AN EXPERIMENTAL STUDY OF THE STABILITY OF NATURAL GAS AND PROPANE TURBULENT NON-PREMIXED FLAME UNDER DILUTING CONDITION

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The stability behavior of a jet diffusion flame developing in a co-flowing stream is studied experimentally, using natural gas and propane as fuel gases. Effects of oxidant and fuel stream velocities and oxidant stream dilution have been studied. The results of experiments showed that with increasing fuel jet Reynolds number, there appears along the flame a point that is accompanied by reaction zone sudden expansion. Flame becomes turbulent downstream from this point. This point is called transition point. More increment of fuel jet Reynolds number moves the transition point to the upstream. Furthermore, two types of stability limits are observed. Blow-off of the rim-stabilized flame is the first stability limit. The second one is the break-off or extinction of the turbulent portion of the flame at the transition point from laminar to turbulent flow. The oxidant and fuel streams are in environmental temperature. In dilution experiments, the oxidant primary stream is oxygen that is diluted with nitrogen or carbon dioxide. In the other experiments oxidant is environmental air.

Key words: *Experimental, Stability, Turbulent, non-premixed flame, Diluting*

1. Introduction

Researching the fuel jet turbulent non-premixed flame is one of the most important and interesting topics from the viewpoint of fundamental and practical researches. In particular, the structure and stabilization of turbulent non-premixed flames have been studied by many researchers. Takeno et al. [1-4] studied natural gas and hydrogen turbulent flames in a high co-flowing air temperature. They compared un-ignited cold jets with flame jets and concluded that the flame presence delays transition. It was ascribed to heat release in reacting jets. Furthermore, extinction of the turbulent portion of flame at the transition point was observed by increasing rim stability through preheating air. This type of stability limit is attributed to the finite rate chemistry of turbulent non-premixed flames. A further experimental study was conducted on the stability of an excess enthalpy flame [5]. They reported that the flame stability limits decreases depending on the rate of mixture ratio. In addition, they found that heat recirculation plays a pivotal role in the flame stabilization. Based on experimental findings, Chih-Yung Wu *et al.* [6] proposed a blow out mechanism for turbulent jet non-premixed flames. They suggested that the point where the radial distance between the elliptic stoichiometric contour and the jet axis reaches a maximum value, can be regarded as the dividing point separating the unstable and stable regions for the lifted flame in the blowout process. The effects of buoyancy on the characteristics of turbulent non-premixed flames were the subject of an experimental study that was performed by Idicheria *et al.* [7]. They observed that the high-Reynolds-number flames have the same flame length irrespective of the gravity level. Experimental results obtained by Pires *et al.* [8] showed that turbulent heat fluxes tend to be restricted to the mixing layer where the large temperature gradients occur. Mungal *et al.* [9] compared reacting and non-reacting jets and reported that heat release in reacting jets narrows the jet width up to 20% and reduces the turbulence intensities up to 40%. Yamashita *et al.* [10] numerical study indicated that the turbulent non-premixed flame structure is an ensemble of instantaneous local premixed, non-premixed and partially premixed flames. A recent DNS simulation of turbulent hydrogen lifted flames indicated some lean diffusion flame islands, surrounding the inner premixed flame [11].

Extensive researches have been performed on fuel and oxidizer dilution in non-premixed flames. Effect of fuel or oxidizer dilution and fuel to oxidant ratio on flame configuration, temperature, lift-off height and consequently on flame stability and pollution are very significant and they are very powerful tools for controlling flame. Effects of diluents on structure and stability of axisymmetric lifted laminar diffusion flames are investigated by Ruan *et al.* [12]. They found that effect of CO_2 on flame structure and stability is more than N_2. Because, CO_2 has upper heat capacity and lower transfer rate in comparison with N_2. In another research that was performed by Sullivan *et al.* [13], methane-air laminar diffusion flame was considered. They diluted methane with ammonia (NH_3) and observed that NO_2 emission level diminished up to 50% in confined use of ammonia. Also, Kumar *et al.* [14] observed a decrease in NO_x emission level with adding H_2 into fuel stream. This was ascribed to the enhanced diffusivity which led to a decrease in residence time of gases.

In the present study, an experimental method is used to investigate the structure of transient and turbulent non-premixed flames. The present study aims to expand the knowledge of the effects of dilution or enrichment of oxidant on the structure and stability of turbulent non-premixed flames in a co-flowing oxidant stream based on the works of Takeno [1-4] and Chih-Yung Wu [6].

2. Experimental Method

A co-flow burner is used for the experiments. Figure 1 shows the schematic of the coaxial burner used in this study. In this burner, the fuel nozzle has 1.7 mm inner diameter which is located in the centerline of a Pyrex tube with 11.14 mm inner diameter. The fuel nozzle thickness is 0.2 mm. The oxidant stream flows from the area between fuel nozzle and Pyrex tube and mixes with the fuel stream which comes out from the fuel nozzle. The axes of Pyrex tube and fuel nozzle are placed coaxially. The Pyrex tube prohibits environmental air to be involved in combustion. In these experiments, oxidant stream is air or pure oxygen which is diluted with carbon dioxide or nitrogen gases. The flow rates of the oxidant and the fuels are metered by calibrated flow meters mounted in their respective feed lines. The accuracy of rotameters for fuel and oxidant metering is $\pm 0.2\%$ of full scale. High quality digital pictures (Power Shot G6 Canon) with high capturing velocity (0.1 msec) are taken for analyzing the flame behavior. For relying on the reported data, experiments repetition is taken into account. The flame stability behavior is studied by increasing the fuel injection velocity until the flame begins to blow off or break off. All of the streams, concerning fuel and oxidant are in the room temperature (25ºC). In the performed tests, a parameter is defined that shows dilution percent. This parameter is indicated by Z.

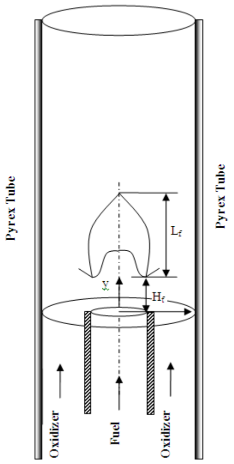

Figure 1. Schematic of the coaxial burner along with the lifted flame

3. Results and discussion

For investigating the transient and turbulent non-premixed flames structure and for both fuels, three tests have been performed. These tests are included considering effect of oxidant stream velocity on non-premixed flame structure, effect of oxygen dilution with N_2 on non-premixed flame structure and effect of oxygen dilution with CO_2 on non-premixed flame structure, respectively.

3.1. Natural gas flame

In the experiments with natural gas fuel, (based on air oxidant) the governing process is introduced and in continuation the results with the dilution are presented. Because of limitations of test apparatus, the natural gas volume flow rate couldn't be more than 4 lit/min.

3.1.1. Experiments concerning environmental air as oxidant

The stability behavior depends on the oxygen concentration in the oxidant stream, as well as on the type of fuel used. When the fuel is natural gas and oxidant is environmental air, one type of stability limit is observed, that is the flame blow off. Figure 2 shows an example of the variations of flame configuration with the fuel injection velocity (U_j). When U_j is low enough (less than 10 m/sec), a laminar flame develops as a slender shape (the first picture). The flame length increases with U_j, so that the maximum length of flame approaches 50 cm. As U_j is increased further (the second picture), there appears along the flame a sharp transition point. According to [15] and [16], there are two transition-generating mechanisms which are related to hydrodynamic instability of the fuel jet very near the axis as a result of friction between air and fuel at the boundary of free jet and pipe flow turbulence inside the fuel injector, respectively. A sinusoidal small-scale fluctuation at the transition point in the jet very near the axis and large-scale fluctuations outside the flame increase heat and mass transfer rate across the reaction zone and cause the flame to expand [3]. The flame becomes turbulent at the downstream from this point. In the transition point, the sudden increase of heat and mass transfer rate across the flame widens the reaction zone. The transition point moves to upstream with increasing U_j (the third picture). Finally, as U_j is increased still further, the flame blows off (the fourth picture). The transition length is the distance between transition point and fuel nozzle outlet (L). For using a non-dimensional parameter, this length is divided on the nozzle diameter. This parameter is named as non-dimensional transition length (X_L). The experiments in this section have been performed for three different velocities of air. For all of them, the governing process is as aforementioned. Figure 3 shows non-dimensional transition length (X_L) against the fuel jet Reynolds number (Re_j) with the air velocity (U_a) as a parameter. Also, Table 1 shows the critical velocity and the relative jet Reynolds number in which flame blows off. The first type is known and it is observed in low concentrations of oxygen in oxidant stream. This type depends on fuel and oxidant streams inter diffusion that forms a combustible mixture in laminar flow region immediately downstream of the injector rim.

Figure 2. Variations of natural gas flame configuration with jet injection velocity U_j .The air velocity is 3 cm/sec.

1) Rej= 1269 ,2) Rej= 1830 ,3) Rej= 2110 ,4) Rej= 2245

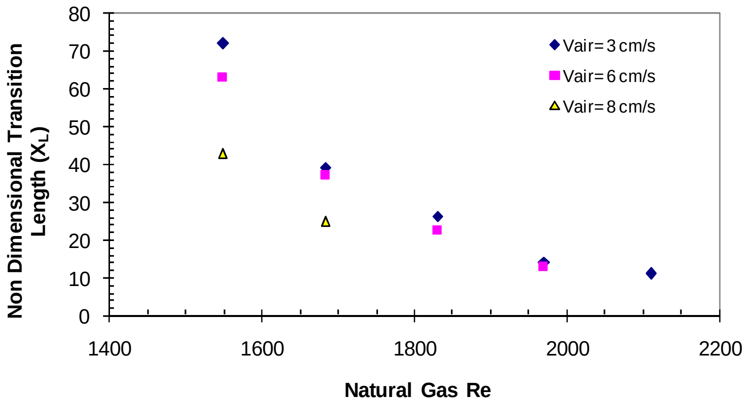

Figure 3. Variations of non-dimensional transition length of natural gas flame with the fuel jet Reynolds number. Oxidant stream is environmental air with 3 different velocities.

As it is observed in Figure 3, increasing air velocity causes the transition point to be moved near the fuel nozzle outlet. As U_a is increased, the air shear layer plays more critical role and causes the transition point to occur earlier along the flame.

Regarding Table 1, it can be inferred that the lift-off height is directly related to the air velocity (U_a). The delay in forming stoichiometric mixture, because of air velocity, is the main reason of increased lift-off height. For all three air velocities, after reaching turbulent regime, the flame length diminishes and this process continues with increasing jet Reynolds number, until the flame blows off.

Table 1- Blow off critical velocity for natural gas flame with air

Lift-Off Height	N.G. Re	Fuel Critical Velocity	Oxidant Velocity
20 mm	2245	18.4 m/s	U_a= 3 cm/s
21 mm	2110	17.3 m/s	U_a= 6 cm/s
22 mm	1830	15 m/s	U_a= 9 cm/s

3.1.2. Effects of oxygen dilution with nitrogen on natural gas flame stability

In this section, the primary oxidant stream is pure oxygen that is diluted with nitrogen stream. The Experiments have been performed for two different dilution percents. Parameter Z is the molar percent of dilution. Figure 4 shows the variations of flame configuration with fuel jet injection velocity for oxidant stream composed of 40 molar percent of nitrogen and 60 molar percent of oxygen. The oxidant stream velocity is 6 cm/sec. The only observed stability limit is diminishing turbulent part length of flame that is located after transition point. It is expected that break-off or extinction happen for turbulent portion of the flame with increasing fuel jet Reynolds number. When U_j is low (less than 15m/sec), a laminar flame develops as a slender shape (the first picture). The flame length increases with the fuel injection velocity (the second picture). As U_j is increased further (the third picture), a sharp transition point appears along the flame, where sudden breakdown of laminar flow happens and flame becomes turbulent at the downstream from this point. Increasing U_j makes the transition point to move toward the upstream (the fourth picture). Eventually, there won't be any change in the location of the transition point with further increase in Uj so that the fully developed turbulent non-premixed flame is established (the fifth picture). Figure 5 indicates the variation of non-dimensional transition length (X_L) with the fuel jet Reynolds number with molar dilution percent (Z) as a parameter.

As Figure 5 implies, increasing oxygen concentration in the oxidant stream brings about more stability for flame so that transition regime happens in upper Reynolds numbers. Additionally, Figure 5 reveals that after crossing from Reynolds numbers about 2500 (when flow in fuel nozzle becomes fully-developed) for two different percents of dilution, non-dimensional length finds almost same value. This trend of spatial variations of transition point in relation to the fuel jet Reynolds number and also its nearly fixed position after pipe flow entering into the fully developed turbulent regime, have been mentioned for hydrogen as a fuel [3].

Figure 4. Variations of natural gas flame configuration with jet injection velocity U_j. Oxidant stream composition is 60 molar percent of oxygen and 40 molar percent of nitrogen. Oxidant stream velocity is 6 cm/sec. 1) Rej= 1403, 2) Rej= 1683, 3) Rej= 1830, 4) Rej=2110, 5) Rej=2818

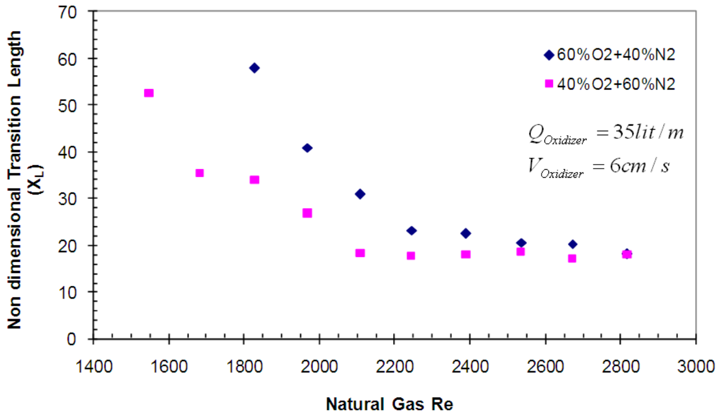

Figure 5. Variations of non-dimensional transition length of natural gas flame with jet Reynolds number. Oxidant stream is formed from oxygen and nitrogen. Oxidant stream velocity is 6 cm/sec.

3.1.3. *Effects of oxygen dilution with carbon dioxide on natural gas flame stability*

Like dilution with nitrogen, the experiments in this section have been performed for two different percents of dilution. For the oxidant stream composed of 60 molar percent of oxygen and 40 molar percent of carbon dioxide, only one type of stability limit is observed that is gradual diminishing in length of turbulent portion of the flame. But for other dilution percents (Z= 60), the stability limit is the flame blow off. Figure 6 shows the flame structure variations with the fuel injection velocity when Z=60 (dilution percent). In Figure 7, non-dimensional transition length (X_L) against the fuel jet Reynolds number (Re_j) and for diluting oxygen with carbon dioxide has been shown. As it is shown in Figure 7, enhancing dilution percent makes the transition point to happen earlier (in lower jet Reynolds numbers). When Z=40, it is interesting to note that for Re_j more than 2500, spatial variations of non-dimensional transition length (X_L) against the fuel jet Reynolds number diminishes remarkably. In fact, when flow in the fuel nozzle reaches fully developed regime, spatial variations of transition point reduces noticeably. Table 2 shows the critical velocity and relevant jet Reynolds number, in which flame blows off.

Figure 6. Variations of natural gas flame configuration with jet injection velocity U_j. Oxidant stream composition is 60 molar percent of oxygen and 40 molar percent of carbon dioxide. Oxidant stream velocity is 6 cm/sec. 1) Rej= 1269, 2) Rej= 1683, 3) Rej= 1830, 4) Rej= 2245, 5) Rej= 2818

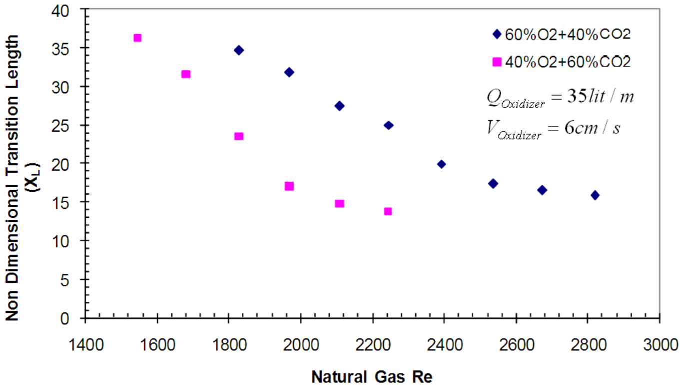

Figure 7. Variations of non-dimensional transition length of natural gas flame with jet Reynolds number. Oxidant stream is composed of oxygen and carbon dioxide. Oxidant stream velocity is 6 cm/sec.

Table 2- Blow off critical velocity for natural gas flame in diluting oxygen with carbon dioxide.

Lift-Off Height	N.G. Re	Fuel Critical Velocity	Oxidant Composition
28 mm	2391	19.6 m/s	40%O_2 + 60%CO_2

3.2. Propane Flame

The stability behavior of the propane flame is studied in the second part of the experiments. Like natural gas, the experiments for propane have been performed in three parts. First, the experiments for air in different velocities and in continuation the experiments have been done for oxygen as the main oxidant with diluting it with nitrogen and carbon dioxide. For propane, there isn't limitation for volumetric flow rate, so that the flames with Reynolds numbers up to 25000 have been examined.

3.2.1. Experiments concerning environmental air as oxidant

Two different velocities for air are used and the results show that the flame blows off after increasing the jet Reynolds number. Figure 8 shows the flame configurations for air stream with 6 cm/sec velocity. Figure 9 shows variations of the non-dimensional transition length (X_L) versus the jet Reynolds number Re_j for the air stream velocity U_a as a parameter. Increasing air stream velocity helps perturbations in the flame boundary to happen sooner. The chemical energy of reactants released in combustion process causes increasing viscosity and decreasing density for the flame jet in comparison with cold and un-ignited jet [9]. Increased viscosity devastates the fluctuations of velocity as they approach to the flame surface and enter to the highly viscous layer. Suppressing the development of the amplitude of flame surface fluctuations in the viscous layer (just inside the flame surface) is another effect of the increased viscosity. If there were no such highly viscous layers, the amplitude of perturbations would diverge quickly [3]. Heat release due to chemical reactions affects the vorticity. The expansion of the fluid flow due to heat release diminishes the vorticity and destroys the local vortex tubes [17]. Propane flame has further heat release rate in comparison with natural gas flame due to additional carbon connections break off. Therefore propane flame not only does not generate turbulence but also, damps it and laminarizes the flow. Comparing Figures 9 and 3 shows consistency with what is expected. The transition regime in natural gas-air flame initiates in lower jet Reynolds numbers. As it is observed in table 3 and it is expected, increasing air velocity enhances the lift off height (due to delay in forming stoichiometric mixture).

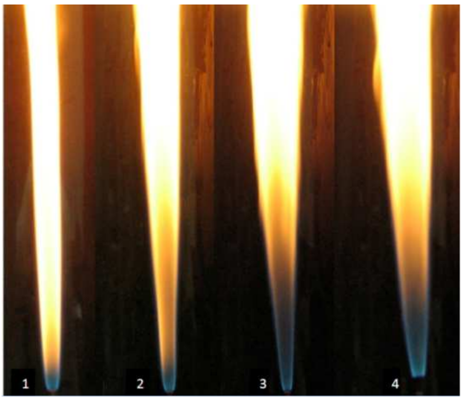

Figure 8. Variations of propane flame configuration with jet injection velocity U_j .Oxidant is air with 6 cm/sec velocity.

1) Rej= 1634, 2) Rej= 2369, 3) Rej= 4248, 4) Rej= 4697

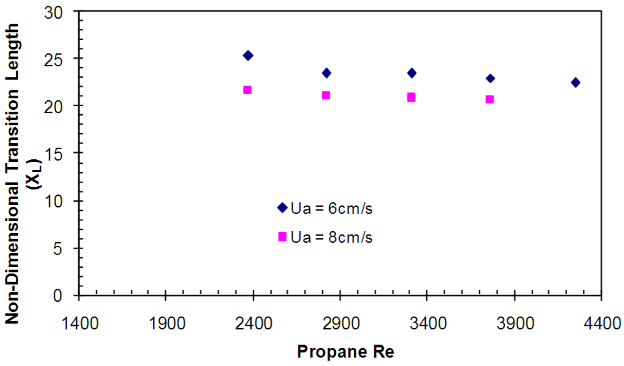

Figure 9. Variations of non-dimensional transition length of propane flame with fuel jet Reynolds number. Oxidant stream is environmental air with two different velocities.

Table 3- Blow off critical velocity for propane-air flame

Oxidant Velocity	Fuel Critical Velocity	Propane Re	Lift-Off Height
U_a= 6 cm/s	11.5 m/s	4697	6 mm
U_a= 8 cm/s	10.4 m/s	3758	7.5 mm

3.2.2. Effects of oxygen dilution with nitrogen on propane flame stability

In this section, the main stream of oxidant is pure oxygen that is diluted with nitrogen. Two different percents of dilution are used. In Figure 10, the variations of flame structure process for 40 percent dilution have been shown. Break-off at the transition point is the observed stability limit. In addition, Figure 11 shows non-dimensional transition length versus fuel injection Reynolds for dilution percent as a parameter.

Figure 10. Variations of propane flame configuration with jet injection velocity U_j. Oxidant stream composition is 60 molar percent of oxygen and 40 molar percent of nitrogen. Oxidant stream velocity is 6 cm/sec. 1) Rej= 1879, 2) Rej= 2369, 3) Rej= 7066, 4) Rej=16500

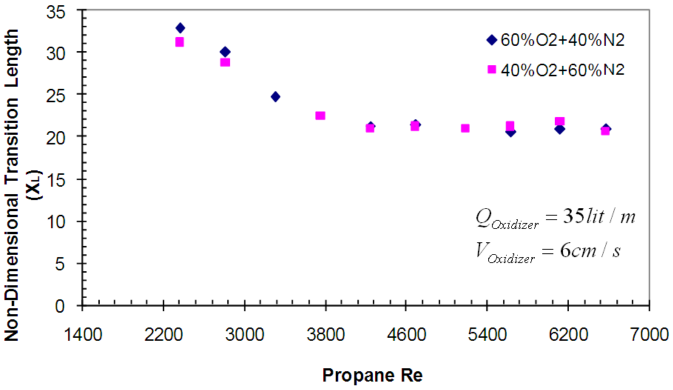

Fig. 11- Variations of non-dimensional transition length of propane flame with fuel jet Reynolds number. Oxidant stream is composed of oxygen and nitrogen. Oxidant stream velocity is 6 cm/sec.

3.2.3. Effects of oxygen dilution with carbon dioxide on propane flame stability

In the last experimental part, effects of propane jet Reynolds number on non-premixed flame structure in transient and turbulent regimes have been investigated. The experiments have been performed in 40 and 60 percents of dilution. In Figure 12, variation of flame structure for oxidant stream that is comprised of 40 molar percent of oxygen and 60 molar percent of carbon dioxide is shown. As figure 12 reveals, both types of stability limits occur. In critical velocity of 17.3 m/sec for the fuel jet, the flame blows off and in continuation with increasing fuel jet velocity (up to 46.1 m/sec) second limit of stability that is extinction of the turbulent portion of the flame at the transition point from laminar to turbulent occurs. The sixth picture in Figure 12 reveals it perfectly. The second stability limit will appear only when rim stability is increased somehow (in our experiments with injecting oxygen). This type of limit is due to turbulent non-premixed flame instability. Instability occurs at the transition point, where the sudden increase in heat and mass transfer rate across the flame is expected to happen. If the enhancement be large enough, the chemical reactions cannot endure against this variation and consequently lead the flame to decreasing temperature and the extinction at the transition point. This instability mechanism is basically the same as the mechanism which happens in a laminar counter-flow diffusion flame. In these flames, enhancing fuel and oxidizer velocity raises molecular diffusion which causes increasing burning rate. However, more increase in reactants velocity raises heat and mass transfer rate noticeably and in this way diminishes the radicals residence time. The finite reaction rate of chemical species can not tolerate this situation so that it will lead to the flame extinction [18]. This Instability can be clarified by using Damkohler number. Additionally, from extracted results, it is obviously concluded that transition from laminar to turbulent flow is delayed noticeably by the existence of the flame. Also, Figure 13 shows the variations of flame configuration for 40 percent of dilution.

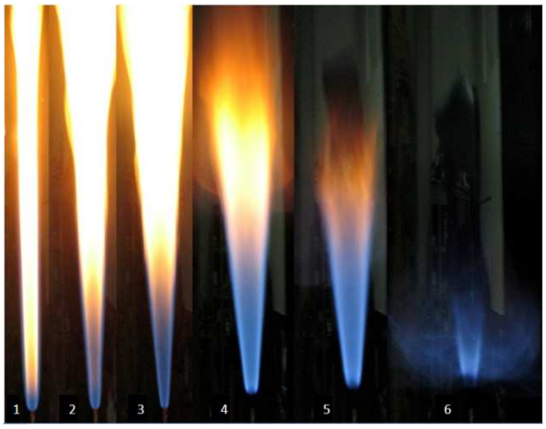

Fig. 12- Variations of propane flame configuration with jet injection velocity U_j. Oxidant stream composition is 40 molar percent of oxygen and 60 molar percent of carbon dioxide. Oxidant stream velocity is 6 cm/sec. 1) Re_j= 1634, 2) Re_j= 2818, 3) Re_j= 5636, 4) Re_j=11763, 5) Re_j= 14132, 6) Re_j= 18829

In this percent of dilution (40%), the only observed stability limit is the extinction of turbulent portion of the flame. It can be seen obviously in fifth picture in Figure 13. Figure 14 shows the variation of the non-dimensional transition length of the propane jet with the jet Reynolds number, with the dilution percent as a parameter. Also, Table 4 presents critical velocity and the relevant jet Reynolds number where lift-off happens.

Fig. 13- Variations of propane flame configuration with jet injection velocity U_j. Oxidant stream composition is 60 molar percent of oxygen and 40 molar percent 0f carbon dioxide. Oxidant stream velocity is 6 cm/sec. 1) Re_j= 2124 ,2) Re_j= 2818 ,3) Re_j= 7066 ,4) Re_j=16500 ,5) Re_j= 24506

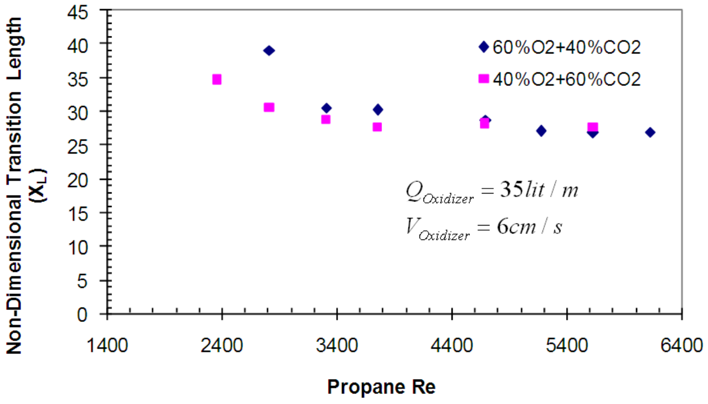

Fig. 14- Variations of non-dimensional transition length of propane flame with fuel jet Reynolds number. Oxidant stream is composed of oxygen and carbon dioxide. Oxidant stream velocity is 6 cm/sec.

Table 4- Blow off critical velocity for propane flame in diluting oxygen with carbon dioxide

Oxidant Composition	**Fuel Critical Velocity**	**Propane Re**	**Lift-Off Height**
$40\%O_2 + 60\%CO_2$	17.3 m/s	7066	4 mm

3.2.4. Comparing effects of oxygen dilution with nitrogen or carbon dioxide

From figures 4-7 and 10-14, it can be inferred that due to higher heat capacity and lower thermal diffusivity of carbon dioxide in comparison with nitrogen, using carbon dioxide for diluting the pure oxygen makes the flame too sensitive to be turbulent or blow off at lower Reynolds numbers. In this regard, diluting the pure oxygen with carbon dioxide leads to impressive variation between the location of transition point for two different levels of dilution with carbon dioxide (40% and 60%) although these variations for the position of the transition point is not so great for the case of using nitrogen as a diluents with pure oxygen. On the whole, it can be concluded that diluting the pure oxygen with carbon dioxide can accelerate the transition of the fluid flow regime from laminar to turbulent and consequently flame blow off so that it can exacerbate the flame instability.

4. Conclusion

The present experimental study on the turbulent propane and natural gas flame stability has led to the following conclusions. With increasing fuel jet Reynolds number, there appears along the flame a point that is accompanied by reaction zone sudden expansion. The flame becomes turbulent at the downstream from this point. This point is called transition point. Additional increase in fuel jet Reynolds number moves the transition point to upstream. Finally, when Reynolds number reaches 2500, the pipe flow enters into the fully developed turbulent region so that the location of transition point will not be displaced for a further increase in Reynolds number. Two types of stability limits are observed depending on jet Reynolds number. The first one is the extinction at the transition point from laminar to turbulent flame, leaving a short, residual rim flame immediately downstream of the injector. The second one is the blow-off of the whole flame from the injector rim. In experiments with oxygen oxidant and for two dilution percents (40% and 60%), with increasing jet injection Reynolds and transition point settling at certain position, the non-dimensional transition length finds equal value for both dilution percents. In propane non-premixed flames, occurrence of the transition point in turbulent regime happens in upper jet Reynolds numbers in contrast with natural gas flames. This is due to additional heat release in propane non-premixed flames that reduces the vorticity and destroys the local vortex tubes in propane flames more than natural gas flames. Also, it should be mentioned that diluting the pure oxygen with carbon dioxide can lead to early occurrence in the transition point and consequently the flame blow off at low Reynolds numbers, so that it can exacerbate the flame instability.

Nomenclature

Z - Dilution percent, [-]

X_I -Molar percent of I in oxidant stream, [-]

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