Lengths of Lifted Laminar Flames under Vertical Magnetic Field Gradient

B. Sarh[1,2], P. Gillon[1], V. Gilard[1,2], J.N. Blanchard[1,2], E. Bodele[2]

[1]ICARE-INSIS-CNRS, 1C Avenue Recherche Scientifique 45071 Orléans cedex 2 France,
[2] IUT, Université d'Orléans, France

1 Introduction

The effect of a vertical magnetic field gradient on lengths of methane-air diffusion lifted flames was numerically investigated. The study was developed for understanding the evolution of theses lengths when coaxial jet air velocity was varied. As the air jet velocity is increased, gradient in mixture fraction and liftoff increase and flame lengths decrease. Calculated reacting flow results of liftoff and flame length are presented for two cases, with and without magnetic field. In this study we used a effective jet diameter [1] for predicting the Froude number for coaxial flame. For the lifted flame under magnetic field, we modified the Froude number to take into account the magnetic buoyancy effect and we show that the correlation proposed by Altenkirch et al [2] can still be applied to represent lengths of lifted flames.

2 Flow configuration and numerical method

The flow configuration was similar to that reported in Ref [3]. A CH_4-air diffusion flame was formed out off the coaxial burner. The internal fuel gas has an inner diameter of 4 mm and rim thickness of 1 mm. The oxidant gas of air has an inner diameter of 10 mm and an outer diameter of 12 mm. A tube length was chosen, longer than the 200 mm needed for fully developed exit velocity to ensure laminar jets. The air mass flow injected in the outer tube was varied while the fuel mass flow injected in the inner tube was fixed and the mean velocity of the fuel at the exit section is U_{CH4}=0.341 m/s.

The simulation is carried out in a 200 mm (r) x 969 mm (x) computational domain, in an axisymmetric coordinate system. The general form of transport equation for two dimensional (r, x) axisymmetric laminar flow is :

$$\frac{\partial}{\partial x}(\rho\, U\, \Phi) + \frac{1}{r}\frac{\partial}{\partial r}(r\, \rho\, V\, \Phi) = \frac{\partial}{\partial x}(\Gamma \frac{\partial \Phi}{\partial x}) + \frac{1}{r}\frac{\partial}{\partial r}(r\, \Gamma \frac{\partial \Phi}{\partial r}) + S_\Phi \quad (1)$$

here ρ denotes the density calculated from the ideal gas law, U the axial velocity, V the radial velocity. The general form of Eq.1, represents the mass, the momentum, the species, the energy conservation equation, depending on the variable Φ. The transport coefficient Γ and the source terms S_Φ are provided in Table 1, where p, λ, μ, Cp, g, ρ_0, Γ stand for pressure, thermal conductivity, viscosity, specific heat of the mixture, gravitational acceleration, density of air and mass production rate of the ith species respectively. Y_i is the mass fraction of mixture component including fuel and air, and D_{i-N2} is the diffusion coefficient of the ith species in a binary mixture of that species and nitrogen. f_i is the external body force per unit mass acting on each chemical species i.

$$f_i = \frac{1}{2\mu_0} \chi_i \nabla(B^2) + g \qquad (2)$$

where the first term of the right-hand side is the magnetic force F_i, estimated by the magnetic force per unit volume acting on chemical species i :

$$F_i = \frac{1}{2\mu_0} \rho Y_i \chi_i \nabla(B^2) \qquad (3)$$

where χ_i is the magnetic susceptibility of chemical species i, and $\nabla(B^2)$ is the gradient of the square magnetic flux density [4].

The global species conservation equation (Eq. 4) and the state equation (Eq. 5) completed the governing equations given by Eq.1.

$$Y_{N_2} = 1 - \sum_1^{N-1} Y_i \qquad (4) \qquad\qquad p = \rho RT \sum_1^N \frac{Y_i}{M_i} \qquad (5)$$

where R is the universal gas constant and M_i is the molecular weight of the ith species.

For the chemical reaction, the reduced kinetic mechanism including 16 chemical species and 26 elementary reaction was used give in [5]. Direct effects of the magnetic field on the chemical kinetics were ignored [6].

Equations	Φ	Γ	S^Φ
Continuity	1	0	
Axial momentum	U	μ	$-\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\mu \frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial r}\left(\mu \frac{\partial V}{\partial x}\right) + \frac{\mu}{r}\frac{\partial V}{\partial x} - \frac{2}{3}\left[\frac{\partial}{\partial x}\left(\mu \frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial x}\left(\mu \frac{\partial V}{\partial r}\right) + \frac{\partial}{\partial x}\left(\mu \frac{V}{r}\right)\right] + (\rho_0 - \rho)\, g + \rho \sum_{i=1}^{N} Y_i f_i$
Radial momentum	V	μ	$-\frac{\partial p}{\partial r} + \frac{\partial}{\partial x}\left(\mu \frac{\partial U}{\partial r}\right) + \frac{\partial}{\partial r}\left(\mu \frac{\partial V}{\partial r}\right) + \frac{\mu}{r}\frac{\partial V}{\partial r} - 2\mu \frac{V}{r^2} - \frac{2}{3}\left[\frac{\partial}{\partial r}\left(\mu \frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial r}\left(\mu \frac{\partial V}{\partial r}\right) + \frac{\partial}{\partial r}\left(\mu \frac{V}{r}\right)\right]$
Energy	H	λ/Cp	$\nabla\left[\frac{\lambda}{Cp}\sum_1^N ((Le_i^{-1} - 1) H_i \nabla Y_i)\right] - \sum_1^N (h_{fi}^{\ 0} \dot{w}_i)$ where $Le_i = \frac{\lambda}{\rho D_{i-N_2} Cp}$
Species mass fraction	Y_i	ρD_{i-N2}	$\dot{w}_i$

Table 1: Transport Coefficients and source terms

The magnetic configuration and the distribution of the vertical magnetic gradient corresponding to the one used in the numerical results of cold flow described in [7], is used here for reacting calculations. The magnetic gradient presents a negative maximum of $-30T^2/m$ at 6 mm above the burner rim. The magnetic force acts in the negative x-direction decelerating the flow of paramagnetic chemical species. Only oxygen specie are treated as paramagnetic. Consequently, at the exit of the burner, air is submitted to a downward magnetic force.

The model, assumptions, numerical techniques and computational domain are detailed in [7].

3 Results

To investigate the flames structure in detail, we calculated the combustion flow out off the coaxial burner with and without magnetic field. The air flow velocity is increased, keeping constant fuel velocity. Figure 1, shows the typical appearances of lifted flames. It can be seen that liftoff, H, increases with the air jet exit velocity (see figure 1a and 1b) and figure 2. When the magnetic field is applied, the liftoff decreases (see figure 1b and 1c). The presence of a negative magnetic gradient reduces entrainment and therefore deprive the flame of oxygen (see figure 3) causing it to move downward along the stoichiometric line, in the lower flow velocity region.

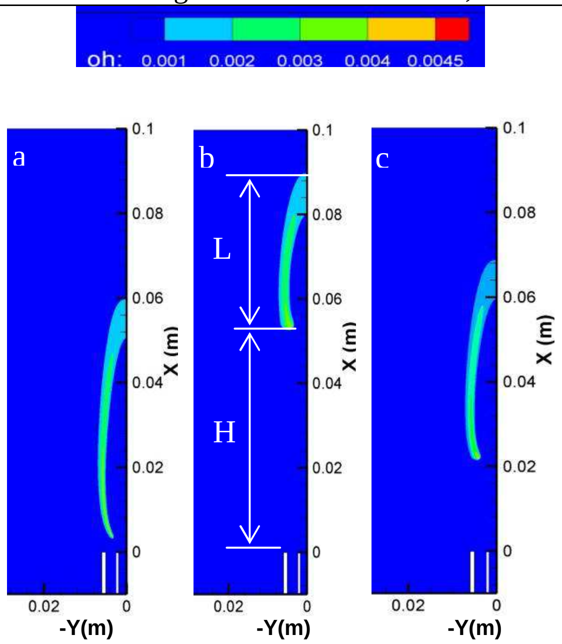

Figure 1: Mass fraction of OH distribution for three flames, U_{CH4}=0.341 m/s : (a) without magnetic field, U_{air}= 0.144 m/s. (b) : without magnetic field, U_{air}= 0.575 m/s. (c) : with magnetic field, U_{air}= 0.575 m/s. (H : Liftoff, L: flame length)

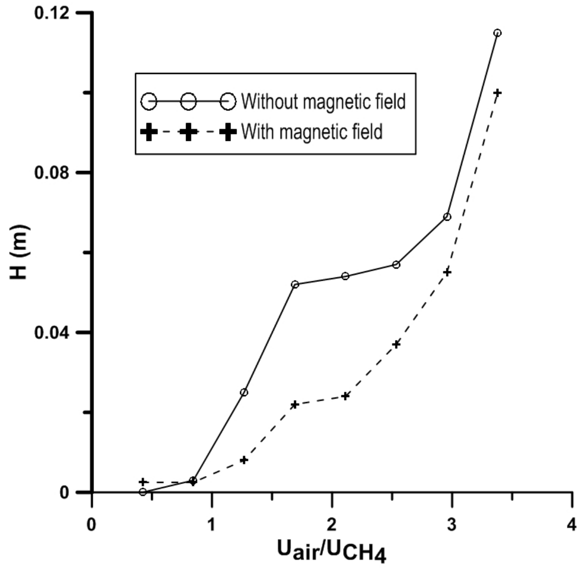

Figure 2: Flame lift-off height versus the velocity ratio of coaxial air to fuel jet. U_{CH4}=0.341 m/s

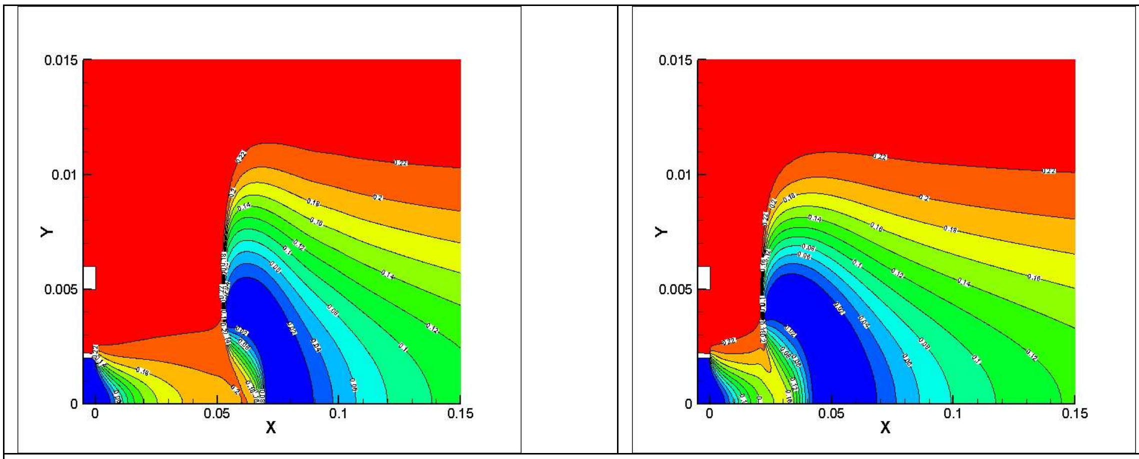

Figure 3: Mass fraction of oxygen distributions, left without magnetic field, right with magnetic field. case U_{air}/U_{CH4}=1.69 and U_{CH4}=0.341 m/s

Conversely, the flame length decreases when the air velocity increases (see figure 1a and 1b), and increases when magnetic field is applied (see figure 1b and 1c). This reduction can be explained by the fact that when air velocity increases, the air penetration and mixing with the fuel over the increased liftoff distance are enhanced, thus resulting in vigorous combustion and a shorter flame, see figure 4. When the magnetic field is applied, a negative magnetic gradient induces magneto-convection which adds to natural convection. Hence, we obtain greater flame lengths, we thus find ourselves, with important effect of buoyancy. This is observed in figure 4.

Flame lengths follow the correlation proposed by [2] expressed in Froude and Reynolds numbers.

$Fr = \dfrac{U_{eff}^2}{(\alpha - 1)\ g\ d_{eff}}$ and $\mathrm{Re} = \dfrac{U_{eff}\ d_{eff}}{\nu_m}$ where U_{eff} and d_{eff} are the expressions written for a coaxial jet [1]. $\alpha = \rho_o / \rho_f$ where ρ_f is density of the hot gas and ρ_o ambient density. In order to take into account the magnetic buoyancy effect we proposed to modify the Froude number by replacing g by Gg where $G = 1 + \dfrac{\alpha}{\alpha - 1}\dfrac{g_{mo}}{g}$. The new Froude number Fr* expression is given by $Fr^* = \dfrac{U_{eff}^2}{|G|(\alpha - 1)\ g\ d_{eff}}$ On figure 5, are reported the results of the correlation using the new Froude number. It is shown that flame lengths follow the correlation proposed by [2] meaning that buoyancy have an important effect on the lifted flame lengths.

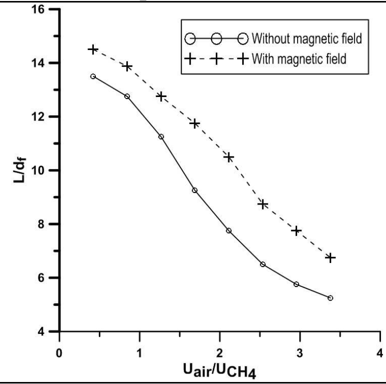

Figure 4: Length flame with velocity ratio of coaxial air to fuel jet. U_{CH4}=0.341 m/s

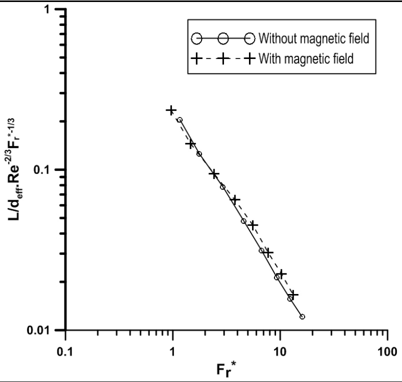

Figure 5: Laminar flame length versus Fr*

3 Conclusion

We have numerically studied the liftoff and lengths of laminar lifted flames formed in the coaxial burner to which is applied a vertical negative magnetic field gradient. The effect of velocity ratio of coaxial air to fuel jet on flame lengths have been characterized with and without magnetic effect. The flame lengths are reduced when the air velocity increases, and the application of the negative magnetic field gradient results in an increase of these lengths.

References

[1] Kim M., Oh J. Yoon Y. (2011). Flame length scaling in non premixed turbulent diluted hydrogen jet with coaxial air Fuel 90: 2624.

[2] Altenkirch RA., Eichhorn, R., Hsu N.N., Bransic A.B., Cevallos N.E. (1976). Characteristics of laminar gas jet diffusion flames under the influence of elevated gravity. Proc. Comb. Inst. 16: 1165.

[3] Gilard V., Gillon P., Blanchard JN., Sarh B. (2008) Influence of horizontal magnetic field on o a co-flow methane/air diffusion flame. Comb. Sci. and Tech. 180: 1920.

[4] Abrahams E., Keffer F., (2002) Mc Graw Hill Encyclop. of Sci. & Tech. 9th Ed. 10: 291. New York

[5] Smooke MD., Giovangigli V. (1994) Simplified transport and reduced chemistry models on premixed and non premixed combustion. Buuckmaster & Takeno Eds. pp. 81-106.

[6] Yamada E., Shinoda M., Kitagawa K. (2002) J. SpectroSoc Japan 51-5: 222.

[7] Delmaere T. Sarh B. Gillon P. (2010) A numerical study of the magnetic influence on coaxial jets' flow upstream from lifted flame. Comb. Sci. and Tech. 182: 1933.