Magnetic influence on lift-off of diffusion flames

Pascale Gillon[1], Virginie Gilard[1,2], Jean-Noël Blanchard [1,2]

[1]ICARE, UPR 3021 ST2I-CNRS,
1C Avenue de la Recherche Scientifique, Orléans cedex 2France

[2]Université d'Orléans, France

1 Introduction

Combustion process control is of considerable interest at both scientific and economical levels as it is related with the problem of energy efficiency and ecological improvement. Among numerous methods of combustion control, application of a magnetic field is one of the most promising. Since Faraday [1], it is well known that combustion flames are affected by magnetic fields. In the interaction of magnetic fields with combustion three mechanisms have been identified: (1) The Lorenz force acting on charged particles, (2) the direct effect of magnetic field on chemical reactions and (3) the indirect effect of magnetic gradients on oxygen.

Influence of the Lorentz force on combustion is based on the basic principle that a current carrying conductor placed in a magnetic field experiences a force perpendicular to both the current direction and the magnetic field lines. This force can be induced in any electroconductive medium either a metal or an ionized gas. Borovskoi et al. [2] have shown an increase of the combustion rate only in the specific configuration of combustion of solid propellant in rocket motors. Inducing a Lorentz force opposed to the flow of ionized gaseous products, decelerates the flow leading to an increase of the static pressure from which depends directly the combustion rate. However, the amount of ionized species and their velocity are too small in ordinary diffusion flames to take into account the influence of the Lorentz force.

Works on magnetic effects on chemical reactions deal with uniform magnetic fields. Y.Mizutani et al. [3] studied the direct effect of a uniform magnetic field up to 5T on chemical kinetics for a premixed laminar flame of propane/air. If high speed chemical reactions seem not to be affected, nitrogen oxide formation shows a slight difference under magnetic influence. J. Baker et al. [4-5] investigated the impact of a uniform magnetic field on equilibrium combustion characteristics. They added a magnetic contribution to the expression of the Gibbs free energy and minimized the changes in the Gibbs free energy for a mixture of paramagnetic and diamagnetic gases. Results were used to determine the equilibrium composition for a methane/air model reaction reported in function of the temperature and the magnetic induction. They showed that magnetic fields above 0.02T can have significant effects on equilibrium composition. In particular, the NO equilibrium concentration was observed to be strongly decreased by the application of a magnetic field especially above 2500K. However, this decrease in the NO production was observed at temperatures well above those existing in practical applications. Other chemical effects are presented by Abe et al. [6]. They have shown that a magnetic field affects the chemiluminescence intensities of the C_2 (d-a) and CN (B-X) systems in the low pressure C_2H_2/N, O flames. Their results show that a magnetic field can influence the reaction kinetics in the gas phase but detailed mechanisms remains unknown.

Non-uniform magnetic fields are known to affect flame behaviour as a result of the paramagnetic and diamagnetic properties of the constituent gases. A paramagnetic substance whose magnetic susceptibility is positive in sign and depends on temperature is attracted in direction of stronger magnetic fields while a diamagnetic one with a negative magnetic susceptibility independent on temperature, experiences a weak repulsion to the applied magnetic field. The magnetic force per unit volume acting on species i, F_i is expressed by the following equation:

$$F_i = (1/2\mu_0)\rho\ Yi\ \chi i\ \nabla(B^2)$$

Correspondence to : gillon@cnrs-orleans.fr

The magnetic force is proportional to the mass density ρ and the magnetic susceptibility χi of the ith chemical species and the gradient of the square magnetic flux density $\nabla(B^2)$.
In diffusion flames, oxygen is the principal paramagnetic gas, fuels, nitrogen, carbon monoxide, carbon dioxide being diamagnetic. Many papers referred to influence of magnetic gradients on combustion. N. Wakayama [7] 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 in [8]. Decreasing magnetic field is found to increase combustion rate for diffusion flames while the magnetic fields had little effect on the premixed flame. It is concluded that the dominant magnetic action is on the oxygen flow into increasing magnetic fields strength. Yamada et al. [9] 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. In [11], Yamada et al. confirmed 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 shows that the magnetic effect is essentially due to the magnetic force acting on O_2 and not directly on OH itself.
In the present paper, we report of investigations on magnetic field influence on lifted diffusion flames. When the fuel mass flow rate exceeds a critical value, the base of the diffusion flame quits the burner tip and remains suspended above at a certain distance of the burner. The phenomenon is known as lift-off. When the mass flow rate increases further, the lift off height increases until the flame becomes flat and then blows out. A lifted flame is stabilized through the triple flame mechanism. In fact, just upstream of the flame, premixing occurs and 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. Behind these two branches, hot fuel and oxidizer burn in a training diffusion flame along a stoichiometric surface forming the third part of the triple flame.

2 Experiments

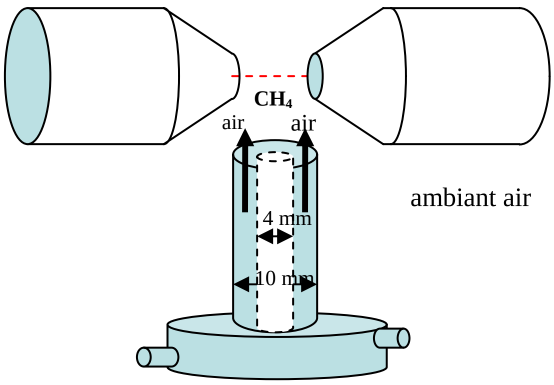

Figure 1: Experimental set-up

The experimental device is schematically represented figure 1. An axisymmetric co-flow burner with a central methane jet and a surrounding air co-flow in open ambient air is chosen to generate a lifted laminar diffusion flame. A permanent magnet can be set between the burner exit and the flame position. Experiments are carried out in ambient air at atmospheric pressure.
The magnet set in front of the burner rim generates a horizontal magnetic field of .35T magnetic induction at its centre and two areas of strong magnetic gradient are observed at 6mm distance from the magnet centre where magnetic forces are the strongest.

3 Results

The methane flow rate is kept constant and for increasing values of the air flow rate, side views of the flame are recorded by a numerical camera. The flame position and length are measured by image analysis. Criteria of blow out are determined when observed in the flow rate range of the experiments. Flame configurations for a fixed value of methane flow rate and increasing air flow rates are shown in figure 2 without the magnet. The flame behaviour changes from a nozzle attached flame fig. 2a, to a near lift off in fig. 2b, and lifted flame in fig.2d-g, fig. 2g is near flame blow-out. Lift height is shown to increase until blow-out.

Figure 2: Flame configurations for a fixed methane velocity of .22m/s and increasing velocity of the air co-flow a)0, b).34, c).52, d).7, e).87, f)1.05, g)1.09 m/s

Variations of the flame lift-off height without and with magnetic field are reported on figure3a and 3b respectively. Application of the magnetic field does not introduce drastic change of the flame configurations. When the methane exit velocity is of the order of magnitude of the air one, the flame lift shows no dependence on the methane flow rate and increases continuously with the air flow rate. For low methane exit velocities (<0.20m/s), a difference with the air one generates a vortex in the methane flow: the lift height curve with air is lower.

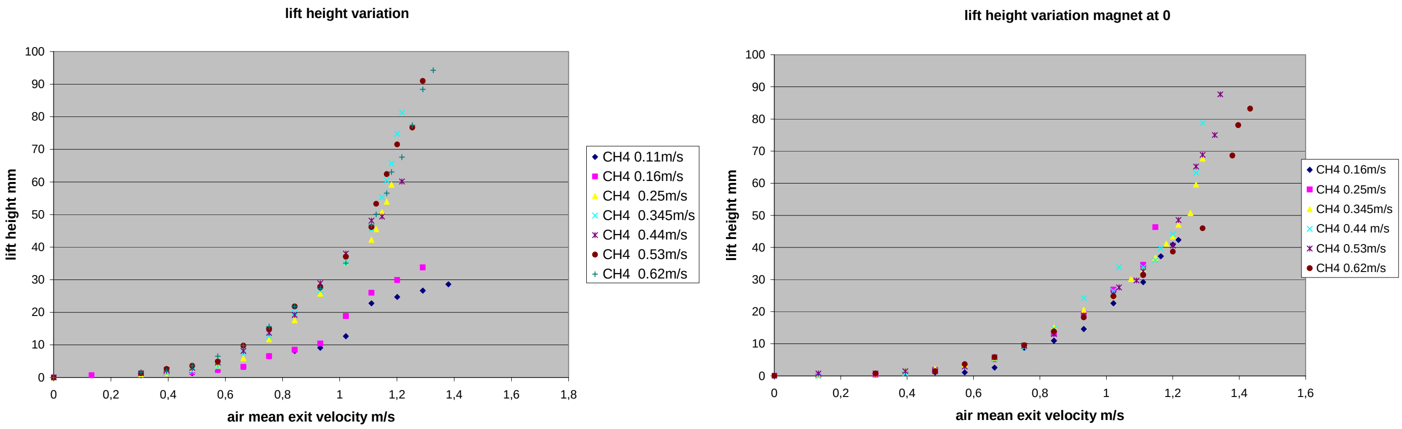

Figure 3: Lift height variation versus the air co-flow velocity without and with the magnetic field

Figure 4 evidences the action of the magnetic field on the lift height: the lift is decreased. Conditions of blow-out are given figure 5 in the 3 conditions of no magnet, magnet set in front and at 10mm above the nozzle; it is seen that blow-out criteria are increased by the magnet presence.

The principal action of the magnetic field consists to attract oxygen hence air inside the bore, maxima of magnetic force being at 6mm apart from the magnet centre. Two effects are expected from this direct force on paramagnetic oxygen: a modification of the mean air co-flow velocity and attraction of ambient air from outside the burner. The presence of a force on the air flow upstream of the flame introduces changes both of the fuel mass fraction and of the flow field. The triple flame then stabilizes at a lower position due to complex hydrodynamic changes in velocity and gas mixing induced by the magnetic force on air.

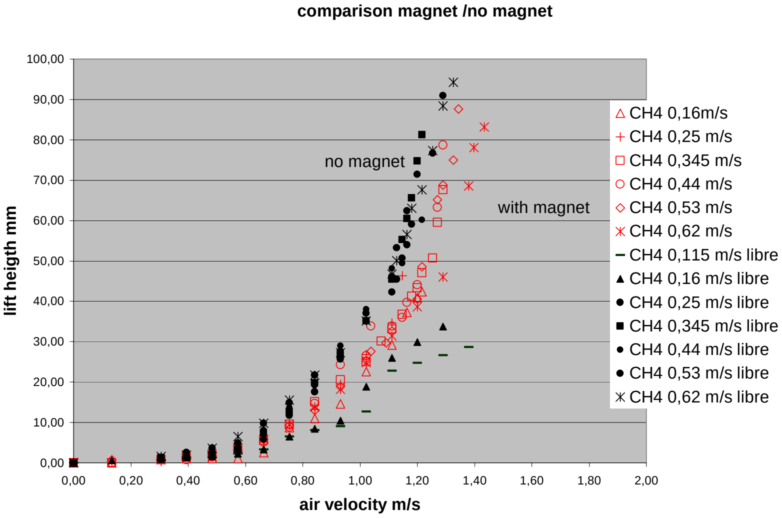

Figure 4

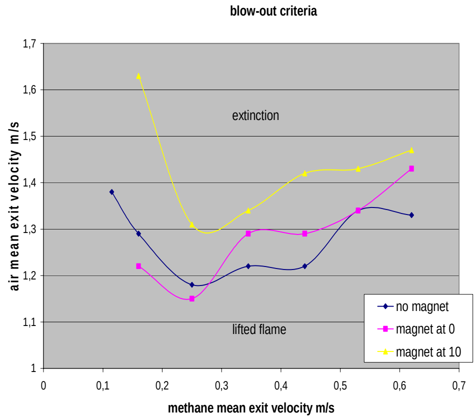

Figure 5

5 Conclusion

Characteristics of the influence of magnetic field on CH_4/air lifted flames were investigated. It is shown that through the modification of the air flow and distribution a permanent magnet of small dimensions and induction is able to produce sufficient action to increase the stability of lifted laminar diffusion flames.

References

[1] M.Faraday, On the diamagnetic conditions of flame and gases, The London Edimburgh and Dublin philosophical magazine and Journal of Science, 31, (210), 401-421, (1847).

[2] I.G.Borovskoi, A.B.Vorozhtsov, Magnetic field control of burning rate and thrust in solid rocket motors, J. Propulsion and power, 11, 4, 824, (1995).

[3] Y. Mizutani, M.Fuchihata, Y.Ohkura, Pre-mixed laminar flames in a uniform magnetic field, Combustion and Flame 125,1071-1073, (2001)

[4] J.Baker, K.Saito, Magnetocombustion: a thermodynamic analysis. J. Propulsion and power, 16, 2, 263, (2000).

[5] A.Gupta, J.Baker Effect of uniform magnetic field on equilibrium combustion composition: constant volume. AIAA Journal, 43, 11, 2438-2444, (2005).

[6] H.Abe and H Hayashi, external magnetic field effects on chemiluminescence intensities from C_2(d) and CN (B) states in low pressure C_2H_2/N,O flames. Chemical physics 162, 225-234, (1992).

[7] N. I.Wakayama, Effect of a gradient magnetic field on the combustion reaction of methane in air. Chemical Physics Letters, 188, 3, 4, 279, (1992).

[8] N. I.Wakayama, Promotion of combustion in diffusion flames, Combustion & Flame, 93:207 (1993).

[9] E.Yamada, M.Shinoda, H.Yamashita and K.Kitagawa, Numerical analysis of a H_2-O_2 diffusion flame in vertical or horizontal gradient of magnetic field. Combust. Sci. and Tech., 174:131-146 (2002).

[10] E.Yamada, M.Shinoda, H.Yamashita and K.Kitagawa. Experimental and numerical analyses of magnetic effect on OH radical distribution in a hydrogen-oxygen diffusion flame. Combustion and flame, 135, 365-379, (2003).

Acknowledgements

We are grateful to Dr I.Gökalp for fruitful discussions and toA. Aymard for the experimental realizations and technical support.