right)$ for establishing toroidal vortices around the fuel nozzle. On the other hand, keeping a constant Reynolds number for a fuel nozzle with lower diameter occurs at lower flow rates (lower equivalence ratios). This also causes that the flame length decreases more than ever. However, for establishing a constant Reynolds number in a fuel nozzle with 3mm in diameter, the more flow rate (higher equivalence ratio) is needed. Thus, by increasing the flow rate, creating a stable flame needs a longer distance from the fuel nozzle. This longer distance is due to this fact that the higher fuel flow rates need the longer time for diffusion in the oxidizer and consequently the flame zone.

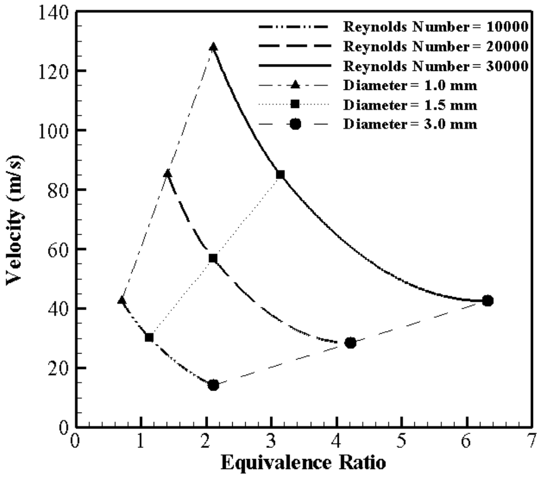


Figure 4. The variation of the average velocity and the equivalence ratio versus variation of the fuel nozzle diameter at the constant Reynolds numbers

3.2 Light emittanceindex

In the following, the results are divided into two sections of the low swirl (swirl angle of 30°) and high swirl combustion (swirl angles of 45° and 60°). Measuring the light emittance from the flame for each swirler was performed at a constant mixing ratio and repeated for five times at least (fig. 6).

As seen in fig. 6, in the case of swirl angle of 60°, it seems that the flame distribution is smoother than those which are related to the swirl angles of 30° and 45°. This may be due to better mixing between the fuel and oxidizer (which can be justifiable just by considering the effect of swirler vanes). Also, as seen in fig. 6, it is of interest to note that variations in the results (the smaller error bars) in the case of swirl angle of 60° are much smaller than those in the cases of the swirl angles of 30° and 45°. This may also be related to the mixing quality of the swirl angle of 60°, which is higher than the two other swirl angles. Therefore, in this case, more uniformity and smaller fluctuations in the combustion field are expected (fig. 7(c)). Moreover, it is seen that discrepancy in the light emittance is increased by decreasing the swirl number. It may be due to this fact that reducing the swirl number (swirl angle) can impair the mixing quality. In fact, most part of the flame luminosity is attributed to the solidified particles (especially soot particles) in the combustion zone. Therefore, as shown in fig. 6, it can be inferred that increasing the swirl angle (the swirl number) can reduce the distribution of light emittance parameter throughout the flame and combustion zone. This may be achieved by improving the mixing quality between the fuel and the oxidizer, increasing the turbulence level, and consequently decreasing generation of soot particles.

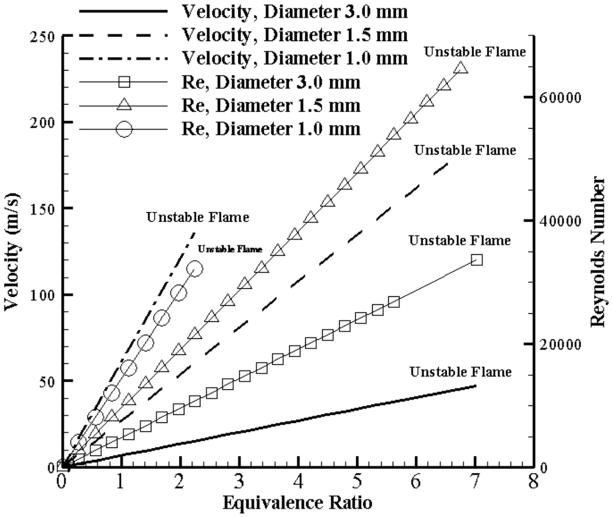


Figure 5.Stability graph of propane-oxygen flame as velocity/Reynolds number versus equivalence ratio for three different fuel nozzle diameters. Unstable flame refers to global blow-out.

Furthermore, it is seen in fig. 6 that for the distances more than 20 cm from the fuel nozzle, the light emittance index is the same for both of the swirl angles of 45° and 60°. However, for the distances under 20 cm from the fuel nozzle, these two graphs are not coincident with each other. This may be due to the fact that a swirler vane with swirl angle of 60° can mix fuel and oxidizer much better than a swirler vane with swirl angle of 45°. Therefore, the light emittance index decreases in the lower zones of the flame, especially near the flame root. As seen in fig. 6, at the swirl angle of 60°, the maximum emitted light from the flame decreases and spreads over the flame zone because of increasing mixing of the fuel with the oxidizer. In the case of low swirl combustion, the maximum emitted light from the flame is higher than the two other swirlers (high swirl combustion cases). This is because of this fact that the mixing process between the fuel and the oxidizer is disturbed due to low swirl motion induced to the flow by the low swirl vane. Consequently, the disparity in the emitted light from the flame in various locations inside the combustion field increases dramatically. Furthermore, for the low swirl vane case, the emitted light from the lower sections of the flame root is lower than that in the high swirl vane cases. This may be related to inability of the swirler vane with swirl angle of 30° to induce a proper rotation in the root section of the flame which is located near the fuel nozzle exit. This can retard the diffusion of the fuel into the oxidizer and, this way, elongate the diffusion length. Therefore, the flame light emittance index (Lux) decreases extensively by increasing the diffusion length.

Moreover, variations in CO and C_xH_y concentrations and also the flue gas temperature for different swirl angles are shown in fig. 7a and b. Here, it should be noticed that C_xH_y is an emission formed through incomplete combustion of hydrocarbon fuels. It is seen that increasing the swirl angle from 30° to 45° increases CO and C_xH_y concentrations. On the contrary, it can be observed that increasing the swirl angle from 45° to 60° decreases CO and C_xH_y concentrations at the exhaust of the chamber. Furthermore, according to fig. 7b and c, increasing the swirl angle from 30° to 45° decreases the flue gas temperature. Also, it can be seen that increasing the swirl angle from 45° to 60° can increase the flue gas temperature to a value more than the two other swirl angles (30° and 45°).

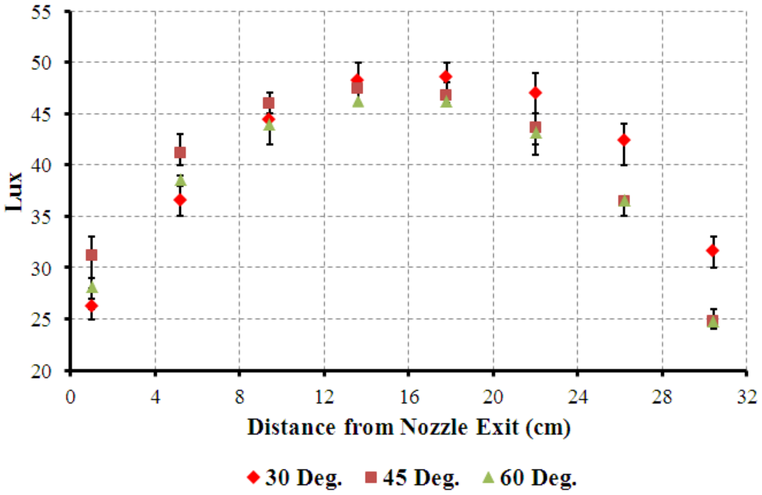


Figure 6. The variations of the average of luminous emittance at a constant equivalence ratio for three different swirlers versus vertical distance from the fuel nozzle exit

Moreover, by measuring the temperature at the specified locations depicted in figs. 1 and 2, it can be shown that increasing the swirl number from 30° to 60° can reduce the temperature distribution level along the chamber axis (fig. 7(c)). Hence, according to fig. 6, it can be inferred that the flame light emittance index (Lux) is directly dependent on the temperature field inside the combustion chamber. Therefore, it can be concluded that increasing the swirl angle from 30° to 60° can significantly influence the combustion process in the combustion chamber. On the whole, it can be maintained that the swirl angle of 60° shows better performance in comparison with the two other swirl angles.

3.3 Soot free length fraction parameter

Based on the definition (fig. 8(a)), increasing SFLF can occur due to extension of the blue combustion zone in the combustion field. By extending the blue combustion zone, it can be inferred that the combustion quality (e.g. the environmental pollution) and efficiency (e.g. fuel saving) are better than before.

As seen in fig. 8(b,c), decreasing the fuel nozzle diameter and increasing the swirl angle have increasing effect on SFLF parameter. This means that increasing the swirl angle and also decreasing the fuel nozzle diameter can improve the combustion by intensifying the mixing process between the fuel and oxidizer. In fact, decreasing the fuel nozzle diameter and increasing the swirl number parameter (by increasing the swirl angle) increase the rim spatial distance $\left(D_{Bluff-body} - D_{nozzle}\right)$ and also intensify vortex breakdown, respectively. These two parameters can strengthen formation of the toroidal vortices which are shaped around the fuel nozzle exit. Also, as seen in fig. 8c, although decreasing the fuel nozzle diameter can extend the flame SFLF parameter, it may destabilize the flame at the high equivalence ratios.

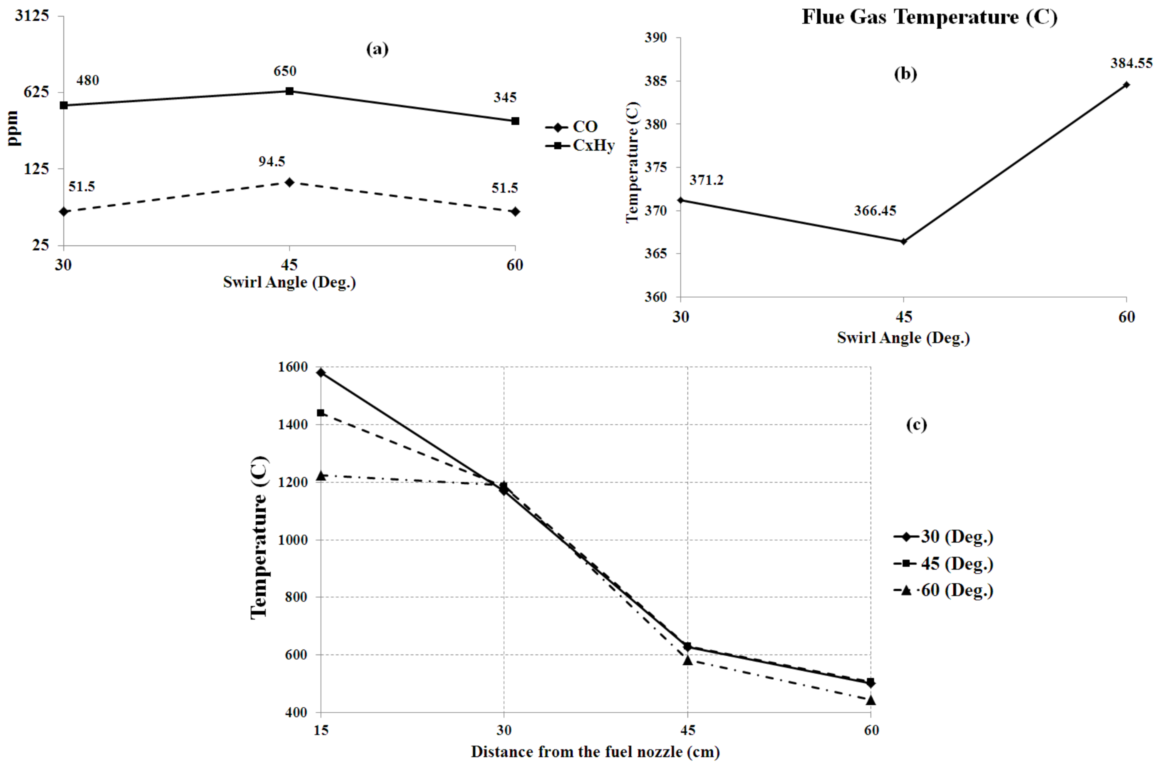
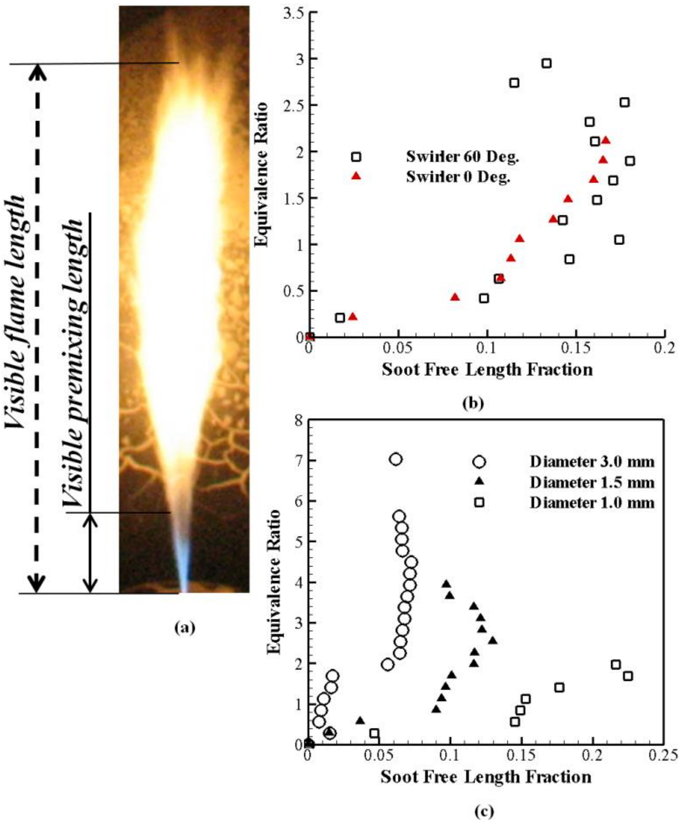


Figure 7. (a) Variations of CO and C_xH_y versus swirl angle (degree) (b) Variations of flue gas temperature versus swirl angle (degree) (c) Temperature distribution inside the combustion chamber for three swirl angles of 30°, 45°, and 60° (Oxygen flow rate: 19 SLM and Propane flow rate: 3.5 SLM)

4. Conclusion

In this study, the behavior of propane-oxygen flame subject to the swirling oxygen flow was experimentally investigated. It was tried to use an easy method to evaluate the combustion quality by quantifying the light emittance characteristics (Lux) of the flames (luminosity). Also, the results were verified by measuring CO and C_xH_y emission levels at the exhaust and temperature distribution along the chamber axis. In this method, the light emittance index (Lux) was introduced as a criterion to detect the various flame zones.

Meanwhile, it was shown that for the high swirl levels, decreasing the fuel nozzle diameter could decrease the flame length. Thus, it was mentioned that although decreasing the fuel nozzle diameter restricted the range of equivalence ratios for stable flame, the optimum condition for flame stabilization occurred at a fuel nozzle with optimum diameter. At this diameter, the flame could be stable in an acceptable range of equivalence ratios and higher Reynolds numbers. Moreover, it was shown that the light emittance index (Lux) can be counted as a parameter to evaluate the mixing process and the flame characteristics in combustion systems. In general, it was found that increasing the swirl of the oxidizer flow and decreasing the fuel nozzle diameter increased the flame stability.



(a)

(b)

(c)

Figure 8.(a) Visual definition of Soot Free Length Fraction (b) Two different swirling angles (the fuel nozzle diameter 1 mm and oxygen flow rate 19.048 SLM) (c) Variations of soot free length fraction versus equivalence ratio for three different fuel nozzle diameters (swirl angle 60° and oxygen flow rate 14.286 SLM)

Moreover, the swirl effect could influence the flame temperature. It was shown that the variation in the flame temperature could change the flame luminosity. Thus, it could affect the maximum value of the emitted light from the flame in the combustion zone. Furthermore, the results showed that increasing the swirl number at the constant oxygen and fuel flow rates and also constant fuel nozzle diameter could reduce the flame light emittance index (Lux). Hence, it was shown that reduction in the flame light emittance index (Lux) was in a direct relation with reduction in the temperature and also the exhaust emission levels. Therefore, investigation of the flame light emittance index (Lux) could give a good clue for studying the quality of reactants mixing, flame phenomenology (such as burning quality (blue flame or sooty flame), localized extinction and so forth), and combustion intensity in non-premixed flames. Moreover, the soot free length fraction (SFLF) as a useful parameter could properly describe the mixing and combustion processes. On the whole, the results showed that increasing the swirl angle and decreasing the fuel nozzle diameter could increase SFLF.

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