Experimental study of a flickering methane diffusion flame with co-flow of oxygen enriched air

Virginie GILARD[a,b], Pascale GILLON[b], Brahim SARH[a,b]
[a] IUT d'ORLEANS
[b] ICARE-CNRS INSIS UPR 3021 ST2I-CNRS
1C, avenue de la Recherche Scientifique – 45071 Orléans Cedex - France
Orléans, France

1 Introduction

Most of the industrial systems of combustion use the diffusion flames where oxidizer and fuel are injected separately. This non-premixed combustion is more safety and easy to implement but is characterized by a stabilization or a non-lifted flame more difficult to control which will determine the performances of the combustion system. Laminar diffusion flames are known to oscillate at low frequency (10 – 20 Hz) depending upon the operating conditions [1]. The phenomenon of flame tip oscillations (flickering) is attributed to the interactions between vortices in the ambient flow and the front flame. The Kelvin-Helmholtz instabilities generate outer toroidal vortices which could be driven by buoyancy at the interface between hot combustion products and cold ambient air [2]. In combustion studies, Froude number ($Fr=U^2/(gd)$) is a dimensionless number comparing inertia and gravitational force and is characteristic of buoyancy [3].

The effects of different factors on flickering motion were explored in many studies. Arai *et al.* [4] used a centrifuge configuration to generate elevated gravity fields and studied the gravity effect on the stability of propane diffusion flames. Frequency of flickering increased with an increase of gravity level. This effect was explained by the increase of the vortices convection velocity and the decrease of the vortices wavelength with an increase of buoyant force acting on the hot burned gas. The flickering frequency at various gravity levels could be summarized by the relation of $St \propto Fr^{-0.57}$, binding Strouhal number with Froude number. Darabkhani *et al*. [3]- [5] studied the effect of fuel and co-flow velocities on the flickering of a methane diffusion flame with air co-flow. They noticed that the flickering frequency is not function of fuel flow rate but varies linearly with the air co-flow rate for low methane flow rate. They also observed that the flame oscillation magnitude and wavelength decrease continuously with increase of the air co-flow. Based on schlieren and PIV images, they observed the disappearance of the flame flickering when the air co-flow rate is strong enough to push the vortices outside the flame zone. The influence of different oxygen concentrations in ambient air on a diffusion flame flickering was investigated experimentally by Gotoda *et al.* [6]. In the case of non-lifted weak diffusion flames of methane, for an increase of the oxygen rate in the ambient air, an increase in frequency and a decrease in the amplitude of the flame tip oscillations are observed. All of these studies refer to non-lifted diffusion flames at low fuel flow rate.

In this paper, we proposed to investigate the effect of the oxygen enriched air co-flow on stability of a lifted laminar diffusion flame of methane. From flame images, flame characteristics, such as length, width, lift-off height and frequency of the flame tip oscillation are obtained. Flame stability is expected to be influenced by shear layer instabilities of jet coaxial configuration but also by the air oxygen enrichment with the modification of chemistry and flame temperature and thus the properties of the oxidizer and buoyancy.

2 Experimental setup

Figure 1 shows a schematic of the burner system that has been used in our previous work [7]. The unconfined, axisymmetric, laminar diffusion flame was established at atmospheric pressure and ambient temperature. The burner consists of two concentric tubes; the inner one of 4 mm diameter (D_i) is surrounded by an external annular tube of 10 mm inner diameter (D_o). Methane was used as the gaseous fuel and supplied through the inner tube, while oxygen enriched air with different oxygen concentrations used as the oxidizer flows through the annular tube. To obtain oxidizer, oxygen rate was mixed with air rate ahead of the burner. The rate of methane and oxidizer were regulated with mass flow controllers with an accuracy of 3%. The different physical parameters of fuel and oxidizer for experiments were reported in the Table 1. The methane jet mean exit velocities are in a range between 0.36 and 0.72 m/s with Reynolds numbers ($Re = U_{CH4}D_i/\nu_{CH4}$) from 83 to 168. The oxidizer mean exit velocities are in the range between 0.36 and 0.81 m/s with Reynolds numbers ($Re = U_{Ox}(D_o-D_i)/2\nu_{ox}$) from 63 to 152. The oxygen concentration in oxidizer was varied from 21 % to 40 % (Table 2). The Froude number is also calculated and gives some information on the buoyancy; it is defined as $Fr = U^2/gd$, where g is gravity constant, U is the average burner exit velocity of gas and d is the characteristic length (4 mm for methane and 2.8 mm for oxidizer).

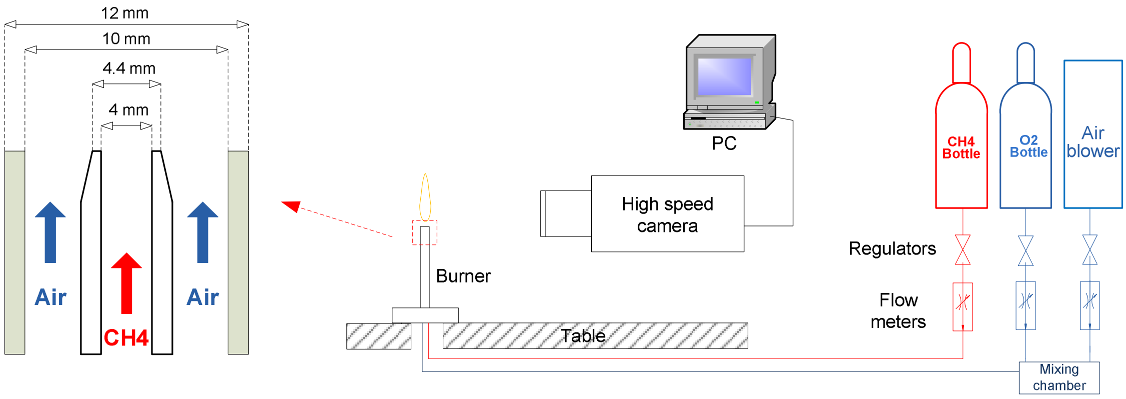

Figure 1: Experimental setup of burner and visualization instrumentation

A high speed CCD Camera (Phantom V1210) was used to capture the evolution of the flame structure. Series of flame images (1200 x 800 pixels) were recorded during 10 s at a framing rate of 100 Hz, with an exposure time were adapted to each configuration. 1024 images were recorded to obtain the convergence of the statistics and to realize FFT analysis.

Through the histogram shape-based threshold method [8] and a median filter, the lower and upper points of the flame were detected in each image, and allow to determine the mean luminous flame length L_f (tip flame height from the nozzle) and the lift-off height H_L(flame base from the nozzle). After acquiring the time series data, FFT analysis were used to evaluate the oscillation frequency of the tip flame. The relative uncertainties were estimated at 0.5 mm for the distance measurements and for the frequency measurement at 0.1 Hz.

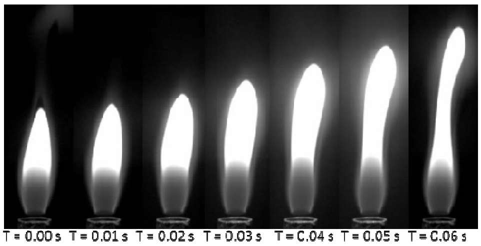

Figure 2: Flame images for QCH4=4.5 cm^3/s and Qair=22.61cm^3/s.

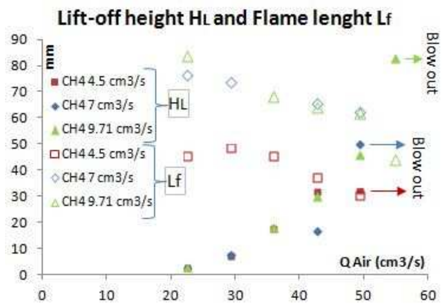

Figure 3: Flame lift-off height and flame length versus the co-flow rate at 4.5, 7 and 9.71 cm^3/s methane flow rate.

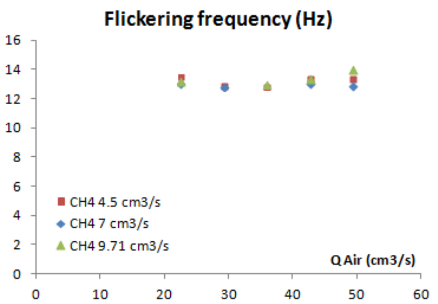

Figure 4: Flickering frequencies versus the co-flow rate at 4.5, 7 and 9.71 cm^3/s methane flow rate.

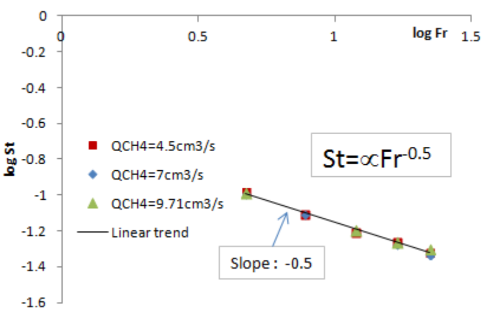

Figure 5: Strouhal number versus Froude number at 4.5, 7 and 9.71 cm^3/s methane flow rate.

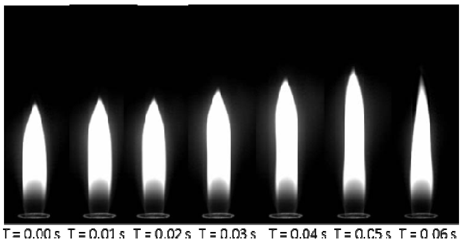

Figure 6: Flame images for QCH4=4.5 cm^3/s and Qox=22.61 cm^3/s with 25.73 % of O2.

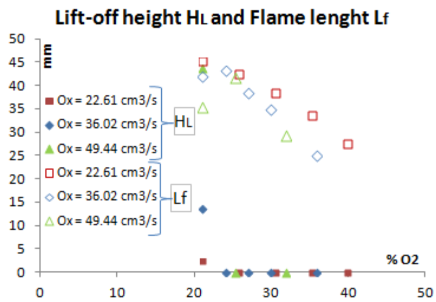

Figure 7: Flame lift-off height and flame length versus the oxygen content for different air flow rate at 4.5 cm^3/s methane flow rate.

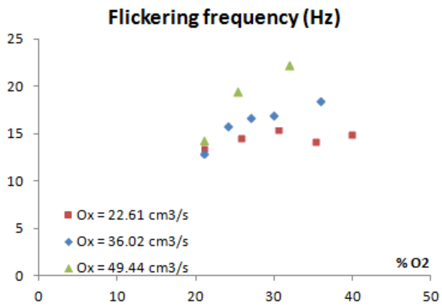

Figure 8: Flickering frequencies versus the % O_2 in co-flow rate for 22.61, 36.02 and 49.44 cm^3/s oxidizer flow rate at 4.5 cm^3/s methane flow rate.

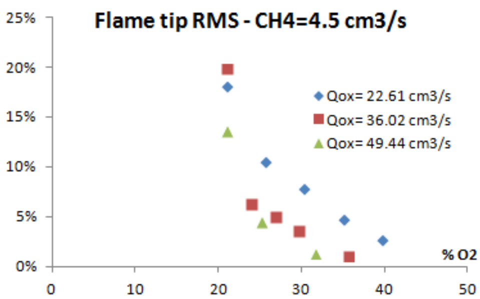

Figure 9: Flame tip RMS versus the % O_2 in co-flow rate for 22.61, 36.02 and 49.44 cm^3/s oxidizer flow rate at 4.5 cm^3/s methane flow rate.

Table 1: Fuel and air parameters

az	Volume flow rate (cm^3/s)	Velocity m/s	Re No.	Fr No.
CH4	4.5	0.36	83	3.27
	7	0.56	129	7.92
	9.1	0.72	168	13.38
Air	22.61	0.36	63	4.64
	29.32	0.46	82	7.81
	36.02	0.57	100	11.79
	42.73	0.68	119	16.59
	49.44	0.78	138	22.21
	54.81	0.87	152	27.29

Table 2: Oxidizer parameters and % O2

Oxidizer volume flow rate (cm^3/s)	Air volume flow rate (cm^3/s)	O2 volume flow rate (cm^3/s)	% O2
22.61	22.61	0	21
	21.27	1.35	25.73
	19.92	2.68	30.38
	18.58	4.07	35.2
	17.24	5.4	39.83
36.02	36.02	0	21
	34.68	1.35	24
	33.34	2.68	26.88
	32	4.01	29.8
	29.32	6.73	35.74
49.44	49.44	0	21
	46.76	2.68	25.29
	42.73	6.73	31.74

3 Results and discussion

Air co-flow effect

Figure 2 shows a sequence of images, representing a characteristic period of the flame structure, obtained at a methane flow rate of 4.5 cm^3/s and an air flow rate without oxygen addition of 22.61 cm^3/s. The time interval between two images is 0.01 s. With these conditions, the flame is lifted above the burner rim at a distance of 2.4 mm. The position of the base of the flame is stable; it does not evolve in time. The flame has a blue base, a yellow middle zone and a white upper part showing the formation of soot. We can also observe that the flame tip location evolves between a lower position to a higher position in the sequence of images. A flickering phenomenon is clearly present. In addition, the front flame appears distorted and suggesting the presence of vortices at the interface of the flame front and the ambient air, which are able to reduce the flame diameter. The vortices follow the front flame downstream direction. The oscillation of the flame tip is formed from interactions between the vortices and the flame front. We observed one of the flickering types called « flickering tip » by Sato *et al.* [9]. For higher air flow rates ($Qair > 40\ cm^3 / s$), the reduction of the flame diameter is sufficient to have a detachment of the top of the flame. The other flickering type called « bulk flickering » by Sato *et al.* [9] is observed here. The zone between flame and the top flame detachment would corresponds to a higher local mixing of methane and air with a higher local flame velocity [6]. It is clearly that the flame structure is influenced by the characteristics (sizes and evolutions) of the vortices in the interface between the front flame and the ambient air. When the air co-flow rate is increased and remains smaller than blow out co-flow rate [10], with a methane flow rate kept constant, the averaged values of lift-off height (H_L) increase and the averaged values of the luminous flame length (L_f) decrease as shown on figure 3 for 4.5, 7 and 9.71 cm^3/s methane flow rate. The values of the flame tip root mean square (*rms*) versus air co-flow rates and for the three values of methane have been determined and are all higher than 1%, indicating that in all configurations the phenomenon of flickering is present [11]. So the flickering frequency is given versus the air co-flow flow rate on figure 4. We can observe, as Darabkhani *et al.* [5], that the frequency is not affected by the methane flow rate. But we do not find a linear trend of the frequency with an increase in air flow rate. Here the frequency is constant and this is confirmed by figure 5, which shows the evolution of the Strouhal number versus the Froude number. Indeed, there is a slope of -0.50, indicating that

$f \propto (g/d)^{0.5}$ and so that the frequency is not dependent of air velocity. With these experimental conditions and the flow rates of methane and air, the flickering frequency is only affected by the burner dimensions.

Oxygen enriched air effect

The increase of the oxygen concentration in air is realized at constant co-flow rate. Figure 6 shows a sequence of images obtained at a methane flow rate of 4.5 cm^3/s and an oxidizer flow rate of 22.61 cm^3/s with an oxygen concentration of 25.73%. The flame is thinner and more stable than with non-enriched air. The flame is attached to the burner rim, has a blue area in the base and has a yellow part before a stretched luminous white zone. The last zone corresponds to the soot emissions which are formed in the end of the flame with a poor combustion conditions due to the oxygen enrichment. As for the non-enriched co-flow case, we can observe that the flame tip location evolves between a lower position and a higher position with no flame detachment in this sequence of images. A tip flickering phenomenon is also clearly present. We note also that the flame front is less disturbed by vortices than non-enrichment case. No flame detachment is observed even with greater oxygen concentration and higher oxidizer flow rate. Figure 7 shows the mean values of flame lift-off height and the flame length versus the oxygen concentration of the oxidizer jet. The lift-off height decreases rapidly and the flame length decreases linearly as oxygen concentration increases so the flame is attached at the burner rim from a 24% oxygen concentration. The oxygen addition stabilizes the flame on the burner rim [7]. Figure 8 shows the flickering frequency versus oxygen concentration for a methane flow rate of 4.5 cm^3 / s and for three constant air co-flow rates of 22.6, 36.02 and 49.44 cm^3 / s. We can observe, as in Gotoda *et al.* [6] studies, that the flickering frequency increases with increase of oxygen concentration. Here, the temperature of the hot combustion products is increased with the oxygen concentration thus affecting buoyancy. The values of the flame tip root mean square (*rms*) versus oxygen concentration for a methane flow rate of 4.5 cm^3 / s and constant oxidizer flow rates of 22.6, 36.02 and 49.44 cm^3/s are presented on figure 9. The tip oscillation amplitude decreases strongly with increase of the oxygen concentration until a value close to 1% for the maximum value of oxygen concentration. This indicates that for the higher values of oxygen concentration the tip oscillations are very low and the flicker is suppressed. It is also observed that when the oxidizer flow rate is greater, suppression of the flickering phenomenon occurs at less oxygen concentration.

4 Conclusion

The effects of the air co-flow oxygen enriched or not on a laminar methane diffusion flame have been studied through flame image experiments. With no oxygen enriched and for ours experiment conditions, the flame flickering frequencies are not affected by methane and air co-flow flow rates. On the other hand, the oxygen addition in air co-flow induces a large change in the temperature of hot combustion products resulting in an increase in the density gradient between these products and the ambient air. We then observed that the flame is attached to the burner rim, the flickering frequency increases with the oxygen concentration and for the higher oxygen concentration, the flickering phenomenon is suppressed.

References

[1] Albers B, (1999), Schlieren analysis of an oscillating gas-jet diffusion flame, Combustion and Flame, 119: 84

[2] Lingens A, Neemann K., Meyer J. , Schreiber M., (1996), Instability of diffusion flames, Symposium on Combustion, 26: 1053

[3] Darabkhani HG, Zhang Y, (2010), Stabilisation Mechanism of a Flickering Methane Diffusion Flame with Co-flow of Air, Engineering Letters, n° 18:4

[4] Arai M, Sato H, Amagai K, (1999), Gravity effects on stability and flickering motion of diffusion flames, Combustion and Flame, 118: 293

[5] Darabkhani HG, Wang Q, Chen L, Zhang Y, (2011), Impact of co-flow air on buoyant diffusion flames flicker, Energy Conversion and Management, 52: 2996

[6] Gotoda HG, Kawaguchi S, Saso Y, (2008), Experiments on dynamical motion of buoyancy-induced flame instability under different oxygen concentration in ambient gas, Experimental Thermal and Fluid Science, 32: 1759

[7] Gillon P, Chahine M, Sarh B, Blanchard JN, Gilard V, (2012) Stabilization of Lifted Laminar Co-Flow Flames by Oxygen-Enriched Air , Combustion Science and Technology, 184: 556

[8] Min J, Baillot F, Guo H, Domingues E, Talbaut M, Patte-Rouland B, (2011) Impact of CO2, N2 or Ar diluted in air on the length and lifting behavior of a laminar diffusion flame, Proceedings of the Combustion Institute, 33: 1071

[9] Sato H, Amagai K, Arai M, (2000), Diffusion flames and their flickering motions related with Froude numbers under various gravity levels, Combustion and Flame, 123: 107

[10] V. Gilard, P. Gillon, J. N. Blanchard, et B. Sarh, (2008) « Influence of a horizontal magnetic field on a co-flow methane/air diffusion flame », Combustion Science and Technology, 180: 1920.

[11] Thomson K, Gulder O, Weckman E, Fraser R, Smallwood G, Snelling D, (2005), Soot concentration and temperature measurements in co-annular, nonpremixed CH/air laminar flames at pressures up to 4 MPa, Combustion and Flame, 140: 222.