Stability of laminar diffusion flames of methane in an oxygen-enriched air co-jet.

P. Gillon, M. Chahine, B. Sarh, V. Gilard, J.N. Blanchard
ICARE-CNRS Orléans France

1 Introduction

Oxygen rich combustion improves the energy efficiency as combustion involves less nitrogen which acts as a thermal trap. Due to a lower loss of heat energy through the flue gas, flame temperature is increased but, at high temperature, NO_x and soot formation is enhanced. Another characteristic of oxygen enriched combustion is the concentration of CO_2 in the flue gas, allowing an easier separation for capture. Diffusion flames are widely used in industries. Due to the injection mode, those flames are particularly unstable: lift-off, oscillations and blow-out perturb the running of the installations.
We propose here to study the influence of oxygen enrichment of air on the behaviour and the stability of a diffusion flame issuing from a laminar jet of methane and a co-jet of O_2-enriched air.

2 Experiment

The apparatus consists of a burner, flow controllers and systems for visualizations. The burner is made of two concentric stainless tubes: pure methane flows out of the inner one of 4 mm i.d. and the mixing O_2+air flows out of the annular one of 10mm i.d. Wall thickness is 1 mm except at the exit where it is of 0.4 mm. The burner length is 210 mm long enough to insure fully developed flows. Air, oxygen and methane flow rates are metered using mass flow meters. Oxidizer stream is obtained by mixing air and pure oxygen prior to the burner. Experiments are performed in ambient air at atmospheric pressure. The protocol is as follows: for a fixed methane flow rate, oxygen content is increased step by step and air flow rate decreased in order to keep the oxidizer flow rate Q_{ox} constant. Table 1 gives the range of experimental conditions used in the experiments and the Reynolds number based on the mean exit velocity of the two jets. Conditions at the exit of the burner are always laminar. Flame lift height and flame length are determined from the images by a numerical treatment, each value reported being the mean value from 100 images.

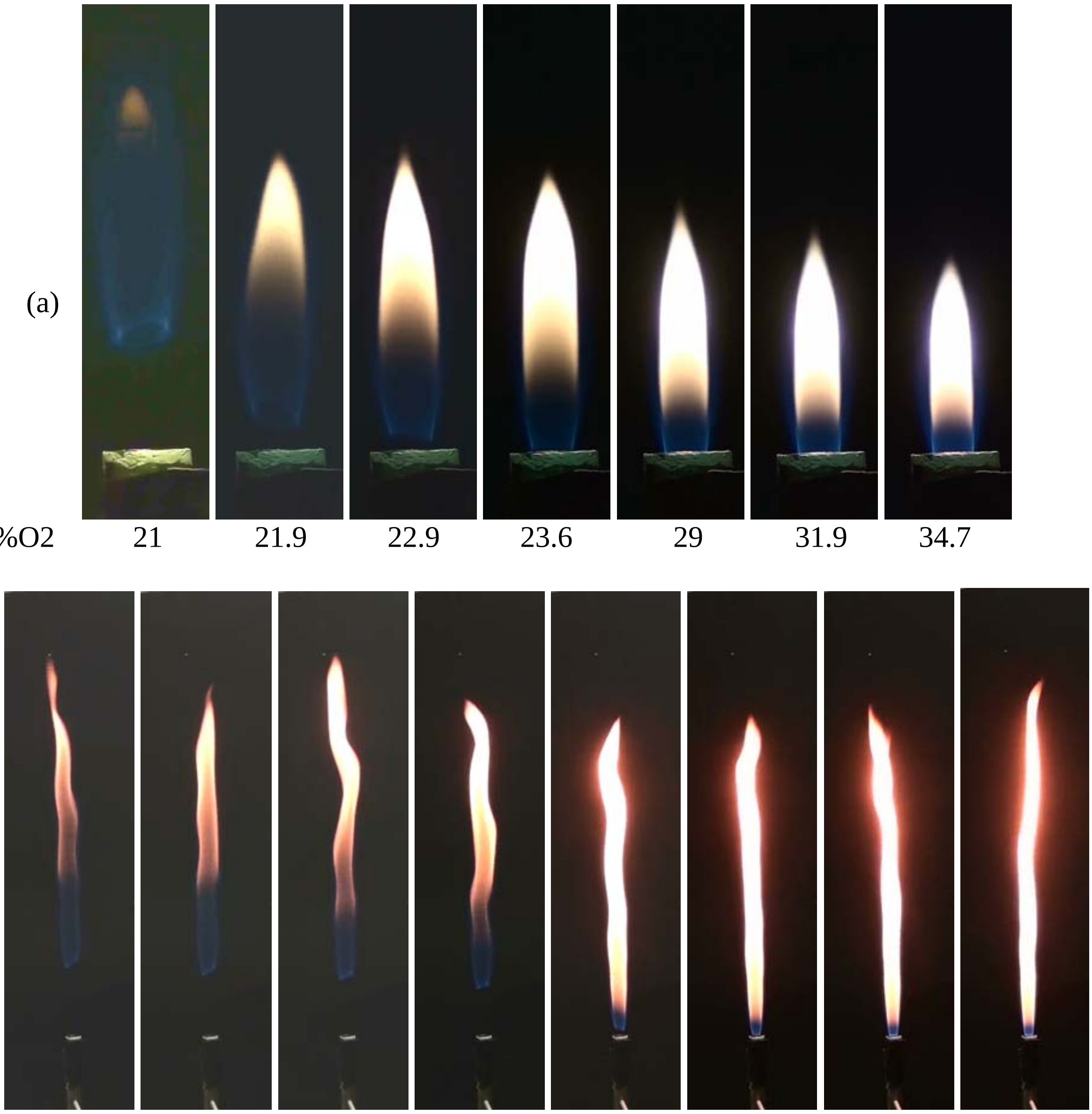
Q_{CH4} (10^{-6} m^3/s)	Re_{CH4}	Q_{O2} (10^{-6} m^3/s)	Q_{ox} (10^{-6} m^3/s)	Re_{ox}	% vol. O_2
3.14	80.6	0-6.16	23-52	68.6-155	21-38
25	460	0-6.8	29-88	86.4-262	21-38

Table 1 : experimental conditions.

Correspondence to: gillon@cnrs-orleans.fr

3 Results and discussion

Photographs of the flame at increasing O_2 content in the oxidizer stream are shown in Fig.1 for the methane jet Reynolds number of 80.6 and 460 defined by Re = $(u_0 d)/\nu$, where u_0 is the mean velocity at the nozzle exit, d the nozzle diameter and ν the kinematic viscosity of methane. For Re=80.6, the flame is lifted in air for 21% and the lift is decreased as O_2 content increases; the flame attaches to the burner rim above 23.5%. The flame blue length and radius decrease and the white zone at the flame top extends and becomes more luminous. The flame is stable showing a smooth flame front typical of a non premixed laminar jet flame.



(a)

%O2 21 21.9 22.9 23.6 29 31.9 34.7

(b)

$\%O_2$ 21 21.6 22.2 22.7 23.9 26.1 28 29.8

Figure1 Flame photographs at increasing oxygen content. (a) $ReCH_4$= 80.6.Q_{ox} =36 10^{-6} m^3/s; (b) $ReCH_4$= 460. Q_{ox} = 55 $10^{-6} m^3/s$.

When the methane Reynolds number is 460, in air (at 21%O_2) the flame is lifted, its position oscillates in time and the flame front at the edge of the flame is perturbed by instabilities. This unstable lifted regime described in [1] corresponds to an instability which develops in the flow field upstream of the flame. Attributed to the difference of velocity between the two jets, this flow instability appears at a certain distance of the burner. At increasing O_2 content, the lift height decreases, the flame edge becomes stable (22-24%) and then the flame anchors at the burner tip above 25%. As O_2 increases, the flame diameter is thinner, with a reducing blue zone and a strong luminous top characteristic of high temperature and soot phenomena.

Variations of visible lift height and flame length with oxygen content are reported Fig.2 for the two Re numbers and for various values of the oxidizer stream flow rate Qox. The decrease of the lift height with the oxygen content is confirmed by the measurements. The value of the oxygen content necessary to anchor the flame to the burner depends not only on the methane exit velocity but also on the velocity of the co annular jet. Considering a set of experiments performed at the same oxidizer and fuel exit velocities, it is observed that increasing the O_2 content leads to a decrease of the lift height. On the curve at $ReCH_4$=460, at increasing oxygen content one can distinguish the unstable lifted regime corresponding to the slow decrease of the lift height, the stable lift regime showing a stronger slope and the attached regime where le lift height is null.

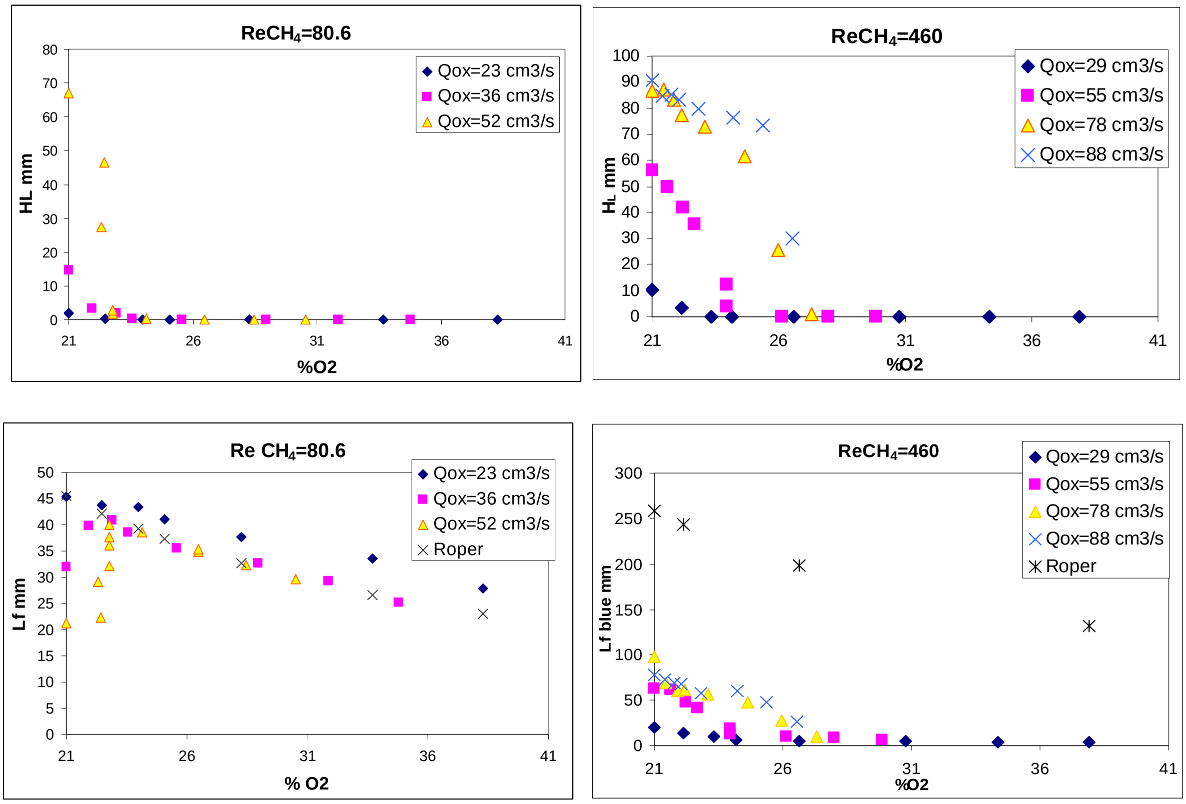


Figure 2: Variation of flame lift height and flame length versus oxygen content of the oxidizer stream for different oxidizer flow rate in cm^3/s.

As detailed in the review article of S.H. Chung [2], a lifted flame exhibits a triple flame structure composed of a fuel-rich, a fuel-lean premixed flames and a trailing diffusion flame, all three connecting at the triple point situated on the stoichiometric line. The lifted flame is stabilized where the local flow velocity matches the flame propagation speed on the stoichiometric line. The propagation speed with respect to the unburned mixture is a key parameter in determining the lift height. Increase the oxygen content of the oxidizer stream will produce different effects all acting on the propagation speed. The laminar burning velocity is shown to increase in the experimental measurements of J.W. Han et al. [3]. Due to thermal expansion, the flow field diverges at the flame edge and this divergence is related to the flame temperature. As the streamlines diverges, the local flow velocity is reduced at the flame edge. Oxygen enrichment increases the flame temperature hence leading to a stronger effect on the local flow velocity. Oxygen enrichment modifies the mixture fraction gradient and as the mixture fraction gradient decreases, the triple flame speed increases (Goshal and Vervish [4]). All these effects conjugate to draw the triple point of the flame downwards as the oxygen content increases.

For Re= 80.6 the total visible flame length is reported, whereas for Re=460, it is the length of the blue part of the flame. In each case, the flame length decreases with oxygen enrichment. Experimental data are compared to the ones obtained using the correlation given by Roper [5] for diffusion flame issuing from a circular port. In the case of Re_{CH4} =80.6, experiments and calculated values show a good agreement whereas the calculated values for Re=460 are much higher than the experimental data. It is due to the difficulty to determine experimentally the exact flame length in this case as the soot phenomena superimposed on the flame contours.

When varying the control parameters, CH_4, air and O_2 flow rates, a variety of flame behaviours is observed corresponding to different mechanisms of flame stabilisation. The observed flame structures are displayed in the two diagrams Fig.3, reporting the limits of the different regimes: anchored flame, stable and unstable lifted flame and extinction by blow-out.

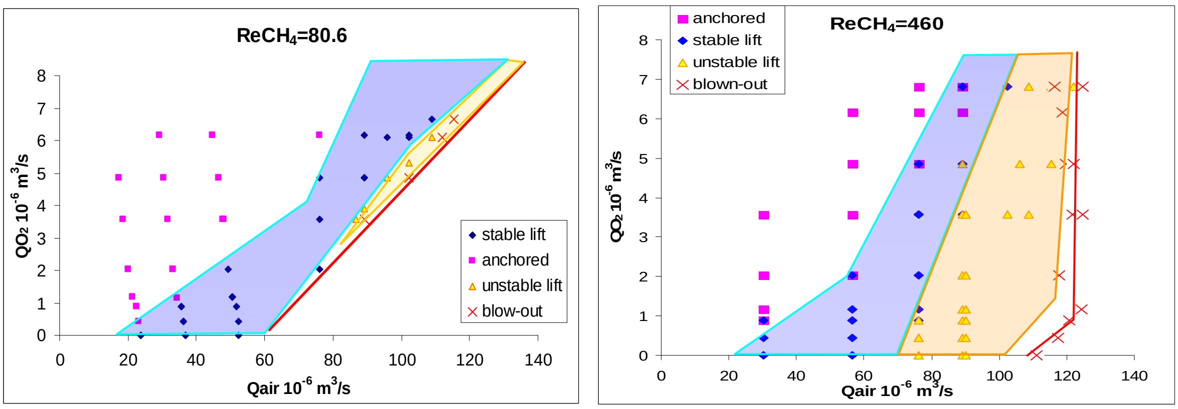


Figure 3 Stability diagrams

The diagrams show that adding oxygen to the air enhanced the stability of the flame. For the case of low methane Reynolds number Re=80.6, the domain of lifted flames appears above a critical air flow rate. Addition of oxygen is stabilizing: at fixed air flow rate, it produces a re-attachment of the flame to the burner. At increasing oxygen flow rates, the lifted flame domain is pushed towards higher air flow rates evidencing a more stable lifted flame against the air flow rate. A regime of unstable lift is observed at high O_2 and air flow rates just before the flame blow-out. This stabilization effect of oxygen enrichment is less pronounced for the case of Re=460. The stability diagram presents the four domains of attached, stable lifted, unstable lifted flames and blow-out with an extended unstable lifted flame domain. It appears that the limits of the different domains are influenced by oxygen only in the very low addition range. Above 2 10^{-6} m^3/s, transitions from one regime to another are essentially defined by the air flow rate showing that flow dynamic dominates chemistry.

4 Conclusion

We experimentally investigated the behavior of a laminar non premixed methane flame from a coaxial burner with a co jet of oxygen enriched air at different oxygen content ranging from 21 to 38 vol. %. We focus on how the lift height and the flame length change with oxygen concentration on the co jet stream. It is shown that the addition of oxygen produces a decrease of the lift-height, a reduction of the length of the reaction zone with an increase in the soot emission and stabilizes the flame structure against the instabilities developing in the flow field upstream. The decrease of the flame lift height can be attributed to an increase of the propagation speed of the flame edge. The redirection of the flow upstream of the flame is enhanced as oxygen content is increased due to a stronger thermal effect which increases the density variations.

References

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