

# Effects of a Magnetic Field on the Stabilization of a Lifted Diffusion Flame

V. Gilard<sup>\*1,2</sup>, P. Gillon<sup>2</sup>, C. J.N. Blanchard<sup>1,2</sup>

<sup>1</sup> IUT, Université d'Orléans, France

<sup>3</sup> ICARE-ST2I-CNRS Orléans, France

## Abstract

An experimental investigation on the behavior of a lifted diffusion flame with a central methane jet and a surrounding air co-flow is presented. Different regimes of flame stability are described from an anchored flame to a stable lifted flame which is destabilized before extinction. In a second part, the influence of a magnetic field on the diffusion flame is studied. The experimental results show that the lift-off height of the flame is decreased in presence of the magnetic gradient. These effects are attributed to the magnetic force which develops on air via its action on the paramagnetic oxygen.

## Introduction

The diffusion flames, where fuel and oxidizer are injected separately, are used in many industrial combustion processes. However, according to the conditions of velocity injection, the diffusion flame presents different behaviors. The flame may be anchored to the burner, lifted above the burner or blown out. These flame instabilities can be harmful for the energetic efficiency or endangered the system when the flame blows out.

The stability of a lifted diffusion flame strongly depends on the gases mixing upstream of the flame. From the two initially separated flows of fuel and oxidizer, the level of homogeneity of the reactants mixing determines the flame position at a specific distance of the injector outlet and the flame stability. Lifted diffusion flame stabilization has been first described by the triple flame model based on a partial premixing (Phillips 1965). Those flames are composed of two premixed flames; one is fuel rich and the other lean, and a trailing diffusion flame. Triple flames propagate along the stoichiometric line where propagation is optimized, the two lateral premixed wings forming the flame surface downstream. The triple flame model has been studied both analytically (Dold 1989, Hartley and Dold 1991, Ghosal and Vervisch 2000), numerically (Ruetsch et al. 1995) and experimentally (Kioni et al. 1993, Aggarwal et al., 2001).

The jet structures are the essential elements which give the adequate mixing condition for the lifted diffusion flame. In the case of two coaxial jets, hydrodynamic instabilities developed in the shear layers influence the mixing process.

Flows from coaxial jets have been extensively studied, however most of the references are dealing with turbulent flows, see for instance (Rehab et al. 1997, Villiermaux 1998, Sautet et al. 1995). Coaxial jets behavior associates the dynamic of a simple round jet with the one of an annular jet. They are characterized by two shear layers: the internal one between the central jet

and the annular jet and the external layer between the annular jet and the ambient air generally at rest. Those layers are of primary importance in the mixing process. The boundary layers developing along the duct wall separating the two streams produce a wake region behind the wall which interacts also within the near flow field.

When a non uniform magnetic field is applied to a medium, a magnetic force develops due to the magnetic properties –paramagnetic or diamagnetic– of the medium. The magnetic force per unit volume  $F_i$  generated by a non uniform magnetic field on species  $i$ , is given by the Equation  $F_i = (1/2\mu_0) \rho Y_i \chi_i \nabla(B^2)$ . The magnetic force (in  $\text{Nm}^{-3}$ ) is proportional to the mass density  $\rho$  ( $\text{kgm}^{-3}$ ) and the massic magnetic susceptibility  $\chi_i$  ( $\text{m}^3\text{kg}^{-1}$ ) of the  $i$ th chemical species of mass fraction  $Y_i$  and to the gradient of the square magnetic flux density  $\nabla(B^2)$  ( $\text{T}^2\text{m}^{-1}$ ). The magnetic susceptibility  $\chi$ , ratio of the magnetization to the magnetic field strength, is positive and depends on temperature for a paramagnetic substance whereas it is negative, with no dependence on temperature for diamagnetics. In diffusion flames, hydrocarbon fuels, nitrogen, carbon monoxide, carbon dioxide are diamagnetic; oxygen is the principal paramagnetic constituent. As the oxygen paramagnetic susceptibility is orders of magnitude larger, the diamagnetic behavior is considered as negligible.

The influence of a magnetic field on combustion has been extensively referenced. N. Wakayama (1992) investigated methane diffusion flames within magnetic field gradients. It was observed that a decreasing magnetic field along the flame caused its shape more elongated and slender while an increasing magnetic field produced shorter and thicker flames. These effects are attributed to the oxygen strong paramagnetic property and the diamagnetic property of the combustion products. The influence of magnetic gradients on partially premixed and diffusion flames in air are presented by Wakayama (1993). Decreasing magnetic field is found to increase combustion rate for diffusion flames while magnetic fields had little effect

\* Corresponding author: [gilard@cnsr-orleans.fr](mailto:gilard@cnsr-orleans.fr)

on premixed flames. It is concluded that the dominant magnetic action is on the oxygen flow into increasing magnetic fields strength. Yamada et al. (2002) investigated numerically the action of magnetic field on OH radical distribution in a  $H_2/O_2$  diffusion flame. The magnetic gradient is found to change the OH density distribution in the flame. The effect is related to the magnetic force on oxygen and is due to the mass density and the magnetic susceptibility of  $O_2$  which is much larger in the peripheral region of the flame. Yamada et al. (2003) confirm their numerical predictions by experiments: a radial migration of the OH towards the central axis of the flame is driven by the magnetic field. Numerical simulations made by solving the equations of gas dynamics and magnetism show that the magnetic effect is essentially due to the magnetic force acting on  $O_2$  and not directly on OH itself.

Baker et al. (2003) present the experimental behavior of a laminar diffusion flame set in an upward decreasing magnetic field. Under certain conditions, the magnetic force is found to decrease the flame height, prevent the flame from attaching to the magnet assembly, increase the intensity of the flame and the flow rate below which the flame extinguish. A dimensionless analysis shows a correlation between, the experimental results and a dimensionless analysis including buoyancy and magnetic convection.

In our previous study (Gilard et al. 2008), we have observed that the application of a magnetic field gradient can reduce the lift-off height (distance between the base of the flame and the burner) of a lifted diffusion flame of methane and air issuing from a coaxial burner.

In the present study, we focus our attention on the flow field upstream of the flame and on the effects of a magnetic field gradient on the mixing of methane and air.

### Experimental setup and flow conditions

The diffusion flame is obtained from an axisymmetric co-flow burner with a central methane jet and a surrounding air co-flow. The burner consists of 4 mm inner diameter methane jet surrounded by a concentric 10 mm inner diameter co-flow tube. Experiments are carried out in ambient air at atmospheric pressure. The experimental setup is described in Figure 1. The flow conditions are given in Table 1. The two methane mean exit velocities studied are 1.6 m/s and 2 m/s and the air mean exit velocity varies of 0m/s to the max value of 1.6 m/s. In our experiment, the value of the methane velocity is kept constant and the air velocity is increased step by step. The dynamic Reynolds number  $Re=Ud/\nu$  is defined with the mean velocity  $U$ , the inner jet diameter  $d$  and the kinetic viscosity  $\nu$  of methane or air. In experiments, flows are laminar.

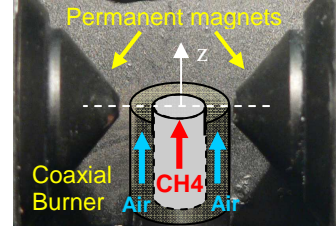


Figure 1: Schematic of the experimental setup.

|             | Mean inlet velocity m/s | Re  |
|-------------|-------------------------|-----|
| Methane jet | 1.6                     | 370 |
| Methane jet | 2                       | 460 |
| Air jet max | 1.6                     | 815 |

Table 1: Experimental conditions.

The exit section of the burner is set between two permanent magnets generating a horizontal magnetic field of 0.35T magnetic induction at its center. The reference axis is the z-axis along the vertical symmetry axis of the magnets assembly and the origin is at the center. The burner axis is aligned with the z-axis and the burner exit section is set at the origin. So gas and flame evolve in an upward decreasing magnetic field.

The distribution of the magnetic induction on the vertical z axis and the calculation of the field gradient square in the vertical direction on the z-axis are given Figure 2. The maximum of  $\nabla(B^2)$   $4.7 T^2m^{-1}$  is reached at  $z = \pm 6$  mm. In these two areas of strong magnetic gradient, the magnetic forces are the strongest.

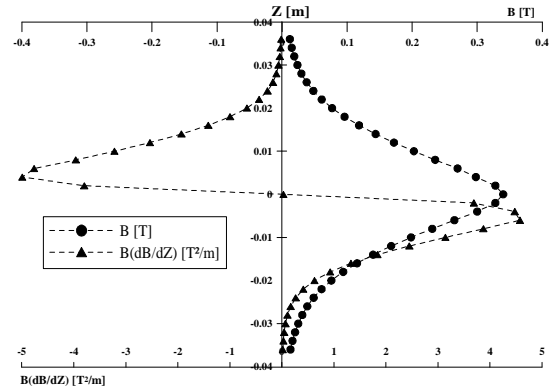


Figure 2: Distribution of the magnetic induction

This study is based on three types of visualizations. First, global visualizations in white light are used to study the lift-off height of the flame and defined the range of the different behaviors of the flame. For this visualization we used a standard numerical camera (Sony HDD, 1megapixels). The flow field upstream of the flame is characterized with the second visualization type. We use the standard numerical camera and the air flow is seeded with incense particles, which are non magnetic, and is lighted by a stroboscope. And last the front flame is observed by a high frame rate intensified CCD camera (Princeton instrument, 1000 Hz, 1024\*1024 pixels).

## Results and discussions

In a first part, the different flame behaviors are described without magnetic field. The lift-off heights of the flame, defined as the distance between the burner rim and the visible base of the flame, are measured from images obtained by global visualization. The variation of the lift-off height with the air mean exit velocity for a methane mean exit velocity of 1.6 m/s is reported on the figure 3.

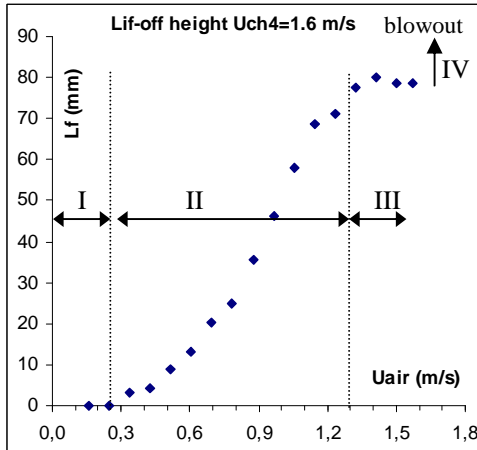


Figure 3: Variation of the flame lift-off height  $L_f$  according to the air mean exit velocity for CH<sub>4</sub> mean exit velocity of 1.6 m/s and without magnetic field.

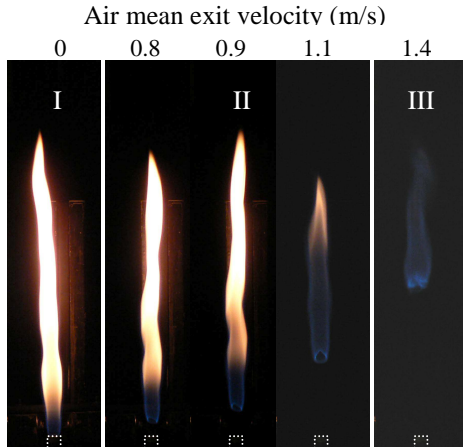
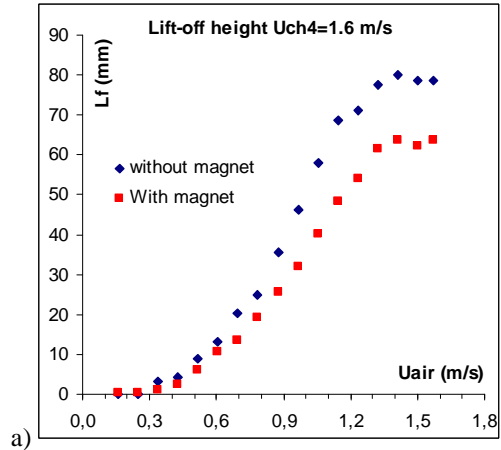


Figure 4: Flame views for  $V_{CH_4} = 1.6$  m/s at different air mean exit velocity and without magnetic field for the three flame behaviors: I attached flame, II stable lifted flame, III unstable lifted flame.

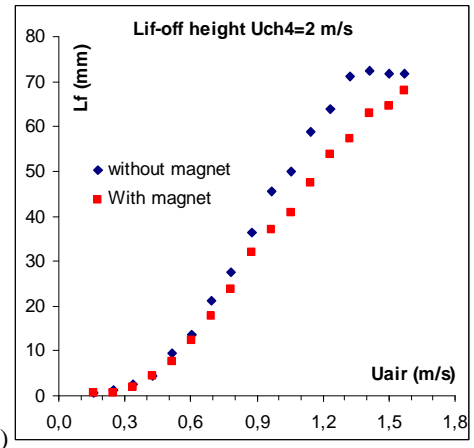
It is observed that the lift-off height of the flame increases with the air co-flow velocity. It is also observed, on the images presented in the figure 4, that the behavior of the flame depends of the air co-flow velocity. So for  $U_{air} < 0.3$  m/s, the flame is stable and attached to the burner rim (regime I), for  $U_{air} > 0.3$  m/s the flame is lifted (regime II and III) and then for  $U_{air} > 1.6$  m/s the flame is blown out (regime IV).

When the flame is lifted two different flame behaviors are observed. In the regime II, for

$0.3 \text{ m/s} < U_{air} < 1.3 \text{ m/s}$  the flame is lifted and stable. This behavior corresponds to a smooth flame base typical of a triple flame. The flame front is formed of two branches: a fuel rich branch develops in the direction of the fuel stream and a fuel lean branch on the air side. The regime III develops for  $1.3 \text{ m/s} < U_{air} < 1.6 \text{ m/s}$ . The tribrachial shape of the lifted flame evolves into a noisy flame with an instable front, quasi planar with spatial and temporal oscillations. In this regime, the lift-off height is found to be constant as  $U_{air}$  is increasing. In the last regime, the flame is suddenly pushed up and then blown out.



a)



b)

Figure 5: Variation of the flame lift-off height  $L_f$  according to the air mean exit velocity, without magnetic field ( $\blacklozenge$ ) and with magnetic field ( $\blacksquare$ ) for  $V_{CH_4} = 1.6$  m/s (a) and for  $V_{CH_4} = 2$  m/s (b).

In a second part, the effect of the magnetic field on the lift-off height of the diffusion flame is investigated. Values of the lift-off height according to the air co-flow velocity for the two methane velocities of 1.6 m/s and 2 m/s with and without magnetic field are reported in figure 5. It is observed that the lift-off height is decreased by the presence of the magnetic field. The reduction depends on the air flow velocity; the decrease in the lift-off height is only sensitive for  $U_{air} > 0.3$  m/s. When the flame is lifted, the flow before the flame evolves in an upward decreasing magnetic field. The magnetic force acts downwards on the paramagnetic oxygen as shown schematically figure 6. Air velocity is

then decreased locally just in front of the magnetic gradient area inducing modifications of the external air mixing layer. As the air velocity is reduced compared to the case without magnetic field, radial diffusion of methane is enhanced. The stoichiometric line on which the flame front is theoretically supposed to develop is displaced by these modifications inducing a reduction of the lift height.

It is also observed (Figure 5) that the value of the air velocity where the lifted flame becomes unstable is delayed with the magnetic field than without magnetic field. Indeed for  $U_{CH_4} = 1.6$  m/s, the lifted flame becomes unstable for  $U_{air} = 1.3$  m/s, while with the magnetic field the instability of the lifted flame occurs for  $U_{air} = 1.4$  m/s.

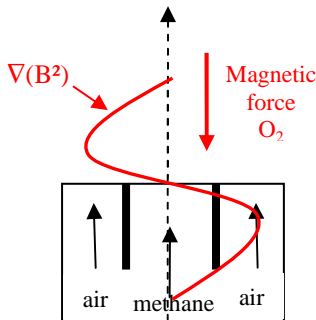


Figure 6: Schema of the magnetic force.

In a last part, in order to understand the effect of the magnetic field on the different behaviors of the flame, the characteristics of the flow field upstream of the flame is related to the flame front behaviors. Visualizations of the jets flow upstream of the flame and front flame images are presented for the stable lifted flame in the figure 7 and for the unstable lifted flame in the figure without magnetic field.

When the lifted flame is stable (regime II), no instability is observed in the external air mixing layer (figure 7-a), the front flame is smooth and regular (figure 7-b). When the lifted flame is unstable (regime III) some instabilities are present in the external air mixing zone (figure 8-a) the corresponding flame front is disturbed and unstable (figure 8-b). In the regime III, the flow field exhibits vortices due to the Kelvin-Helmholtz instability. These vortices appear as an undulation and develop into rolls up shapes further down-stream. The comparison of regimes II and III shows clearly that the flame front perturbations are directly correlated to the vortices in the air jet just upstream of the flame. So the interaction between the flame and the jet structures constitutes an important parameter for the flame behavior.

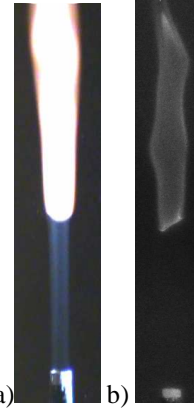


Figure 7: Flow visualizations before the flame (a) and the front flame (b) without the magnetic field for the regime II.



Figure 8: Flow visualizations before the flame (a) and the front flame (b) without the magnetic field for the regime III.

## Conclusion

The behavior of the flame and the effect of a magnetic field on the lift-off height are investigated experimentally in the configuration of a laminar diffusion flame of a methane jet in an air co-flow. Different regimes of flame stability are described from an anchored flame to a stable lifted flame which is destabilized before extinction according to the mean exit air velocity. It is shown that the lift-off height for a fixed methane mean exit velocity depends of the air mean exit velocity. Application of an upward decreasing magnetic field just at the burner exit is shown to decrease the flame lift-off height. The magnetic force which acts downwards on the paramagnetic oxygen reduces the air velocity along the external air/air mixing layer. Position of the flame front which depends on the stoichiometric line position, is displaced downwards due to the air velocity reduction.

Characterizations of the jets flow upstream of the flame in the lift regimes establish a correlation between the flow instabilities and the flame front behavior.

## References

- Aggarwal, S., Puri, I. and Qin, X. (2001) A numerical and experimental investigation of “inverse” triple flames, *Phys. Fluids*, 13, (1), 265-275.
- Baker, J. and Calvert, M.E. (2003) A study of the characteristics of slotted laminar jet diffusion flames in the presence of non-uniform magnetic fields, *Combustion and Flame*, 133, 345-357.
- Dold, J. (1989) Flame propagation in a non uniform mixture: analysis of a slowly varying triple flame. *Combustion and Flame*, 76, 71-88.
- Ghosal, S. and Vervisch, L. (2000) Theoretical and numerical study of a symmetrical triple flame using a parabolic flame path approximation, *J. Fluid Mech.*, 415, 227-260.
- Gilard, V., Gillon, P., Blanchard, J.-N., Sarh, B. (2008) Influence of a Horizontal Magnetic Field on a Co-Flow Methane/Air Diffusion Flame, *Combustion Science and Technology*, 180, 1920-1935.
- Hartley, L. and Dold J. (1991) Flame propagation in a non uniform mixture: analysis of a propagating triple flame. *Combust. Sci and Tech.* 80 (1/3) pp. 23-46.
- Kioni, P., Rogg, B., Bray, K. and Liñàn, A. (1993) Flame spread in laminar mixing layers: the triple flame. *Combust. Flame*, 95, (3), 276-290.
- Phillips H. (1965) Flame in a buoyant methane layer Proceedings of the 10<sup>th</sup> Int. Symposium on Combustion, 1277-1283, Pittsburgh, *The Combustion Institute*.
- Rehab, H., Villermaux, E., Hopfinger, E. (1997) Flow regimes of large velocity ratio coaxial jets, *J. Fluid Mech*, 345, 3.
- Ruetsch, G. Vervisch, L. and Liñàn, A. (1995) Effects of heat release on triple flame. *Phys. Fluids*, 6, (7) 1447-1454.
- Sautet, J.C., Stepowski, D. (1995) Dynamic behaviour of variable density, turbulent jets in the near development fields, *Physics of Fluids*, 7, 11.
- Villermaux E. (1998) Mixing and spray formation in coaxial jets, *J. Propulsion and Power*, 14, 5, 807.
- Yamada, E., M. Shinoda, M., Yamashita, H. and Kitagawa, K. (2002) Numerical analysis of a H<sub>2</sub>-O<sub>2</sub> diffusion flame in vertical or horizontal gradient of magnetic field, *Combust. Sci. and Tech.*, 174, 131-146.
- Yamada, E., M. Shinoda, M., Yamashita, H., Kitagawa, K. (2003) Experimental and numerical analyses of magnetic effect on OH radical distribution in a hydrogen-oxygen diffusion flame, *Combustion and flame*, 135, 365-379.
- Wakayama, N. I. (1992) Effect of a gradient magnetic field on the combustion reaction of methane in air, *Chemical Physics Letters*, 188, 3, 4, 279.
- Wakayama, N. I. (1993) Promotion of combustion in diffusion flames, *Combustion & Flame*, 93:207.