STABILITY OF A LAMINAR JET DIFFUSION FLAME OF METHANE IN AN OXYGEN ENRICHED AIR CO-JET.

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Abstract
The effect of adding oxygen in the combustion of a laminar flame methane/air is studied. The volume content of oxygen obtained varies between 21% (air) and 30%. The results relate to the heights of dropping flame based on initial rates of CH_4, air and oxygen percentages. Stability diagrams showing the states of the flame and transitions between these states are built. The reduction drop observed during the addition of oxygen is explained by the increase in laminar flame speed and increased heat release due to a higher flame temperature.

Keywords: laminar diffusion flame – lifted flame – oxygen enriched air – flame stability.

Introduction

Oxygen is the component of air which plays the dominant role in the combustion reactions. Many studies have been conducted on flames in air enriched with oxygen and several objectives are aimed: increasing the flame temperature and thus improving energy efficiency, reducing fuel consumption, increasing the concentration of CO_2 emissions and reducing emissions of nitrogen oxides. Previous studies have been conducted to examine the effect of this enrichment on flame characteristics: laminar speed boundary extinction, frequency and amplitude of oscillations and vortices instabilities.

The effect on the frequency and amplitude of oscillations of the top of the flame was studied by Gotoda et al. [1]. The flame was issued from a burner with coaxial jets of methane and a mixture of oxygen and nitrogen. They found that oxygen enrichment decreased the amplitude of the oscillations and increased their frequency. The impact of several factors including the oxygen enrichment on the flickering frequency and amplitude of the flame was also studied by Legros et al. [2]. They found that increasing O_2 content induces a shift towards lower flickering frequencies and smaller relative amplitude; they explained it by the decrease of the flame height relatively to the almost constant length scales of the structures forming at the burner tip. Takahashi et al. [3] were interested in the extinction of the flames methane/air and methane/oxygen-enriched air by adding diluents including nitrogen gas N_2. The objective was to find the minimum concentration of diluents capable of blowing off the flame. By increasing the percentage of oxygen in the air, the minimum concentration becomes larger which means a stabilization of the flame. Indeed, the extinction by adding diluents gases is the result of a reduction in the reaction rate, the laminar flame speed and range of flammability. Han et al. [4] studied the velocity of premixed flame méthane/O_2/N_2 where the percentage of oxygen in the air ranged from 21% to 98.5% at different equivalence ratios. They showed that for a given percentage of oxygen, this speed always has a maximum at stoichiometry, and that increase of the oxygen content from 21% to 98.5% increased by 600% the laminar flame speed at stoichiometry.

F. Lacas performs experiments on liquid ethanol/oxygen diluted by air flame [5]. The injector sends two vertical coaxial jets in a vertical combustion chamber with an outlet for gases burned. The flame is visualized using a CCD camera through a filter centred on the emission band of CH radicals. By decreasing the mass fraction of oxygen, several changes concerning the flame structure, stability and training pollutants are observed. This dilution has the effect of increasing the thickness of the flame and makes it less stable, which may be explained by the decreased laminar flame velocity with dilution. Regarding the structure of the flame, decreasing the oxygen mass fraction leads to a longer and thicker flame; this is due to the location of the area near the stoichiometric flame. From a stability point of view of the flame, the extinction decreases with dilution: the higher the oxygen percentage is, the more flame is stable.

Further studies summarized the behaviour of the flame after the injection conditions by establishing stability diagrams. Wyzgolik et al. [6] established a stability diagram for a flame issuing from turbulent coaxial jets of methane and air and proposed two mechanisms responsible of the lift-off of flame: the triple flame configuration where the flame is composed of three branches after an even point whose position is determined by the balance between flow velocity and propagation speed of the flame. In the second mechanism, it is local extinction resulting from an imbalance between heat transfer by conduction and the flow of heat from the reaction.

Interest is also paid to the evolution of the flame length by enriching the air with oxygen. Thus, Roper theoretical calculation of the flame length [7] depended on the adiabatic flame temperature.

Several studies [8], [9], [10], investigated the soot formation in diffusion flames where the oxidizer was oxygen enriched air; they proved the increase of soot formation with oxygen enrichment.

In this study the effect of enriching the air with oxygen on flame behaviour (attached to the burner rim, lifted or blown) is investigated and the flame stability is summarized.

Experimental set-up and conditions.

The burner used consists of two concentric tubes of stainless steel of thickness 1 mm. The central tube of inner diameter 4 mm is placed at the centre of an annular tube whose inner diameter is 10 mm. These tubes have a length of 200 mm, in order to ensure laminar flow output. The entrance to the central tube is connected to a direct supply of methane G20. That of the outer tube is connected to a supply of oxygen-enriched air. This enrichment is provided through two channels of flow control: one for air, the other for oxygen. These two flows arriving at the input of a mixer whose output in oxygen-enriched air is connected to the outer tube. Oxygen ALPHAGAZ, resulting from gas cylinder B50 is a purity of 99.5%. A security valve is placed in the circuit between the oxygen bottle and the flow meter. It allows instant switching of the flow of oxygen when needed. Compressed air composition (20.5 ± 0.5% O_2 and 78 ± 0.5 %N_2) and methane is the G20 with purity above 98%.

The experiments were conducted by fixing the flow rate of methane Q_{CH4}. For each flow rate of methane, we choose to fix the air flow rate above those corresponding to the lift-off of the flame and lower than those corresponding to the extinction of the flame. When the air flow rate, Q_{air} is fixed, we proceed with oxygen enrichment, increasing the oxygen level by level. The flame is being filmed for two minutes (the estimated time needed for the stabilization of the lift-off height for each case) using a HDD camera SonyHDR-XR105E (50 Hz, 25 frames per second). To locate the points of blow out, we set the oxygen flow rate fixed and increase air flow rate continuously. The experimental conditions are given in Table 1. Q_{tot}

the total flow of oxidizer (oxygen-enriched air) is equal to the sum of Q_{air} and Q_{O2}. The percentage of oxygen is equal to: % O2 = (0.21 *Q_{air} +Q_{O2}) / Q_{tot}.

From digital images, the lift-off height is determined by measuring, on the flame axis, the distance between the burner and the position of the brightest spot corresponding to the triple point.

Q_{CH4} (10^{-6} m^3/s)	U_{CH4} (m/s)	Re_{CH4}	Q_{air} (10^{-6} m^3/s)	Q_{O2} (10^{-6} m^3/s)	Q_{total} (10^{-6} m^3/s)	$U_{oxidizer}$ (m/s)	$Re_{oxidizer}$	%O_2 volumique
3,14	0.25	57.8	23.65-53.8	0-4.86	23.65-58.66	0.37-0.93	146-381	21%-28%
15	1.19	275	23.65-69.53	0-6.16	23.65-75.69	0.37-1.2	143-486	21%-31.4%
20	1.59	367.6	30.21-76.09	0-6.16	30.21-82.25	0.48-1.3	179-526	21%-29.4%
25	1.99	460	30.21-89.2	0-6.8	30.21-96	0.48-1.52	179-611	21%-29.4%

Table1: experimental conditions.

The Reynolds number is defined as the characteristic length is equal to the diameter of the central tube for methane and Di_{air}-De_{CH4} for annular flow of air (Wyzgolik et al. [6]).
The values of cinematic viscosity are as follows ν_{CH4} =1.73*10^{-5} m^2/s and ν_{air}= 1.59 *10^{-5} m^2/s. For air-oxygen mixtures where the oxygen percentage varies between 21% and 30%, values are derived from a study of Hellemans et al [11].

Results and Discussions

Evolution of the behaviour of the flame for the case of a methane flow rate of 20*$10^{-6}$$m^3$/s and an initial air flow of 77.24 *$10^{-6}$$m^3$/s is shown Figure1. The flame, unstable at 21% oxygen (a) stabilizes at 22.2% oxygen (b). The lift-off height H (distance between the burner rim and the position of the triple point) is less and less important until the attachment of the flame to the burner for an oxygen percentage of 26.9% (c). In addition, the flame being entirely blue turns into an attached flame yellow mainly through the formation of radiating soot.

	(a)	(b)	(c)
Q_{tot} (*$10^{-6}$$m^3$/s)	76.5	77.3	82.3
%O_2	21.5	22.2	26.9

Figure 1. Photos of evolution of flame behaviour Q_{CH4}=20*$10^{-6}$$m^3$/s and Q_{air}=76.09*$10^{-6}$$m^3$/s function of the oxygen flow added to air.

For the methane flow rate of 3.14, 15, 20 and 25*$10^{-6}$$m^3$/s, the variation of the lift-off height for different air flow rates, with the percentage of oxygen is shown in Figure 2. Results published in Gilard et al. [12] for a methane/air flame at 21% of oxygen are also reported figure 2.

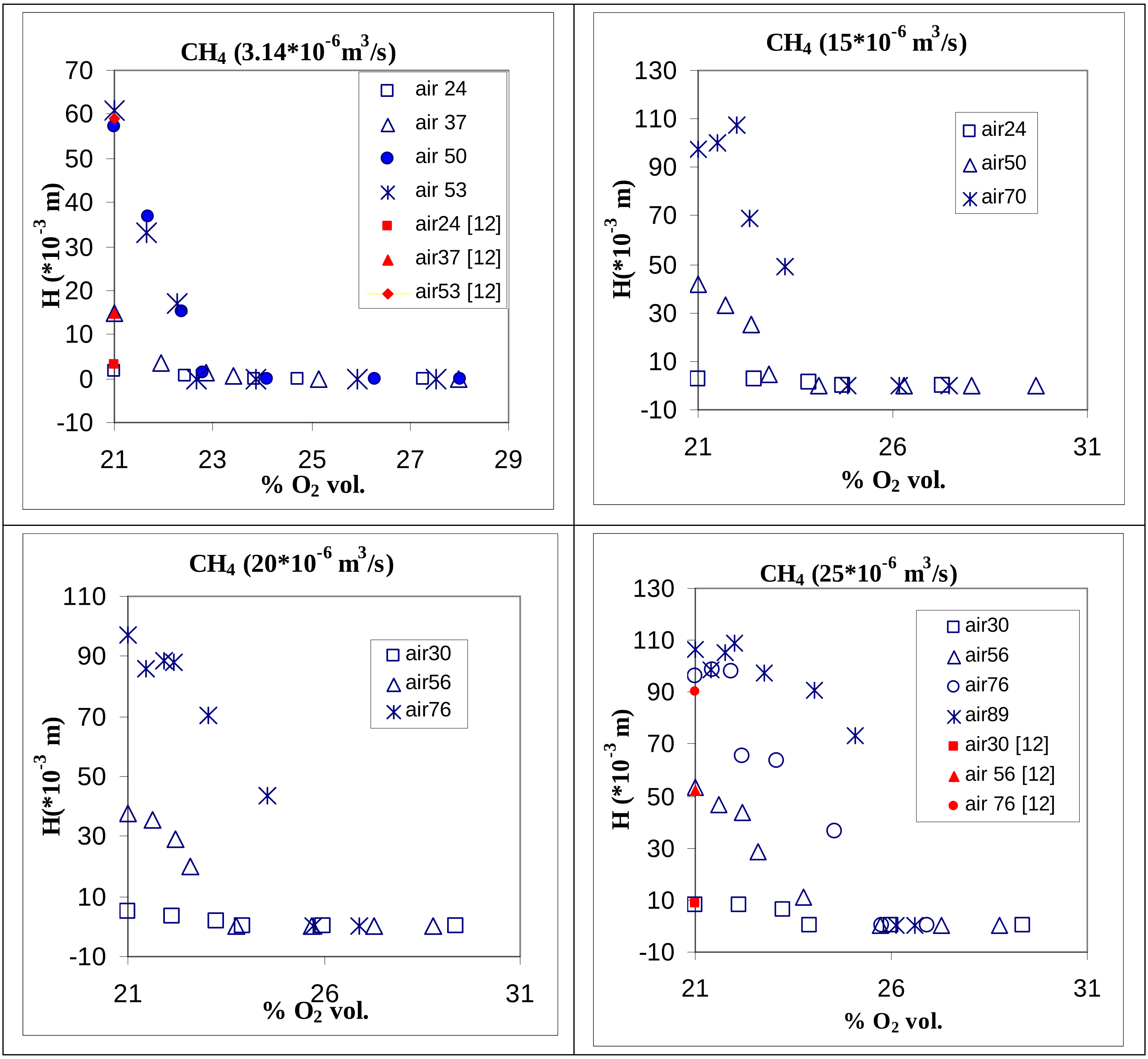

Figure 2.Evolution of lift-off height with the oxygen percentage in air and air flow rates ($*10^{-6}m^3/s$).

We note that, in agreement with the Gilard's results, the lift-off height to 21% oxygen is more important for a greater initial air flow rate. This is validated for the four studied cases of methane flow rate. This is also true for all cases where the flame is lifted. Oxygen enrichment contributes to the reduction of the height of lift, to anchor the flame at the burner rim (H = 0).

The percentage of oxygen corresponding to the attachment of the flame depends on the flow rates of methane and air. For $3.14 *10^{-6}$ m^3/s of methane, the flame is attached to the burner for oxygen percentages ranging between 22.5 and 25%. The lower bound of this interval is increased to 24% for $15*10^{-6}m^3/s$ of methane. For $20*10^{-6}m^3/s$ of methane and depending on the initial air flow rate injected, attachment of the flame to the burner occurs between 23.7 and 25.7% oxygen. This interval extends from 23.8 to 26.1% for a methane flow rate of $25*10^{-6}m^3/s$.

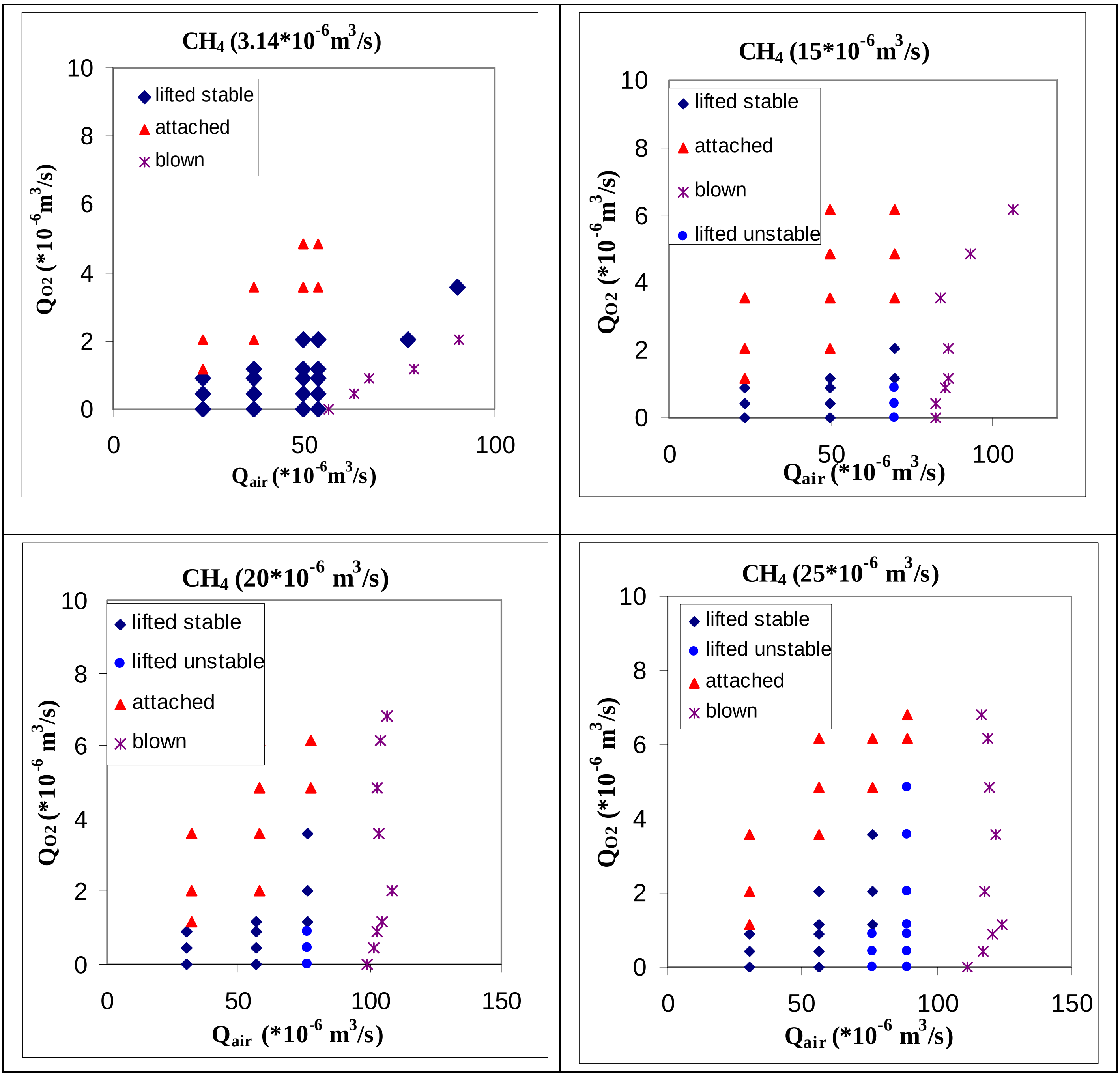

Figure 3. Stability diagram of the flame function of Q_{air} ($*10^{-6}m^3/s$) and Q_{O2} ($*10^{-6}m^3/s$).

The different behaviours of the flame under injection conditions of air and oxygen are summarized in stability diagrams shown in Figure 3 for each methane flow rate investigated. Four states of the flame are identified: attached to the burner, stable lifted flame corresponding to a flame base position varying slightly over time, the state of unstable lifted flame entirely blue coloured showing a position of front flame strongly oscillating and the case where the flame is blown out conditions of equilibrium between propagation speed and flame speed flow cannot coexist.

For a methane flow rate of $3.14*10^{-6}m^3/s$, only three states of the flame are reported in the ranges of air and oxygen flow rates. For oxygen flow rate less than $2*10^{-6}m^3/s$, and increasing the flow rate of air, flame changes from a lifted stable to blown. The air flow rate able to blow out the flame with increasing oxygen flow rate. The flame is stabilized by adding oxygen. Similarly, for greater initial air flow rate, the oxygen flow rate needed to attach the flame increases.

For $15*10^{-6}m^3/s$ of methane and initial air flow rate of $71*10^{-6}m^3/s$, the flame initially becomes stable by adding $1*10^{-6}m^3/s$ oxygen before adding attaching for $3.5*10^{-6}m^3/s$ of oxygen. This same behaviour is observed for a methane flow rate of $20*10^{-6}m^3/s$ and an air flow rate of $76*10^{-6}m^3/s$, and for 25 cm^3/s of methane and $76*10^{-6}m^3/s$ of air. Whereas, for $25*10^{-6}m^3/s$ of methane and $90*10^{-6}m^3/s$ of air, the flame undergoes a direct transition between the lifted unstable state and an attached flame by adding $6.2*10^{-6}m^3/s$ of oxygen. The limit curve of blowing is pushed towards greater air flow rates by increasing the methane flow. Transitions, lifted flame – blown-out, are denoted by a line almost straight. The flame stabilized at the exit of the burner becomes more difficult to blow out.

The theoretical flame length, calculated using the formula given by Roper [5]:

$$L_f = \frac{Q_F \left(T_\infty / T_f\right)^{0,67}}{4\pi D_\infty \ln(1+1/s)}$$

where Q_F is the fuel flow, T_f is the flame temperature, D_∞ is the diffusion coefficient of O_2 in N_2 and *s* is the stoichiometric ratio between fuel and oxidizer. L_f is shown in Figure 4. This length depends on the flow rate of methane and oxygen percentage. It increases with the flow rate of methane. For Q_{CH4}=$3.14*10^{-6}$ m^3/s, the experimental flame length is represented and values are close to the calculated values. However, for the same flow of methane, when adding oxygen in the air, this length decreases. The slope of decline increases with the flow rate of methane.

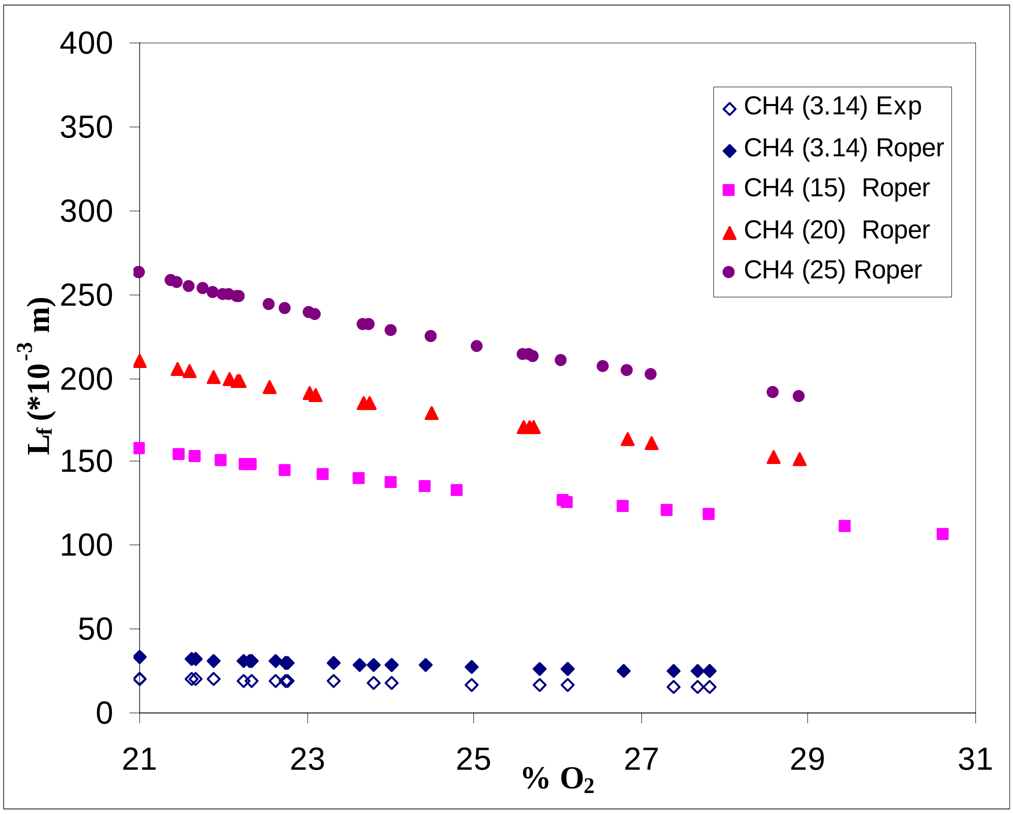

Figure 4. Experimental and theoretical flame length calculated according to Roper's formula for different methane flow rates ($*10^{-6}$ m^3/s) and oxygen percentages.

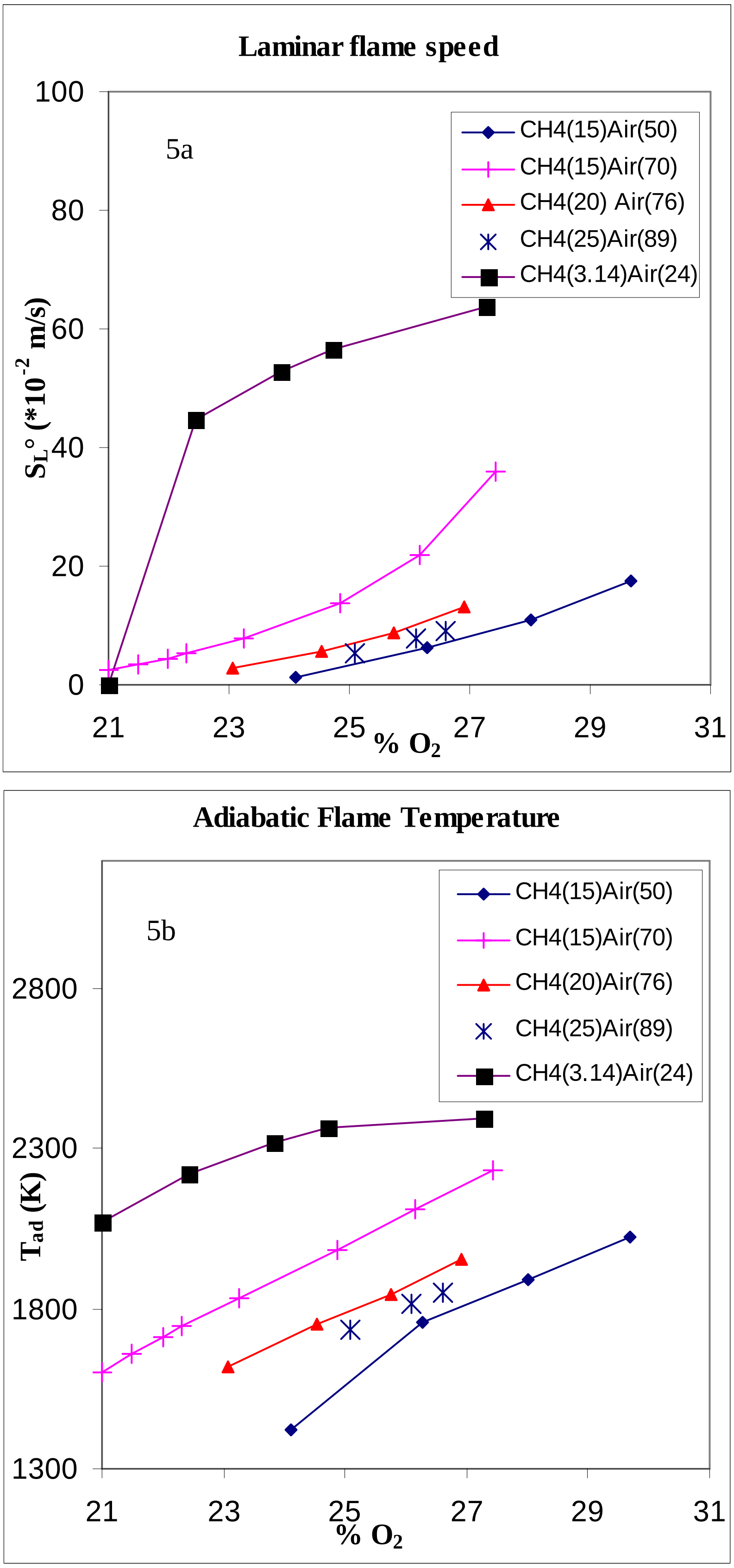

Figure 5. Laminar flame speed and adiabatic flame temperature calculated for different methane and air flow rates (*$10^{-6}m^3/s$) and oxygen percentages.

The mechanism of the experimentally decrease of the lift-off height in oxygen enriched air, can be based on the description of a laminar lifted flame. As described by S.H. Chung [13], lifted flames stabilized in jets possess a tribrachial structure: a diffusion flame, a lean premixed flame, and a rich premixed flame that all extend from a triple point situated on the stoichiometric contour. The position of this triple point (which corresponds to H) is determined by the balance between the local flow velocity at this point and the flame propagation speed. To support this, we calculate the laminar flame speed S_L^0 corresponding to each experimental condition. Premix code (CHEMKIN package) with the GRI-Mech 3.0 is used. Results are reported figure 5a. It is shown that increase in O_2 content of air flow leads to an increase in the laminar flame speed. At constant local flow velocity, an increase of the flame propagation velocity induces a decrease of the lift-off height.

In the same calculations with Premix, the adiabatic flame temperature T_{ad} is obtained and results are reported figure 5b. It appears that T_{ad} is increasing with O_2 enrichment. As T_{ad} increases, the flow redirection at the triple point due to the heat release is increased [14]. Hence, the local flow velocity at the triple point is less. It is another mechanism explaining the decrease of the lift-off height.

We can also note that the adiabatic flame temperature increases when the oxygen percentage increases (see Figure 5b). Since the theoretical length of the flame is inversely proportional to the adiabatic flame temperature, according to Roper [5], this leads to a theoretical length of the flame decreases with oxygen enrichment (see Figure 4).

Conclusions

An experimental study on the effect of enriching the air with oxygen on the behaviour of a laminar flame after a circular central jet of methane and a coaxial jet of air is achieved. Stabilization of an unstable lifted flame and attachment of a lifted flame are noted. The theoretical and experimental flame lengths are reduced. These results can be explained by the simultaneous increase of the laminar velocity and adiabatic flame temperature while enriching air with oxygen.

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