Magnetic Effects On Flickering Laminar Methane/Air Diffusion Flames

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1 Introduction

Most diffusion flames, employed in industrial applications are unsteady, at high speed, turbulent and 3D. Such flames are too complex to be studied in detail. Instead, the study of time-varying laminar diffusion flames offers the possibility to fill the gap between steady laminar combustion and turbulent combustion especially by taking into account the complex coupling between chemistry and fluid flow. We will focus our attention to a specific type of flame instability, naturally occurring in flames known as flickering in which a periodic fluctuation of the flame tip is observed. Origins of the flickering have been attributed to gravity combined to large density gradients present at the flame front: hot gas inside the flame is pushed upwards by buoyancy while cold outer gas is driven downwards creating a shear layer in which sets the Kelvin-Helmholtz instability. The gravity effects using Strouhal and Froude numbers have been summarized in a relation of $St=Fr^{-0.57}$ [1].
Pollutant emissions constitute a large drawback of any combustion system and preoccupations to reduce them are constantly animating researches in the combustion domain. Flame instabilities are known to influence the flame pollutant emissions. Shaddix et al. [2] have shown that a flickering flame is able to emit four times more soot that a steady flame and even seven times in case of flame tip pinch off.
Few references are dealing with external control of this type of flame instability. We propose to investigate the influence of a magnetic force. Magnetic interaction with combustion is essentially due to the force which develops on paramagnetic oxygen when the flame is set in a non-uniform magnetic field. The magnetic effects result from two mechanisms. Paramagnetic materials are drawn toward increasing magnetic fields in order to align their magnetic dipole moments, the force of attraction F_m per unit volume being given by Eq. (1).

$$F_m = (1/2\mu_0)\, \rho\, Y_i\, \chi_i\, \nabla(B^2) \qquad (1)$$

The magnetic force is proportional to the mass density ρ (kgm^{-3}), the magnetic susceptibility χ_i (mass magnetic susceptibility m^3kg^{-1}) of the ith chemical species of mass fraction Y_i and to the gradient of the square magnetic flux density $\nabla(B^2)$ (T^2m^{-1}).
The second effect is related to the generation of a convective instability in a fluid with a non-uniform distribution of magnetic susceptibility. Similar to buoyancy convection driven by gravity in non-isothermal fluids due to the variation of density with temperature, magnetic convection is driven magnetically due to the spatial variation of paramagnetic susceptibility due to either temperature or concentration variation. Considering a vertical magnetic force, thermomagnetic convection enhances

(resp. slows down) the gravitational-induced convection in a negative (resp. positive) magnetic gradient [3]. Baker and Calvert [4] have carried out experiments on a laminar jet methane diffusion flame in different configurations of negative magnetic gradients using an assembly of permanent magnets. They observed that a downward magnetic force on oxygen decreased the flame length, the flow rate for soot inception, and increased the flow rate at extinction. Gilard et al. [5] using an assembly of permanent magnets, have shown that the stability of a laminar methane flame jet with a co-annular air is enhanced when the flame edge is placed in the increasing magnetic field zone. The upward magnetic force which develops on the oxygen in air causes the decrease of the flame lift height and the air flow rate at extinction. In [6], in the case of longer flames, an upward magnetic force is shown to increase the flame length and decrease the lift height for the range of inlet velocity of methane and air coflow from 0.8 to 5.6 ms^{-1} and from 0.7 to 4.3 ms^{-1} respectively.
Recently, Legros et al. [7] demonstrated that the application of a downward magnetic force was able to trigger flickering of a laminar methane diffusion flame issued from a co-annular coflow of oxygen enriched air. This phenomenon results from an enhanced convective motion, a thermomagnetic convection driven in the surrounding oxygenated air by the magnetic force on the paramagnetic oxygen being superimposed to the buoyancy convective instability.
Here we propose to study the influence of a magnetic gradient on the stability of methane diffusion flames with annular air coflow. We focus on the effects of the sign of the magnetic gradient both at injection, in the cold part where the direct attraction force on oxygen develops and along the flame front where magneto convection occurs.

2 Experiments

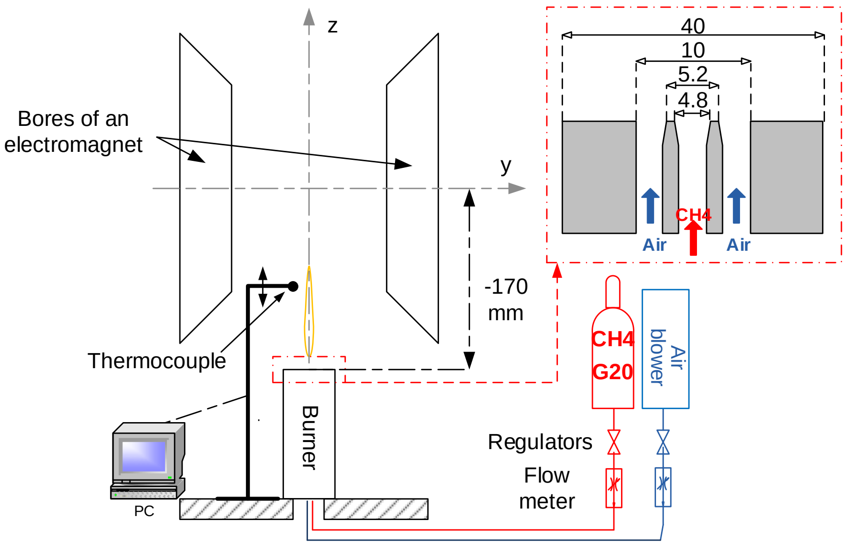

Figure 1. Experimental setup and burner geometry

The experimental set-up is illustrated schematically in Fig. 1. The diffusion flames with air coflow were established over a coaxial burner consisting of two concentric tubes as described in [6]; methane flowing out the inner tube while air was supplied through the annular one. The methane flowrate is fixed at 15 cm^3s^{-1} (corresponding to an exit velocity of 0.86 ms^{-1}) and air flowrates regulated with a mass flow controller were ranging from 0 to 59.3 cm^3s^{-1} (air exit velocity from 0 to 1 ms^{-1}).
Magnetic field is generated by a water-cooled electromagnet. Normalized magnetic flux density and gradient of the square of the magnetic flux density values (later called magnetic gradient) on the vertical axis are reported Fig. 2 above and below the magnet center (z=0). Two vertical positions of the burner inside the magnet bore were tested: one at z=-170 mm in the positive magnetic gradient and one at +70 mm in the negative magnetic gradient as specified in Fig. 2.

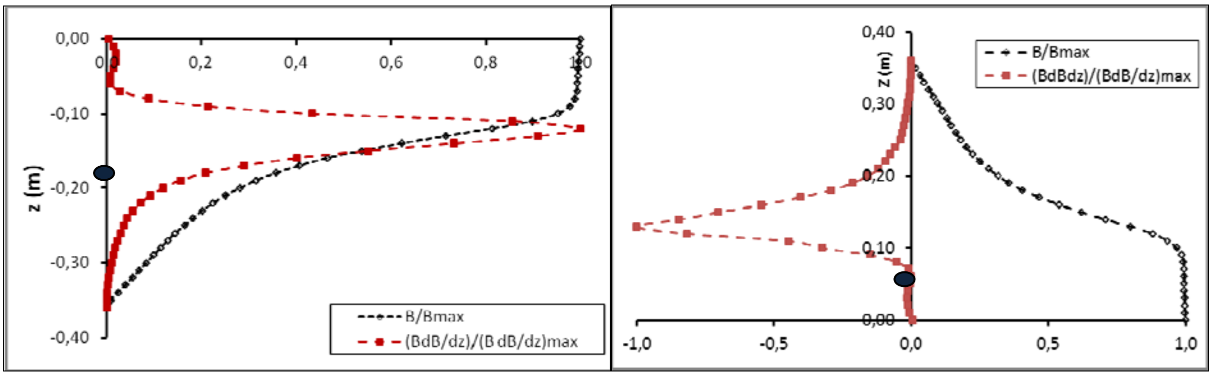

Figure 2 Magnetic field and magnetic gradient configurations and positions of the burner exit

Natural flame luminosity images (1296*2304 pixels with a scale of 0.2 mm/pixel) were recorded by a video camera at a framing rate of 25 Hz. For each experimental condition (air injection velocity, magnetic gradient), the combustion process is characterized by various averaged values of flame length, lift height and luminosity. An image luminosity value was defined as the sum of the pixels for which the luminosity is above a given limit and the total luminosity as the sum of 76 image luminosities. A high-speed digital camera was used to determine the time-dependent flame response with an image resolution of 1024x1024 pixels and a frame rate of 100 fps. Simultaneously, a thermocouple was used to determine the oscillation frequencies of the flame tip. The temperature signal was time recorded using a type K thermocouple of 60 µm diameter set in the upper area of the flame (Fig. 1). 100 data per second were recorded along 120 seconds by a data acquisition device. We did not observe soot deposition on the thermocouple presumably due to the fact that soot is repeatedly deposited and oxidized in the time varying flame. The oscillation frequency of the flame tip was determined with a FFT analysis using MATLAB programming.

3 Results and discussion

Experimental results are reported on Fig. 3 to 5. Figure 3 presents the comparison of the mean visible flame length and mean visible flame lift height deduced from the natural flame luminosity images for the three cases of positive, negative and zero applied magnetic gradients versus air velocity. The lift height is decreased (resp. increased) by the action of a positive (rep. negative) magnetic gradient whereas the flame is found longer in the two cases.

Variations of the flame position are due to the magnetic force exerted on air towards the bore: at -170 mm, air is attracted upwards, leading to an enhanced oxygen supply to the flame edge. It produces an increase in the flame propagation velocity. The flame edge position which results from an equilibrium between upward injection velocity and downward propagation velocity is hence pushed downwards. At +70 mm air is magnetically pushed downwards, reducing the oxygen supply, the reverse mechanism leads to a slight increase of the lift height. The magnetic effect on the flame edge is quite small due to the small value of the magnetic force in front of the edge except when the lift height is high enough (at higher air velocity) to position the flame edge in front of a stronger magnetic gradient.

The influence of the magnetic force is evidenced on the variation of the flame flickering frequency shown Fig. 4. The frequency is reduced in the positive magnetic gradient and increased in the negative one; the magnitude of the effect being related to the relative position of the flame to the maximum of the magnetic gradient [8]. Flickering is due to a natural buoyant instability that triggers vortices on the air side of the high-temperature reaction zone of the flame. When submitted to a magnetic force, it is the combination of the magneto buoyancy convection to the gravity buoyancy one which produces this effect. In the positive gradient the upward magnetic force opposed to gravity leads to a reduced convection in air along the flame and in the negative magnetic gradient, the downward magnetic force adds to gravity to drive a stronger convective motion in air at the flame tip explaining the observed variation of the flickering frequency.

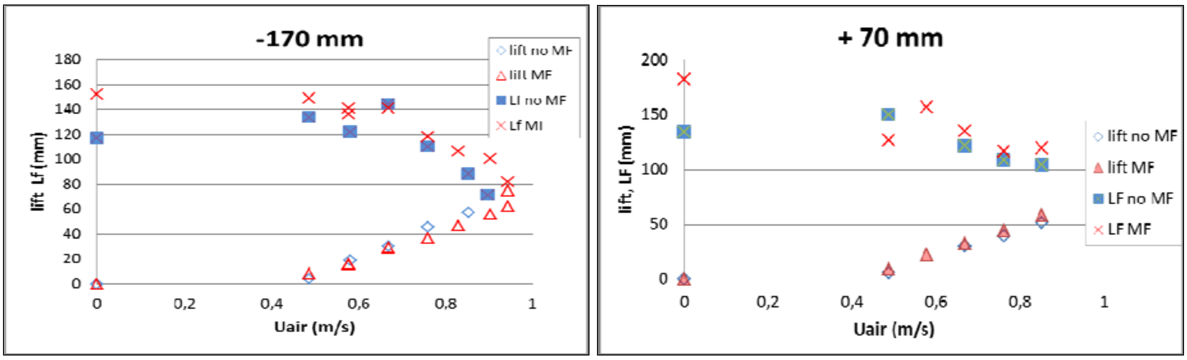

Figure 3. Flame lift height and flame length versus air injection velocity without (no MF) and with magnetic gradient (MF) in the two burner positions.

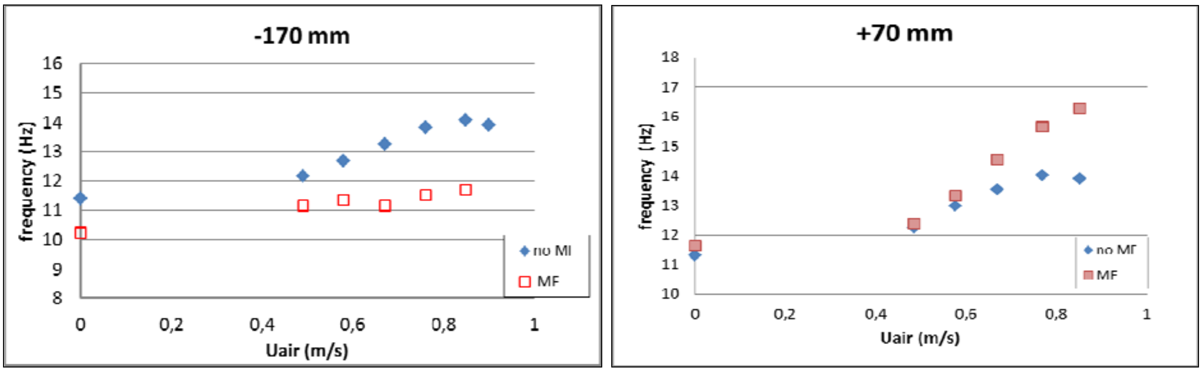

Figure 4. Flickering frequency versus air injection velocity without (no MF) and with magnetic gradient (MF) in the two burner positions.

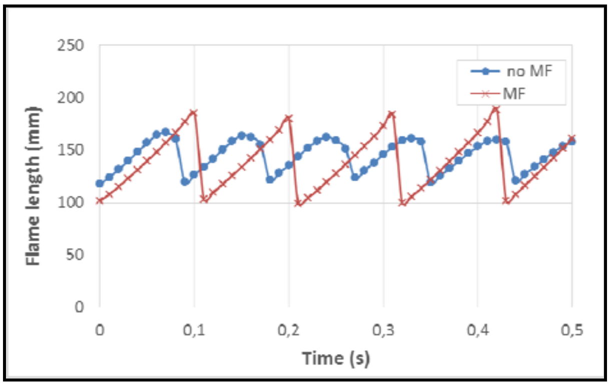

Figure 5. Time variation of the flame length along 0.5 s for the case of Uair=0 and position of the burner in the magnetic bore z= -170 mm.

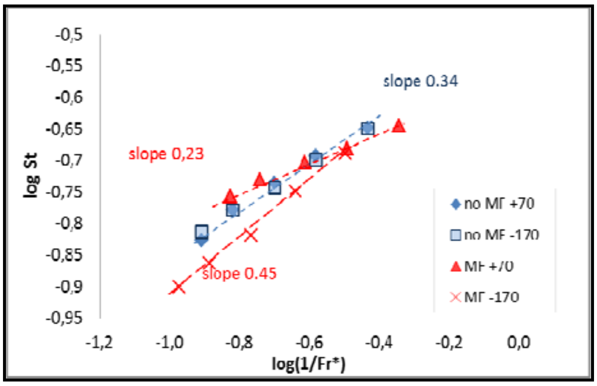

Figure 6. Relation between the Strouhal number and the inverse Froude number without and with positive (-170mm) and negative (+70 mm) magnetic gradients.

Influence of the positive magnetic gradient on the time-variation of the flame length is illustrated on Fig. 5. Comparison between no MF and MF experiments confirms the shift of the flickering frequency that has been reported Fig. 4. Figure 5 shows that magnetic gradients act also on the amplitude of the flickering and on the signature of the phenomenon.

To take into account both gravity and magnetic force in convection, a modified gravity factor g* is defined following Eq. (2).

$$g^* = Gg \qquad (2)$$

with $G=1+(gm_0/g)$ and $gm_0=-\chi_{mair}/\mu_o$. BdB/dz and BdB/dz=14T²/m.

Without magnetic field, g*=g. This new gravity factor is introduced in a modified Froude number Fr* defined as:

$$Fr^*=U^2/g^*d \qquad (3)$$

Figure 6 reports the frequency f in term of the Strouhal number ($St=f\ d_{air}/U_{air}$) versus the modified Froude number Fr* in which the magnetic effect is taken into account. The graph shows that the data obtained with and without magnetic field are following correlations close to the one proposed by Arai et al. in [1], when the magnetic effect is introduced in the definition of the Froude number.

Figure 7 shows the variation of the natural flame luminosity when submitted to a magnetic field gradient compared to the case without magnetic field fixed at one. In the positive magnetic gradient, the flames are found to be more luminous whereas in the negative magnetic gradient the flames are found to be less luminous than the flame without magnetic field application.

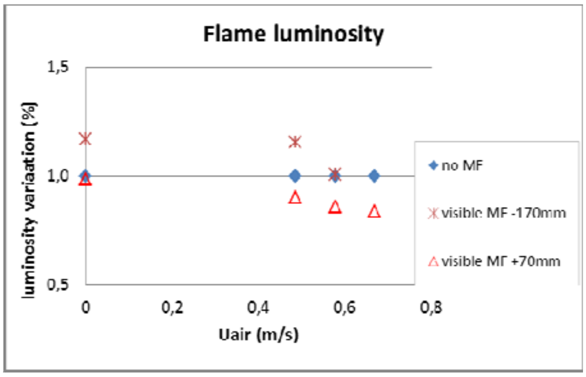

Figure 7. Comparison of natural flame luminosity variation without (no MF) and with magnetic gradient (MF) in the two burner positions at different air injection velocity

Considering the hypothesis of a correlation between soot production and natural flame luminosity and based on the fact that soot production is function of local temperature, stoichiometry and residence time, the observed increase of luminosity in the positive magnetic gradient can be attributed to various magnetic effects: one is the complementary supply of oxygen that leads to an increase of the flame temperature through a stoichiometric effect; a second is the reduced convection in the side air that contributes also to an increased flame temperature and the decreased flickering frequency can be related to an increased residence time. A higher local temperature and a longer residence time are favorable to the flame soot production. Conversely, the observed decrease of flame luminosity in the negative magnetic gradient may be explained by the reverse argumentation: less oxygen at the flame edge (attested by a smaller lift) and an increased convection in the flame side air (attested by a higher flickering frequency) result in a smaller flame temperature leading to less soot characterized by a decrease of flame luminosity.

4 Conclusions

The averaged values of flame lift height, flame length and flame luminosity have revealed the effects developed when magnetic field gradients apply on flickering laminar diffusion flames of methane /air from coaxial injection. Upward increasing magnetic field attracts paramagnetic oxygen upwards and counteracts the gravity convective motion in the air aside the hot zone of combustion whereas the upward decreasing magnetic field, generates a downward magnetic force on oxygen, depriving the flame edge of oxygen and enhancing the gravity convection in air along the flame. These effects act on the time dependent interaction of the external vortex rings with the flame structure as demonstrated by the variation of the flickering frequency, influencing local stoichiometry, temperature and soot residence time. In order to assess the role of magnetic gradients on soot production, a detailed study of the variation of soot production in flames has then to be performed.

References

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