EXPERIMENTAL STUDY ON PROPANE/OXYGEN AND NATURAL GAS/OXYGEN LAMINAR DIFFUSION FLAMES IN DILUTING AND PREHEATING CONDITIONS

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In the present study, propane/oxygen and natural gas/oxygen diffusion flames within laminar regime have been investigated experimentally to determine the effects of oxidant preheating and diluting. This research has been divided into two parts. At first, effect of oxygen dilution with nitrogen and carbon dioxide gases has been investigated. In this section, stability and flame configuration variations are studied. Furthermore, it is inferred that combustion of natural gas and propane with pure oxygen can increase flame stability against increasing the fuel jet velocities through increasing burning velocity of the flame as compared with the combustion of natural gas or propane with normal air. In the other part, oxidant stream preheating up to 480 K and contemporaneous diluting with nitrogen or carbon dioxide are investigated and results are compared with non-preheating tests. Preheating causes more flame stability with respect to dilution process. Also, Due to combustion products temperature rise and also reduction in ignition delay time in preheating, these flames are more stable and also visually more luminous in comparison with normal temperature flames.

Key words: *Experimental, Diffusion flame, Preheating, Diluting, natural gas, propane, oxygen*

1. Introduction

In diffusion flames, mixing rate comparing to the reaction rate is slower, so that mixing process controls the burning rate. In such flames, fuel and oxidizer come together in reaction zone due to molecular and turbulent diffusions. The fuel can be a gaseous fuel jet or a condensed medium (either liquid or solid) and the oxidant may be a liquid or gas stream or environmental air. The distinctive characteristic of a diffusion flame is that the burning rate is determined by the mixing rate [1]. Diffusion flames are very important from the viewpoint of practical and fundamental research.

Extensive researches have been performed on fuel and oxidizer dilution in diffusion flames [2-6]. 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 effective tool for controlling flame. Therefore, effects of diluents on structure and stability of axisymmetric lifted laminar diffusion flames have been investigated by Ruan *et al.* [2]. They found that effect of CO_2 on flame structure and stability is more than N_2. Because, CO_2 has greater heat capacity and lower transfer rate in comparison with N_2. In spite of investigating methane diffusion flame structure for different oxygen percents, they didn't study the effect of preheating reactants stream. Juddoo *et al.* [3] reported an enhanced maximum temperature and combustion products mass fraction due to decreased nitrogen level in mixture on laminar counterflow diffusion flames. Moreover, Ghosal *et al.* [4] studied theoretically on lift-off and subsequent blowout in laminar diffusion flame. This research despite rendering solution for diffusion flame lift- off height, (because of assuming species diffusion rate constant) couldn't give reliable results in diluting conditions. Usowicz [5] considered visible region length as ethylene diffusion flame length. In another research that was performed by Sullivan *et al.* [6], 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.

Preheating is one of the other topics in diffusion flames which mainly investigated [7-12]. Oxidizer preheating provides stable flame in expanded range of mixing rates and also brings more uniform thermal characteristics within the combustion chamber. So increases combustion efficiency. Preheating is one of the flame stabilizing mechanisms that specially becomes important in lower levels of oxygen in oxidant [7].

The effects of preheated air on laminar co-flow propane diffusion flames under normal and microgravity conditions were studied by Ghaderi Yeganeh [8]. With optical emission spectroscopy and direct flame photography, CH and C_2 emission intensity profiles were obtained as three dimensional spatial distributions. He reported that 400 degrees increase in air temperature causes a 37.1% decline in flame length. Gupta *et al.* [9] utilized an industrial burner for preheating and diluting air with N_2 in methane, propane, acetylene and hydrogen diffusion flames. They preheated oxidizer up to 1100 K and reported a 30% reduction in energy consumption. Christo *et al.* [10] and Medwell *et al.* [11] studied co-flow diffusion fuel jet combustion along with a secondary burner combustion products and environmental air. It was concluded that diminishing oxygen concentration in oxidant stream from 9% to 3%, reduced gas temperature up to 13%. Mishra *et al.* [12] investigated the effect of adding H_2 into composite LPG-H_2 fuel jet on laminar flame length, gas temperature and NO_x emission level. Research was accomplished for non-preheating and preheating up to 470 K situations. They realized that adding H_2 results in flame length reduction. They also observed that preheating air along with adding hydrogen to fuel stream, decreases flame length further than non- diluting state. Moreover, with preheated air, flame length diminishes further in comparison with non- preheating state. Moore *et al.* [7] studied the effect of preheating reactants in methane- oxygen diffusion flame. They varied temperature in the 298-398 K range. They showed that increasing temperature diminished residence time due to enhanced velocity. Therefore stoichiometric mixture formed in upper height and lift-off height rose.

Regarding The literature review, it is inferred that coincident implementation of incoming oxidizer preheating with adequate dilution can be an effective remedy for establishing a high efficient, stabilized flame with fuel saving and pollutants reduction in practical combustion systems. Also, according to the literature review, it seems that experimental research on the effects of adding nitrogen and carbon dioxide on natural gas and propane flame structure (as commercial, on hand and widespread energy resources) in coaxial diffusion flames have not been investigated adequately. Hence the present study is focused to investigate the effects of adding nitrogen or carbon dioxide along with preheating oxidizer on visible flame length and flame structure in propane and natural gas laminar diffusion flames.

2. Experimental Method

A co-flow burner is used for experiments. Figure 1 shows a schematic of the burner. In this burner, fuel nozzle has 4.8 mm inner diameter which is located in the centerline of a pyrex tube with 11.14 mm inner diameter and 1 meter height. The material of the Fuel nozzle is brass with a 0.4 mm thickness. The Oxidant stream flows from area between fuel nozzle and pyrex tube and mixes with outlet fuel from nozzle. The axis of pyrex tube and fuel nozzle are placed coaxially. Pyrex tube prohibits environmental air to be involved in combustion. In these experiments, we initiate from pure oxygen and gradually with decreasing oxygen molar percent, nitrogen or carbon dioxide enters into the oxidant stream (dilution process). An electrical heater is used for preheating the oxidant stream. The flow rates of the oxidant and the fuels are metered by the calibrated flow meters mounted in their respective feed lines. High quality digital pictures (Power Shot G6 Canon) with high capturing velocity (0.1 msec) are taken for analyzing the flame behavior. In this study, luminous zone length is taken as flame length [8]. Flame length measurement accuracy is a tenth of millimeters. For relying on reported data, the experiments have been carried out for several times. The Parameters served for demonstrating flame length (L_f) and lift-off height (H_f) are indicated in Fig. 1. The Flame stability behavior is studied by increasing the oxidizer dilution percent until the flame begins to blow off. Fuel stream is always in the room temperature (25ºC). In performing tests, a parameter is defined that shows dilution percent. This parameter is indicated by Z. When the base of the diffusion flame lifts off from the burner tip and remains suspended at a certain distance above the burner, we call this phenomenon lift-off.

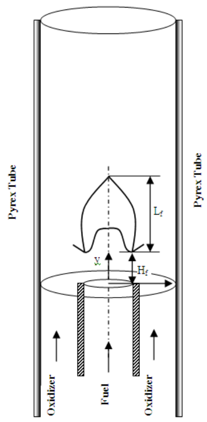

Figure 1- Schematic of the coaxial burner along with a lifted flame

3. Results and discussion

In this study, first the effect of increasing fuel stream velocity while oxidant stream velocity is kept constant is studied; and in continuation for each of the fuels four experiments have been accomplished. These experiments are effect of oxygen dilution with N_2, effect of oxygen dilution with CO_2, effect of preheating and oxygen dilution with N_2 and effect of preheating and oxygen dilution with CO_2, respectively.

In diluting experiments process, the fuel velocity is always 6 cm/s. the Oxidizer velocity is selected as equal to the fuel velocity. In preheating conditions, the oxidizer stream temperature is 480 K and without preheating is equal to the room temperature (298 K). The Fuel temperature is 298 K in all of the experiments.

3.1. Effect of fuel stream velocity

In this section, for investigating the effect of fuel stream velocity in constant oxidant stream velocity, 2 separated experiments have been done for each fuel. Air and pure oxygen are utilized as oxidants respectively. In both experiments, the oxidant stream velocity is constant and equal to 6 cm/s. the Oxidant and the fuel inlet temperatures are both 300 K. Reynolds number varies from 4 to 150 for natural gas and from 15 to 250 for propane in laminar regime confines.

3.1.1. Effect of natural gas fuel velocity

As figure 2 demonstrates, the flame length is lower in pure oxygen state comparing fuel/normal air combustion. This is due to increase in oxygen concentration in mixing zone and raising oxygen mixing rate with fuel that causes flame length decline. The presence of enough oxygen in combustion zone leads the mixing and consequently combustion processes to the fast and complete mixing and reaction in combustion zone. For instance, in the combustion of the fuel with pure oxygen, with the imagination of the fuel and the oxidizer streams as parcels, these parcels can meet each other and then create stochiometric combustible parcels in the nearest parts to the fuel and the oxidizer inlet ports, so that these combustible parcels can burn intensively and efficiently inside the limited zone. According to this impression, in air oxidizer situation, lower measure of oxygen in mixing zone makes flame to have further length. It is considered that with increasing the fuel jet velocity, the flames length discrepancy enhances through increasing the fuel measure in constant oxidant amount and is predictable. Variations are linear for both oxidants. It is necessary to note that on the basis of equation (1) [13]:

$$Z_{f,L} \propto \frac{\overline{V}(\pi r_j)^2}{2\pi D} \tag{1}$$

(where $Z_{f,L}$ is the laminar diffusion flame length; $\overline{\mathbf{V}}$ is the fuel stream velocity; r_j is the fuel nozzle radius and D is the mixing rate, respectively) laminar diffusion flame length has straight proportion with fuel stream velocity and inverse with mixing rate [13]. The Fuel stream velocity effect results agreement with theoretical equations shows experiments implementation process veracity. Furthermore, as it can be seen in Fig. 2, the natural gas/ pure oxygen flame is very resistant and stable against increasing trend of inlet velocity of fuel. This is due to this fact that using pure oxygen instead of normal air increases the flame burning velocity and this way it can broaden the flame stability region so that the flame can be stable even at higher velocities as compared to natural gas/normal air flame velocity [14].

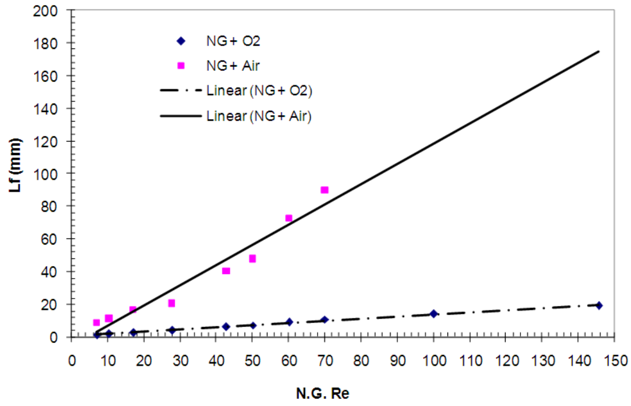

Figure 2- Natural gas flame length variations with increasing fuel stream velocity for air and oxygen

3.1.2. Effect of propane fuel velocity

As it is evident in figure 3, the propane flame length is lower in pure oxygen state. The result is more accessible oxygen and consequently rising mixing rate. The Propane flame has higher flame length in similar oxidant condition in comparison with natural gas flame. This is due to further carbon radicals in reaction zone that makes them to traverse further distance to approach their necessary oxygen. Regarding constant flow rate of oxidant stream for both natural gas and propane conditions and more carbon of propane as compared to natural gas, for stoichiometric combustion of propane and normal air/pure oxygen comparing natural gas combustion, more oxygen is needed. Achieved results from this section have coincidence with eq (1) and confirm our experiments implementation process.

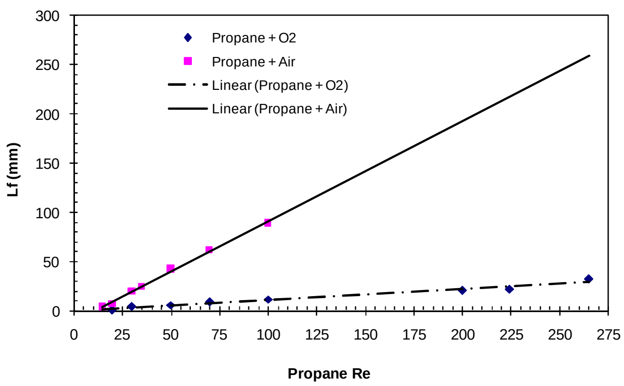

Figure 3- Propane flame length variations with increasing fuel stream velocity for air and oxygen

3.2. Effect of oxygen dilution with N_2 and CO_2

In this part of the study, effect of oxygen dilution is studied. The Oxidant stream volume flow rate is chosen 36 lit/min so as to the oxidant stream velocity becomes 6 cm/s.

3.2.1. Dilution including propane as fuel

As it is shown in figure 4, increasing N_2 percent in oxygen enhances the flame length gradually. This is due to diminishing available oxygen for fuel decomposed radicals which causes them to traverse farther distance for perfect mixing. In dilution process, with increasing N_2 percent, luminosity of flame and also combustion products such as carbon dioxides and water vapors decrease. These phenomena occur through lack of enough oxygen in combustion zone and also the flame temperature reduction and consequently emission intensity reduction from carbon radicals and combustion products such as carbon dioxide, water vapor and etc. In high percents of dilution, flame lift-off occurs and finally flame blows out. Flame blow-out limit in diluting oxygen with N_2 and with propane as fuel is in 85 molar percent of N_2. The flame color follows from radiation of distinct wavelengths that exits during the combustion process. The bluish-white and blue color of the high calorific fuels, like propane, with high oxygen concentration is results from chemical reaction of atomic carbon to carbon monoxide and subsequently carbon dioxide during combustion process. The yellow part of the flame follows from the imperfect combustion of the carbon within the fuel. The Flame lift-off from the fuel nozzle occurs due to delay in stoichiometric mixture formation. Because dilution diminishes oxygen molecular concentration level and consequently it requires more time for making stoichiometric mixture. As a result, stoichiometric mixture forms in a higher height from the fuel nozzle. Moreover, diluting diminishes flame maximum temperature. Figure 5 indicates images captured from dilution process of oxygen with CO_2 related to propane fuel. In this test, blow-out limit arises in 75 molar percent of CO_2. With increasing CO_2 molar percent in oxidant stream, again gradual flame luminosity reduction is observed. As illustrated in prior part, this is due to decrease in flame maximum temperature. In diluting with carbon dioxide blow-out happens in lower percents of diluents in comparison with N_2 addition method. Since CO_2 has higher thermal capacity than N_2 so that it reduces flame maximum temperature further and makes it more unstable. Consequently flame diluted with CO_2 blows out earlier.

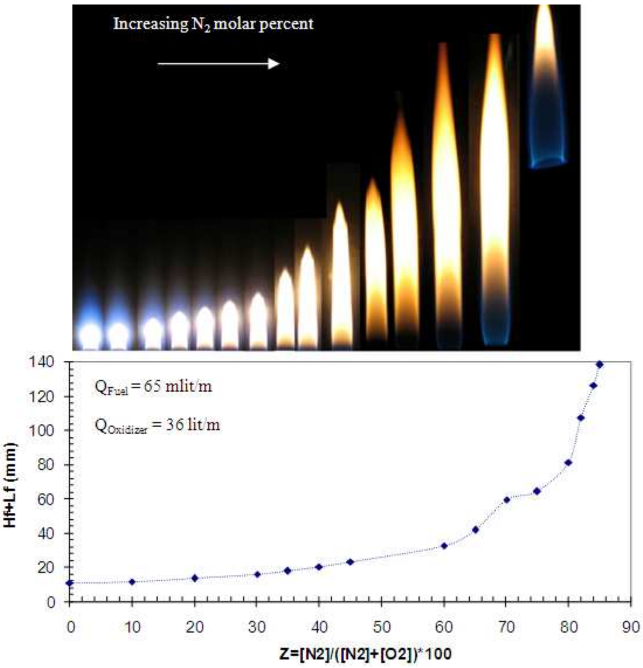

Figure 4- Effects of diluting oxygen with N_2 along with propane fuel. Each of the figure points matches with one of the flames from left to right, respectively.

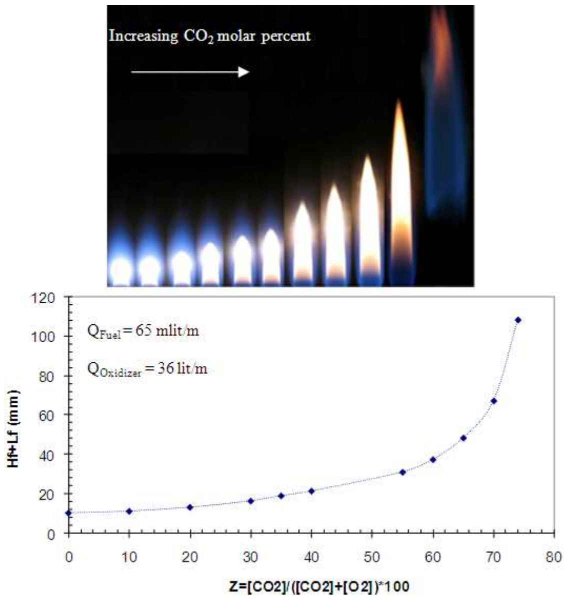

Figure 5- Effects of diluting oxygen with CO_2 along with propane fuel. Each of the figure points matches with one of the flames from left to right, respectively.

3.2.2. Dilution including natural gas as fuel

In figure 6 dilution of oxygen with N_2 and for natural gas fuel is indicated. The Flame blow-out limit in diluting oxygen with N_2 and for natural gas as fuel is 79 molar percent of dilution. It is discovered that in low percents of dilution, a luminous zone can be seen so that this zone disappears gradually with increasing dilution percent. In high percents of dilution, first, the flame lifts off and subsequently blows out. In lift-off situation the flame color in all of the points becomes blue and luminous zone decays. Because of lower maximum temperature, natural gas flame lightens less than equivalent propane flame, i.e. in the same dilution percents, propane flame shines in contrast to natural gas flame. Additionally, lift-off height is greater in natural gas flame. In figure 7, the effect of oxygen dilution with CO_2 on natural gas flame has been investigated. In this test, like the other tests at the present study, the dilution causes flame shininess reduction, height enhancement and eventually lift-off and blow-out. Flame blow-out limit for this experiment is in 73 molar percent of CO_2.

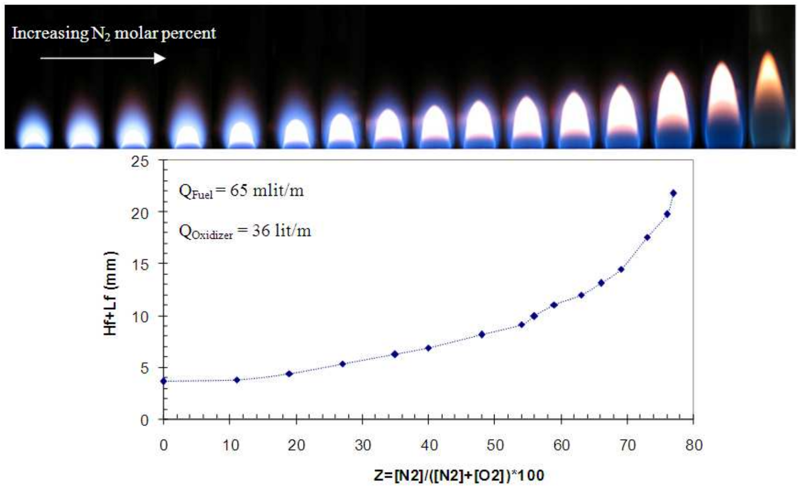

Figure 6- Effects of diluting oxygen with N_2 along with natural gas fuel. Each of the figure points matches with one of the flames from left to right, respectively.

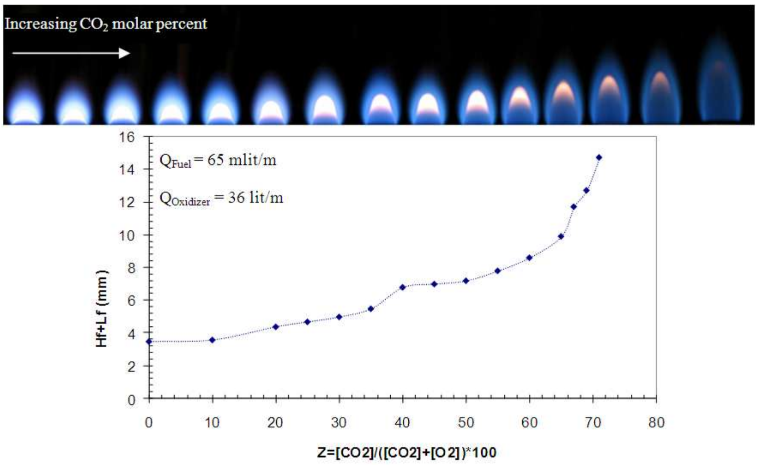

Figure 7- Effects of diluting oxygen with CO_2 along with natural gas fuel. Each of the fig. points matches with one of the flames from left to right, respectively.

3.3 Effect of preheating and diluting oxygen with N_2 and CO_2

In this section of the experiments, effects of oxygen diluting and preheating have been studied. The Oxidant stream temperature during mixing with the fuel stream is 480 K. However, the fuel stream has 298 K temperature. For diluting oxygen stream, N_2 and CO_2 streams are used. In this part, the flame length is compared to without preheating section.

3.3.1 Diluting and preheating oxidant stream including propane as fuel

The Direct images captured from propane diffusion flame with preheating and diluting oxygen with carbon dioxide are demonstrated in fig. 8. Diluting with CO_2 reduces flame shininess and finally with increasing flame dilution percent, lift-off and blow-out occurs. In dilution process, the flame's height due to reduction in oxygen content increases. In this experiment, the flame blow-out happens in 77 molar percent of carbon dioxide. Propane preheated flame has higher maximum temperature than natural gas preheated flame which causes more luminosity. Obviously, due to this fact that preheated oxidizer brings an additional enthalpy to combustion zone, it can raise combustion products temperature resulting in more luminous flames. Furthermore, because of increasing the flame stability region against increment of the fuel jet velocity in preheated oxidant condition and also raising oxygen radicals' reactabilities level than non-preheating state, Oxidizer preheating delays lift-off time, i.e. lift-off occurs in upper dilution percents

[15]. However, due to bringing more enthalpy to combustion zone and also reduction in ignition delay time, lift-off height diminishes. Variations of the flame length and lift-off height aggregate as a function of oxygen dilution percent with CO_2 and in two states of with and without oxidant preheating have been brought in fig. 8. As it is indicated, with preheating oxidant, flame visible region length decreases. The Flame length reduction value for the process along with oxidant preheating than non-preheating state enhances from about 5% for pure oxygen (X_{CO2}=0) to 30% for 70 percents of dilution (X_{CO2}=0.7).

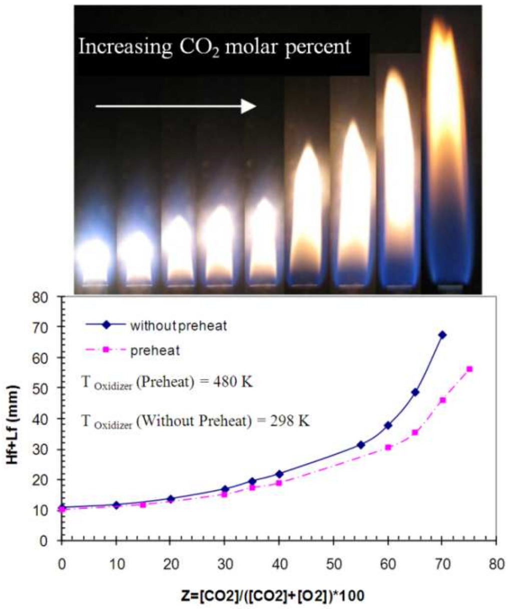

Figure 8- Comparing flame lift-off and height sum with dilution percent in diluting oxygen with carbon dioxide and with propane fuel in oxidant preheating and non-preheating states.

Figure 9 shows direct images taken from propane diffusion flame with preheating and diluting oxygen with N_2. As figure 9 implies, increasing N_2 molar percent in oxygen makes flame length greater and eventually brings lift-off and blow-out. Dilution diminishes flame shininess. In this experiment, flame blow-out takes place in 87 molar percent of nitrogen. The Rise in temperature of combustion products due to oxidant preheating causes shininess for preheated flame with respect to not-preheated flame. Comparing oxygen dilution with N_2 and for propane fuel in two estates of preheated and not-preheated flame has been performed in fig. 9. As figure 9 indicates and it is expected, preheating diminishes flame length and stabilizes it in respect of dilution process. This reduction is negligible with respect to flame length in lower percents of dilution. In this way, due to increasing mixture reactability and reaction rate, Preheating is one of the stabilizing mechanisms of flame during dilution procedure. The Flame length reduction value for the process along with oxidant preheating than non-preheating state enhances from about 3% for pure oxygen (X_{N2}=0) to 20% for 80 percents of dilution (X_{N2}=0.8).

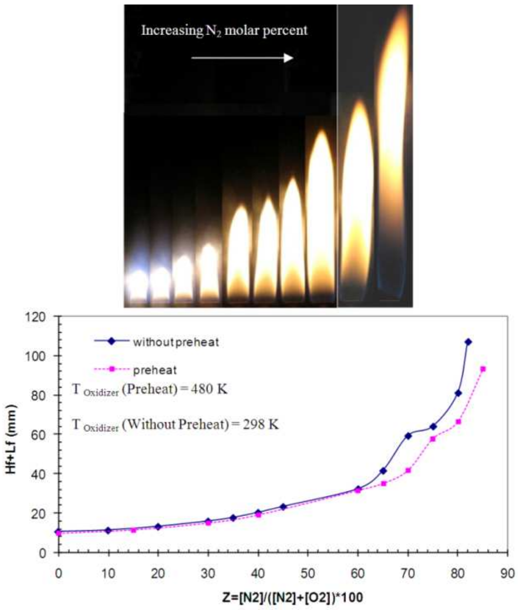

Figure 9- Comparing flame lift-off and height sum with dilution percent in diluting oxygen with nitrogen and with propane fuel in oxidant preheating and non-preheating states.

3.3.2 Diluting and preheating oxidant stream including natural gas as fuel

Figure 10 shows pictures of the flame during preheating and diluting oxygen with carbon dioxide including natural gas as fuel. Like the other preheating states, the oxidant temperature is 480 K. During dilution process, as it is expected, the flame elongates and gradually loses luminosity. This is due to decrease in the flame maximum temperature and oxygen content. Eventually, the flame color becomes thoroughly blue and afterwards lift-off occurs. The Flame blow-out limit in this case is 75 molar percent of CO_2. Although, the oxidant preheating reduces lift-off amount, lift-off occurs in upper percents of dilution. Rising oxygen radicals' reactability is the primary reason. Moreover, as it is mentioned before, preheated oxidant can broaden flame stability region by regulation of the diluted flame burning speed in combustion zone. For instance, by preheating of incoming vitiated oxidizer, the reaction rates, ignition delay time and consequently burning velocity can be affected so that it can lead to higher burning velocity in a mixed parcel of diluted oxidizer and specific fuel [16]. The flame length reduction value for the process along with oxidant preheating than non-preheating state enhances from about 5% for pure oxygen (X_{CO2}=0) to 20% for 71 percents of dilution (X_{CO2}=0.71). In figure 10, the effect of oxygen dilution with carbon dioxide including natural gas fuel and in two states of preheating oxidizer and without preheating oxidizer has been shown. By increasing the oxidant stream temperature, combustion completes within a smaller domain and results in a shorter flame size. Natural gas total conclusions are the same as propane. In preheating case, blow-out occurs in 75 molar percent of CO_2 and without preheating happens in 73 molar percent of CO_2.

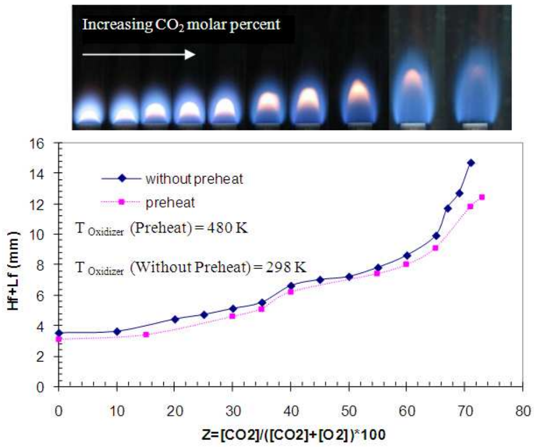

Figure 10- Comparing flame lift-off and height sum with dilution percent in diluting oxygen with carbon dioxide and with natural gas fuel in oxidant preheating and non-preheating states.

In figure 11, digital pictures captured from preheating and diluting oxygen with N_2 and with natural gas fuel are observed. Mixture (N_2+O_2) temperature is 480 K during integrating into fuel stream. In this case, like the previous cases, preheating diminishes lift-off height sorely. The Flame blow-out occurs in 84 molar percent of nitrogen. The flame length reduction value for the process along with oxidant preheating as against non-preheating state enhances from about 3% for pure oxygen (X_{N2}=0) to 33% for 73 percents of dilution (X_{N2}=0.73). In figure 11, comparing between preheated flame and normal temperature flame for diluting oxygen with N_2 has been carried out. With preheating, blow-out occurs in 84 molar percent of N_2 and without preheating occurs in 79 molar percent.

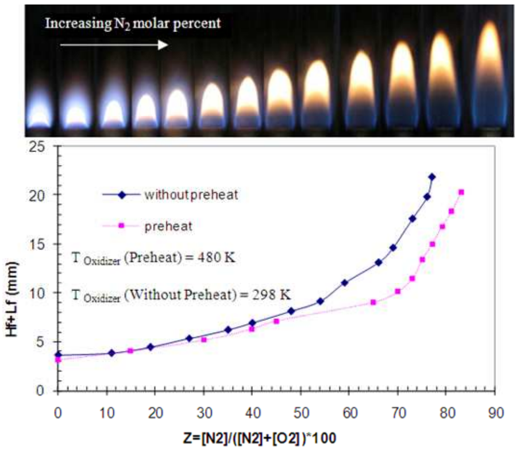

Figure 11- Comparing flame lift-off and height sum with dilution percent in diluting oxygen with nitrogen and with natural gas fuel in oxidant preheating and non-preheating states.

3.3.3 Effect of changing fuel type on preheating and diluting oxygen oxidizer

Figure 12 contrasts propane with natural gas in preheating and diluting oxygen oxidizer with carbon dioxide. As figure 12 implies, propane flames are longer and more stable, i.e. blow-out occurs in upper dilution percents. This is through higher order of propane in respect of natural gas and having further carbon radicals in combustion process. With increasing dilution percent, scale of the flame length variations is greater in propane flames than natural gas flames, i.e. dilution, raises discrepancy between natural gas and propane flames length. This matter is related to physical properties of propane as compared to natural gas which almost comprises of methane as a prevalent fuel. Regarding combustion characteristics of propane and methane, propane flame has lower auto ignition temperature and higher burning velocity in air and consequently wider stability zone for proper burning [16]. In figure 13, similar to previous figure, the effect of replacing fuel type on preheating and diluting oxygen oxidizer with nitrogen has been investigated.

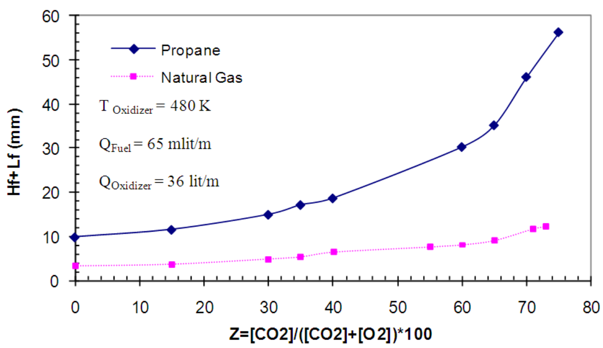

Figure 12- Effect of changing fuel type on preheating and diluting oxygen oxidizer with carbon dioxide.

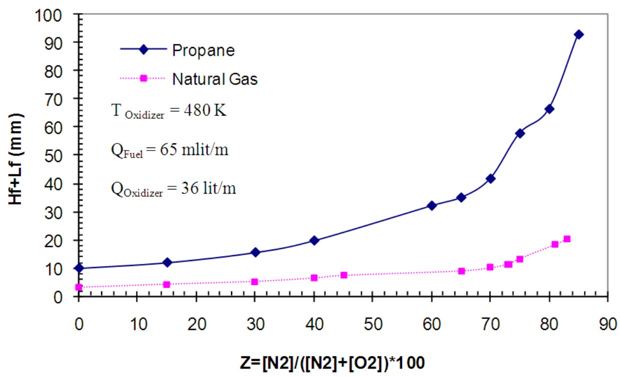

Figure 13- Effect of changing fuel type on preheating and diluting oxygen oxidizer with nitrogen

4. Conclusion

In this research investigating the effects of pure oxygen oxidant diluting and preheating on natural gas and propane laminar diffusion flames is oriented. In this study, it is inferred that Diluting oxidizer with CO_2 & N_2 eventually causes lift-off and blow-out. For diluting oxygen with carbon dioxide this lift-off occurs in lower percents of dilution. This is due to upper thermal capacity of carbon dioxide. Also, in diluting with propane fuel lift-off takes place in upper molar percents of CO_2 & N_2 in respect of diluting with natural gas fuel. Furthermore, it is understood that with increasing dilution percent, length increase slope is greater in propane flame in comparison with natural gas flames.

From preheating of normal and vitiated oxidizer viewpoint, the following results are extracted. First, Oxidizer preheating diminishes visible region length, i.e. increases chemical reaction rates. Secondly, preheated oxidant stabilizes flame against dilution process and lift-off occurs in upper dilution percents. Thirdly, Propane flame is so longer than natural gas flame through presence of more carbon radicals that enlarges reaction zone. Also, Due to more heat release in propane combustion, these flames are more luminous than their natural gas counterparts. Moreover, from considering the flame luminosity aspect, it is found that preheated flames are more luminous than normal temperature flames visually, because of rising flame maximum temperature. Also, preheating oxidizer decreases lift-off height sorely. However, delays it; i.e. lift-off occurs in upper dilution percents.

Nomenclature

Z - Dilution percent, [-]

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

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