Numerical study of the magnetic influence on entrainment in laminar jets

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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. Three mechanisms have been identified in the interaction of magnetic fields with combustion: Lorentz force on charges particles, direct magnetic effect acting on chemical reactivity and indirect effect of magnetic gradients on oxygen. Here we are dealing with the effects of non-uniform magnetic fields. They 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:

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

The magnetic force is proportional to the mass density ρ, the mass fraction Yi and the magnetic susceptibility χi of the i^{th} 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 [2] 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 [3]. 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. [4] 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 [5], 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 show that the magnetic effect is essentially due to the magnetic force acting on O_2 and not directly on OH itself.

The effect of a magnetic field on the lift phenomenon of a methane/air laminar diffusion flame from a coaxial burner is presented by Gillon et al. [6]. It is shown that the lift is reduced when the flame is submitted to a magnetic gradient and this effect is attributed to the magnetic force on the paramagnetic air. As the major influence of the magnetic presence is related to its action on the oxygen flow field, we present in the present paper a numerical investigation of the variation of the entrainment of coaxial jets of air and methane when submitted to a magnetic field following the experimental configuration of lifted diffusion flames presented in [6].

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2 Numerical modeling

Coaxial methane and air jets are numerically described following the experimental configuration. The burner is 219mm long, methane is flowing through a central tube of 4mm inner diameter and air through the external one of 10mm inner diameter. The burner rim is set in a numerical domain of 250mm in the axial x-direction and 50mm in the radial y-direction. The origin of the coordinate system is set at the burner exit.
The magnetic field used in the experiments is simulated by a Gaussian distribution. This magnetic field distribution is applied up to 12mm in the radial direction corresponding to the bore distance of the real magnet and it is supposed to be constant with y.
The volumetric magnetic force which develops in the axial direction on oxygen molecules is expressed by :

$F_{O_2} = X_{O_2} \cdot B \cdot \frac{dB}{dx}$ N/m^3 with $X_{O2} = \frac{1}{2\mu_0} \rho(T) \cdot Y_{O_2} \cdot \chi_{mO_2}$ and the oxygen mass magnetic susceptibility χ_{mO_2} = 1. 33.10^{-6} kg^{-1}.

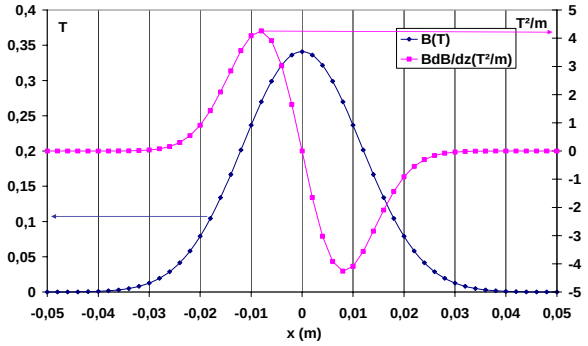


Figure 1 Distribution of B and B dB/dx versus the vertical x-axis

The magnetic force is added as a source term to the momentum equation.
The magnetic field distribution and the fied.field gradient product on the vertical x-axis are represented figure 1 in the case of a 0.35T magnetic induction.
The distribution of the field.field gradient shown figure 1, indicates that the magnetic force will be maximum at 8mm apart from the magnet centre. Below the magnet centre, the field.field gradient is positive, hence the magnetic force on paramagnetic is positive directed upwards whereas above the magnet centre paramagnetics are attracted downwards.

The governing equations for an axisymmetric non reacting flow consist of the continuity and momentum equations in which the buoyancy term takes into account the 2 species : air and methane and the magnetic force is introduced as a source term.
Boundary conditions are as follow:

- constant inlet velocity of the two gases at the base of the burner
- constant pressure conditions at the lateral, inlet and outlet domain limits. The pressure is set at 101325Pa.
- Magnet centre set at x=0, in front of the burner rim.

The governing equations are solved in the laminar case using the FLUENT© 6.2. software. It has to be noticed that the physical space occupied by the magnet is not taken into account.

3 Results

Velocity distributions are reported Figure 2 for two conditions of inlet air velocity (0.264m/s and 1m/s) and three magnetic gradient intensities (0; 4.2 and 42 T²/m), the inlet methane velocity being kept constant at 0.62m/s. The length of the represented graph is 50mm.
It is observed a very slight difference between the flow field at 0 and 4.2T²/m : the magnetic gradient seems to slow the air flow just upstream the burner exit.
When a magnetic gradient of 42T²/m is applied the flow field is strongly perturbed. In the 0.264m/s air velocity case, the air flow field is stopped and deviated downwards before being re entrained along the methane jet which does not appear to be influenced.
The 1m/s air case shows a strong braking of the air flow with a reduction of the air jet spreading angle.
Velocity and methane mass fraction are reported Figure 3 for a radial position off axis of 3.6mm; i.e. in the air co-flow jet. In the case of the low air inlet velocity, the action of the magnetic gradient on the air flow velocity is confirmed: a slight reduction of air velocity in front of the magnetic gradient of 4.2T²/m which disappears above 50mm of axial distance and a reversed air flow at 42T²/m. Through its influence on the air flow field, the

magnetic gradient induces modifications of the methane mass fraction. At 4.2T²/m, the methane mass fraction is higher than without magnetic field and this difference is sensitive until 150 mm in the axial direction. Whereas the behaviour when 42T²/m is applied is different, the methane mass fraction increases in front of the magnetic gradient and then decreases below the 0-magnet case.

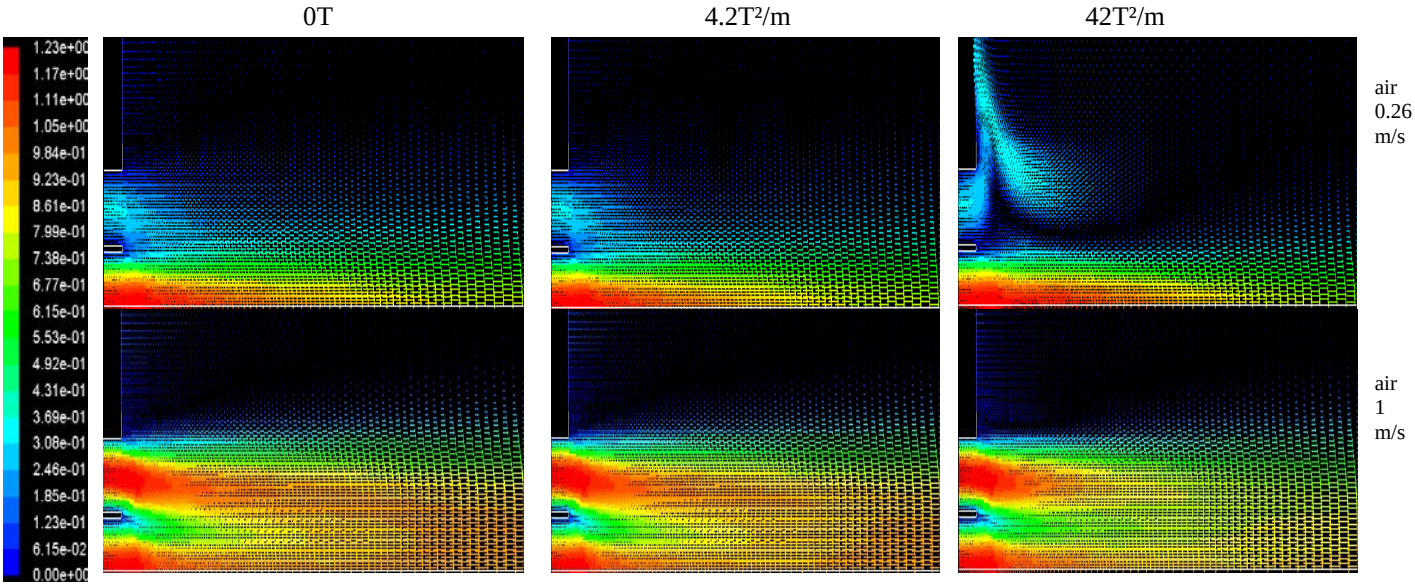
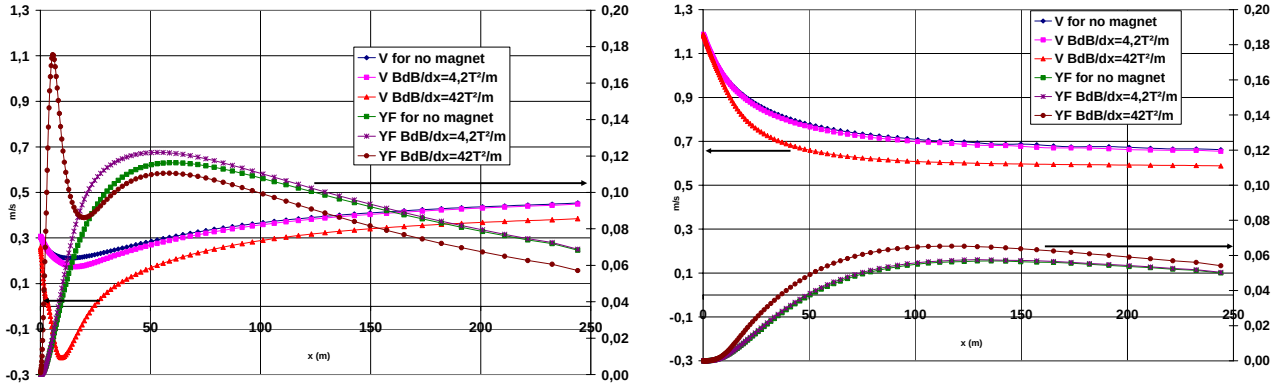


Figure 2: Evolution of methane and air flow velocity. Conditions: inlet methane velocity=0.62m/s, inlet air flow velocity 0.26m/s and 1m/s at various magnetic gradient 0; 4.2; 42 T²/m



V CH_4=0.62m/s, Vair=0.26 m/s, y=3.6mm V CH_4=0.62m/s, Vair=1 m/s, y=3.6mm

Figure 3. Axial evolution of CH_4 mass fraction and flow velocity at a radius y=3.6mm.

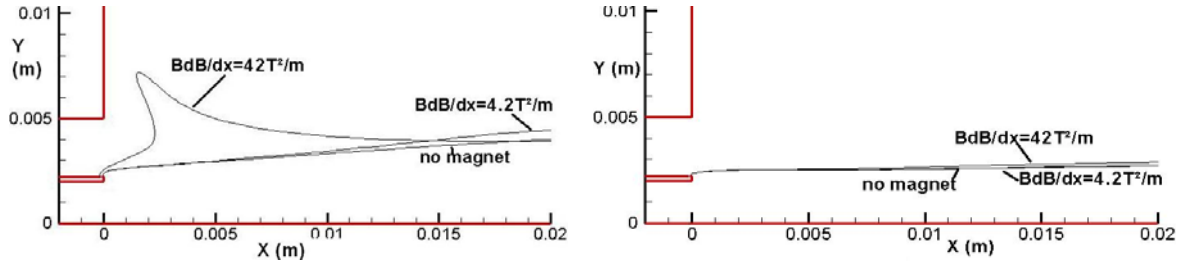
For the higher inlet air velocity case of 1m/s, the effect of the magnetic gradient is much less sensitive. The air velocity is very slightly reduced at 4.2T²/m. The air flow velocity is reduced of a maximum of 10% by a 42T²/m magnetic gradient, and this reduction is transported along the axial direction. The methane mass fraction is shown non-affected by the 4.2T²/m magnetic gradient along the axial direction and is increased in presence of a 42T²/m magnetic gradient.

4 Interpretation-conclusion

The magnetic force on oxygen is directed downwards. It brakes locally the air flow field in front of the gradient maximum; this braking effect induces consequently different effects depending on the air flow inlet velocity. This effect can be quantified by a dynamic magnetic Froude number which characterizes the ratio of

inertia to magnetic force as defined by Kaldi [7]. All the results obtained at the low magnetic gradient of 4.2T²/m evidence inertia dominated flow, however, the case at 42T²/m and a low air velocity shows clearly a magnetic dominated flow field.
Moreover, the magnetic braking air flow induces effects on the species distribution.
In figure 4 the stoichiometric mixture fraction is represented in the numerical space for the two inlet air flow cases. The flame boundary can be defined as the location of the stoichiometric mixture fraction which is defined by: $Z_{st} = \frac{1}{1+(\frac{A}{F})_{st}}$; in the case of the methane/air mixture $(\frac{A}{F})_{st} = 17.4$ hence Z_{st} =0.054.

In [6], the experimental results demonstrated that the application of a 4.2T²/m magnetic gradient is characterized by a decrease of the lift height, small in the case of 0.26 m/s air velocity but rather large in the 1m/s air case. However, the modification of the stoichiometric mixture fraction distribution by the magnetic effect is not sufficient to explain the important effect on the lift height observed experimentally.



a) Vair=0.26m/s b) Vair=1m/s

Figure 4: Stoichiometric mixture fraction distribution.

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