Energy Efficiency of a Laminar Jet Methane Flame in a Co-annular Jet of Oxygen-Enriched Air

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1 Introduction

Improving the energy efficiency is a very important concern as the cost of energy is continuously increasing. Oxygen enriched air is useful in energy saving technologies in combustion. Compared to traditional air/fuel combustion, in which nitrogen, used as the inert gas, siphons away a part of the energy to form flue gas, the oxygen enriched combustion involves higher thermal efficiency, lower loss of heat energy through the flue gas, hence higher available heat [1]. Moreover, it contributes to increase the CO_2 in the flue gas, allowing an easier separation for capture process. Diffusion flames are largely used in industry due to the safety link to the separate injection of fuel and air. However, they generally present unsteady behaviour. As shown in a previous paper [2], in the configuration of a coaxial burner, a flame initially lifted off the burner by a co-jet of an air, is gradually dropped down until reattachment when oxygen is incrementally added to air. The stabilization effect of oxygen addition on the flame behaviour is noticeable even at low air enrichment (<25%). The flame adiabatic temperature is strongly increased as oxygen is added: from 2200K for a methane/air flame to 3100K for a methane/oxygen flame. Here, we propose to characterize the flame behaviour through the measurement of the heat transmitted to a heat exchanger as a function of injection velocities and oxygen enrichment.

2 Experiment

Schematic of the experimental set up is shown Fig 1. Combustion of methane is generated at the exit of a coaxial burner and heat transmitted to a system of two exchangers is measured. 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 burner positioned on a vertical stage is inserted inside a cylindrical heat exchanger of 90 mm i.d. and a length of 0.6 m opened at both ends with copper double wall. A second plane exchanger inclined at 45° captures heat leaving from the top end of the first one. Water flows from tap to the first cylindrical exchanger to the plane exchanger at a flow rate of 19.2×10^{-6} m^3/s. Temperature difference of the water between the entrance of the first exchanger and the exit of the second one is measured with thermocouples. At a fixed value of methane, air and oxygen flow rates, the protocol consists to ignite the flame and then to introduce the burner in the exchanger; after 14 minutes, time at which a stationary state is attained, the methane is cut off. Measurement of the temperature difference is performed during 25 minutes after the introduction of the flame.

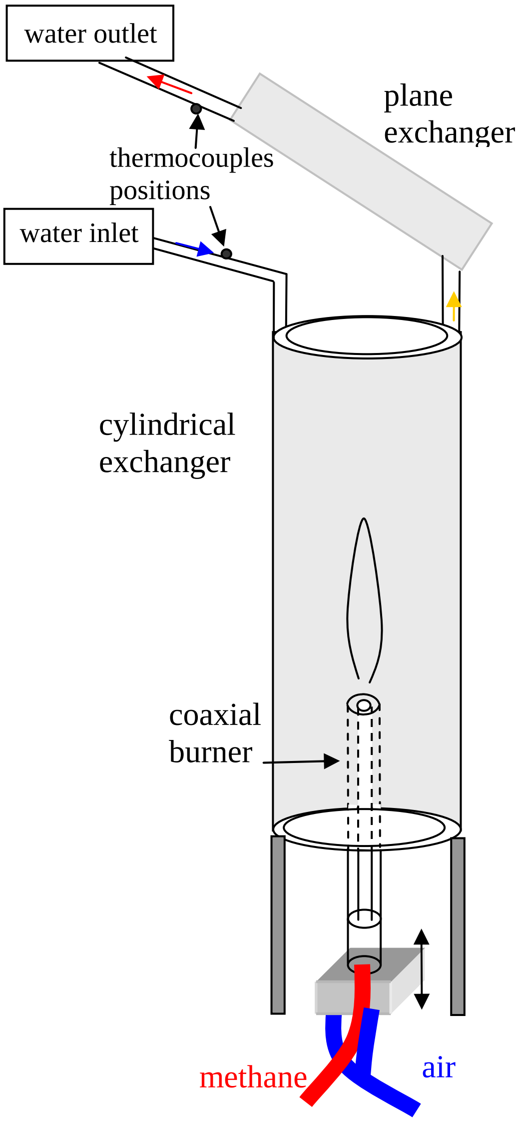

Figure 1: Schematics of the experimental set-up.

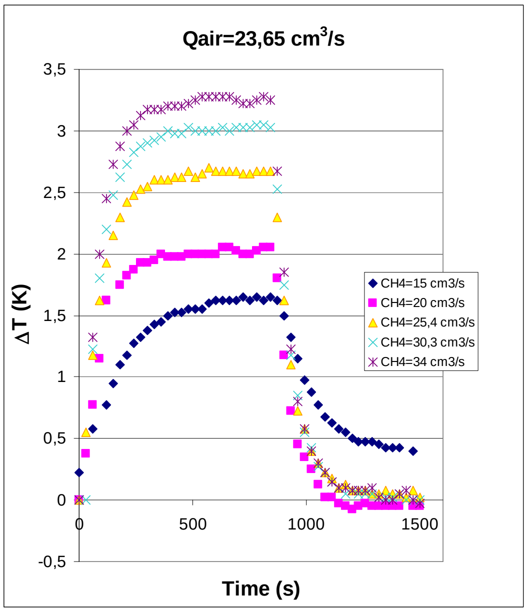

Figure 2: Evolution of temperature difference vs time at Q_{air}=23,65×10^{-6} m^3/s.

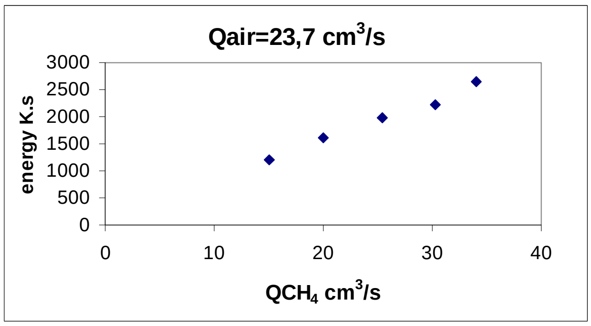

Figure 3: Transmitted energy vs methane flow rate

3 Results

Variation of methane flow rate

The evolution of the temperature difference at different injected methane flow rates for a fixed air coflow rate of 23.7 cm^3/s is shown Fig.2. Each graph is divided in three steps: an increase corresponding to the heating of the volume inside the exchanger, a plateau when the heat produced is balanced by the losses and a sharp decrease corresponding to the cooling in absence of flame.
As expected the plateau is directly related to the injection methane flow rate as also shown on Fig.3 where the energy (as the integral of the temperature curve along the first 14 min) is reported in terms of the methane flow rate.

Variation of air flow rate

Increase of the air flow rate Q_{air} at a fixed methane injection modifies the heat transmitted to the exchanger. As the air injection is increased the water temperature difference between entrance and exit of the exchangers system is observed to decrease. The energy extracted from the thermal graphs is reported for the three methane injection conditions on Fig.4. The observed decrease is explained by an increase of the heat losses at the open top of the cylindrical exchanger as the air flow is increased at injection.

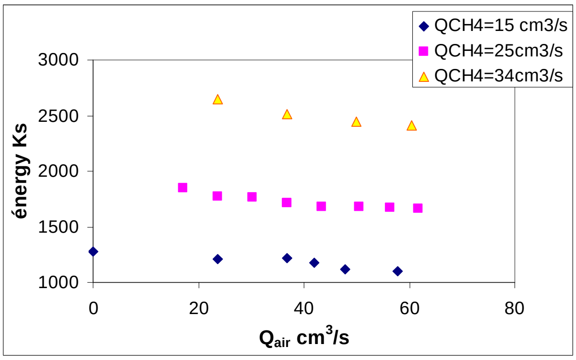

Figure 4: Transmitted energy vs air flow rate at 3 methane flow rates

Oxygen-enriched air

It has been shown that the oxidizer flow rate Q_{ox} is an important parameter in the efficiency of the heat exchangers. To determine the influence of oxygen content on the transmitted heat to the exchangers, experiments are performed at fixed methane and oxidizer injection flow rates. Results for Q_{CH4}=20 cm3/s and 2 values of Q_{ox} are reported on Fig.5 at different oxygen content.

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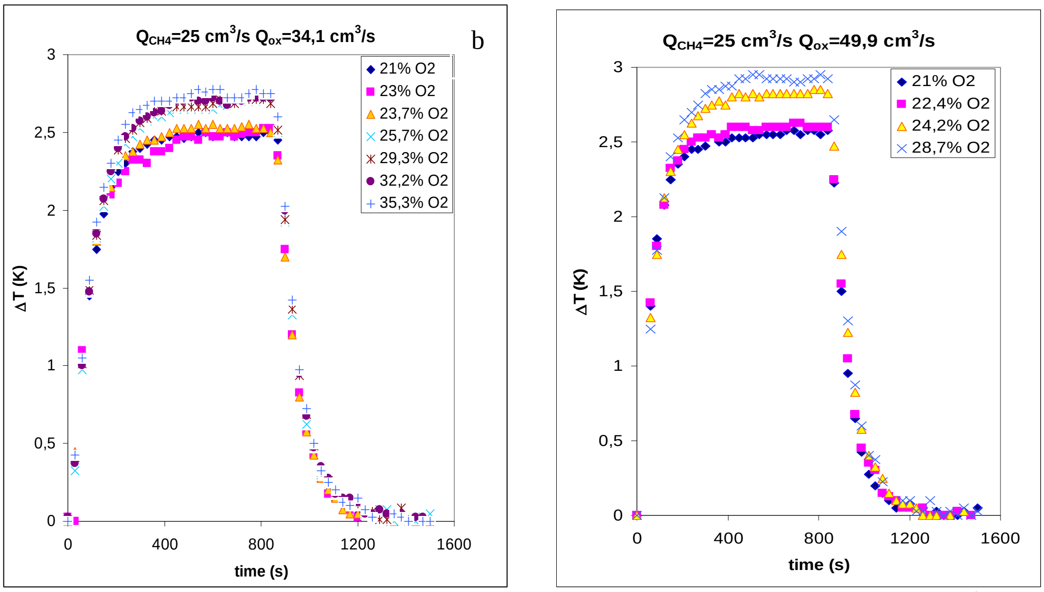

Figure 5: Exchangers heating vs time at different O_2 content (a) Q_{ox}= 34.1 (b) 49.9 cm^3/s

Fig. 5 shows that oxygen enrichment of air increases both the plateau i.e. the maximal temperature difference and the time necessary to attain it. For a same heating value, taken for example at 2.4 K in the present system, it takes 360 s at 21% O2 and 190 s at 41.6 %O2 (at Q_{ox}= 23.7 cm^3/s) to attain the plateau. This gain in time corresponds to a saving of 47% in methane to produce the same heating effect. Two distinct groups of curves appear on figures 4a (4b) illustrating a gap in temperature difference when oxygen content is increased from 23.7 to 25.7% in the case of Q_{ox}=34.1cm^3/s (22.4 to 24.2% in the case of Q_{ox}=49.9 cm^3/s).

In the range of conditions of Fig.5, the flame presents different regimes: anchored to the burner, lifted (stable or unstable). These regimes have been detailed in [2] and a stability diagram has been established. Correlations between the results of fig. 5 and the stability diagram show that the gap observed in the temperature difference corresponds to a shift in the flame regime from a lifted flame to an anchored flame when the oxygen content is increased.

Fig. 6 summarizes the energy dissipated in the exchangers for two oxidizer flow rates of 34.1 and 49.9 cm^3/s as a function of oxygen percentage. Oxygen enrichment is characterized by an increase of the energy transmitted to the exchangers. The results show a change in the slope of two straight lines and the conditions of the transition, materialized by arrows, correspond to the transition between a lifted flame and an anchored one as determined in [2].

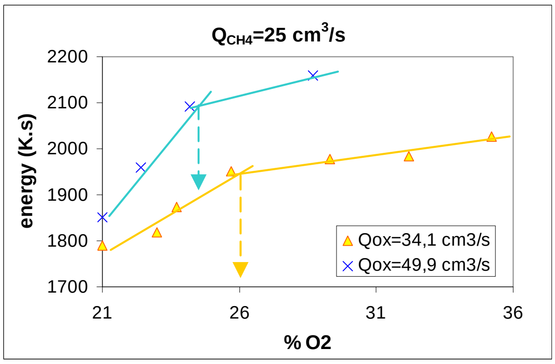

Figure 6: Energy vs oxygen pourcentage

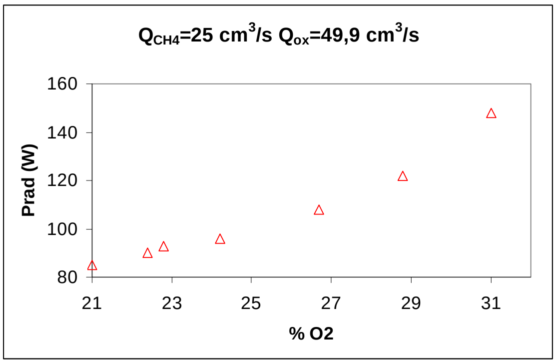

Figure 7: Radiative power vs oxygen percentage

The energy transfer from the flame to the exchangers is composed of conduction, radiation and convection. The radiation depends on the flame temperature, emissivity coefficient and flame surface. For each injection conditions, estimation of the flame adiabatic temperature is performed using the code Premix and the Gri-mech 3.0 mechanism, the flame surface is deduced from measurements of flame length and flame radius and emissivity coefficient is taken to be 0.1. The result for the case of Q_{CH4}=25 and Q_{ox}=49.9 cm^3/s is reported fig. 7. The increase in the energy efficiency when increasing oxygen content is essentially due to the increase of the radiation power. From this, the coefficient of convection can be deduced: it is reported Fig.8 for two cases. The transition from a lifted flame to an anchored flame produces a slope change in the characteristic of the convection coefficient.

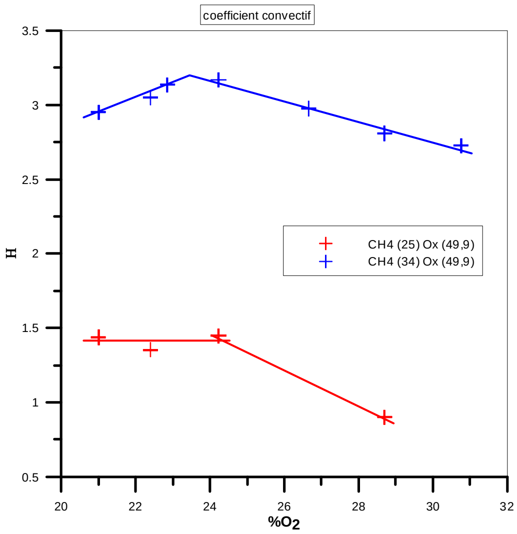

Figure 8: Convection coefficient vs oxygen pourcentage

Conclusion

As expected, oxygen enrichment of air produces a gain in the energy efficiency of a given flame. Less expected is the possibility to deduce the flame behaviour (anchored or lifted) from the measurement of the convection coefficient.

References

[1] Baukal CE. (1998) Oxygen-enhanced combustion. New York: CRC Press.

[2] Gillon P, Chahine M, Sarh B, Blanchard JN, Gilard V. (2012) Stabilization of Lifted Laminar Co-Flow Flames by Oxygen-Enriched Air. Comb.Sci and Tech.184:556.