# Magnetic Effects on Flickering Methane/Air Laminar Jet Diffusion Flames

P. Gillon[1], W.Badat[1], V.Gilard[1,2], B. Sarh[1,2]
[1]ICARE-CNRS, 1C Avenue Recherche Scientifique 45071 Orléans France,
[2] IUT, Université d'Orléans, France

## Abstract

The paper investigates the responses of buoyant jet diffusion flames to the application of magnetic field gradients. In a magnetic gradient, the paramagnetic oxygen is submitted to a magnetic force of attraction directed to the center of the magnet. Positive and negative magnetic gradients effects were compared to the case with no applied magnetic field. Measurements in methane/air flames from a coaxial injector show that over a range of air coflow velocity, the magnetic gradients affect both the oxygen supply at the flame edge and the displacement of the vortices in the air side of the high temperature reaction zone. Upward increasing magnetic field attracts paramagnetic oxygen upwards leading to variations of the lift height and the flame length and counteracts the gravity convective motion attested by a noticeable decrease of the flickering frequency whereas the upward decreasing magnetic field generates a downward magnetic force on oxygen, depriving the flame edge of oxygen attested by a higher lift height and enhancing the gravity convection in air along the flame evidenced by an increase of the flickering frequency. The flame visible luminosity is shown to be impacted by the magnetic field gradient; effect that is related to the soot production through modifications of local temperature, stoichiometry and residence time..

## 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 subjected to a gravity field known as flickering in which a periodic fluctuation of the flame tip is observed. Origins of the flickering have been attributed to buoyancy forces initiated by the 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. In the case of flames burning in ambient air, gravity effects have been summarized using Strouhal and Froude numbers by Arai et *al*. (1999) in a relation of $St=Fr^{-0.57}$ with $St=fd/U_{fuel}$ and $Fr= U_{fuel}^2/gd$ with U fuel injection velocity, d injection diameter and g gravity factorCarpio et al. (2012) investigated the pinch-off that may occur simultaneously to the flame flickering, corresponding to the flame tip breaking in two parts, with the detachment from the main flame of a pocket of gas which burns upward.

Adding a surrounding coflow of air to the central fuel jet allows a better control of the flame; moreover fixing conditions of outer flow is easier to implement numerically and experimentally. However, it could be a source of instability when the air coflow velocity is increased. The flame initially attached to the nozzle could be lifted with the lift height increasing with the coflow injection velocity. Addition of an air coflow introduces a momentum shear layer which acts on the flickering instability. H. Gohari Darabkhani et *al.* (2011) have shown that flickering frequency of anchored laminar methane diffusion flames increase linearly with the coflow rate.

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. Studies by Shaddix et *al*. (1994) have reported 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 $\rho$ ($kgm^{-3}$), the magnetic susceptibility $\chi_i$ (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 as first described by Braithwaite et al. (1991). 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 as demonstrated in air by Khali et *al.* (2005). Magnetic field effects on combustion have been studied by Baker and Calvert (2003). They 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. Wakayama and Sugie (1996) found that a decreasing magnetic field was able to promote combustion in diffusion flames. Gilard et *al*. (2008) 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 the case of longer flames (Gillon et al. 2010), 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.

Influence of magnetic gradients on flame temperature and temperature profile has been investigated in a butane diffusion flame using a circular grating Talbot interferometer (S. Agarwal et *al*. 2015). It has been shown that applying an upward decreasing magnetic field (resp. upward increasing magnetic field) leads to an increased (resp. decreased) flame temperature.

Recently, Legros et *al*. (2011) 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 despite the low Reynolds numbers of the methane and oxidizer injected flow. 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. Recently, Jocher et *al*. (2015) investigated the modification of soot production of steady laminar ethylene flames submitted to an upward increasing magnetic field. Motivated by the relationship between the flame instabilities and the pollutants formation, this work proposes to study the potential of a magnetic field as an actuator able to control the stability of laminar jet diffusion flames especially in conditions of high fuel and coflow exit velocities presenting long flames in which flickering is naturally present. To this end, we have carried out an experimental study of the influence of a magnetic gradient on a methane diffusion flame 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 Experiment

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 Gillon et al. (2010), methane was flowing from the inner tube while air was supplied through the annular one. The methane flowrate is fixed at 15 $cm^3s^{-1}$ (corresponding to a mean exit velocity of 0.83 m $s^{-1}$ and a

Reynolds number of 232) 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 $ms^{-1}$and Reynolds numbers from 266 to 564). Methane and air velocity range at burner exit ensured laminar flow.

Magnetic field was 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,the magnet center corresponding to z=0. The electrical current supplied to the coils is chosen constant for all the magnetic experiments corresponding to a value of $B_{max}$ =2.3T and $BdB/dz_{max}$=14T²/m. Two vertical positions of the burner inside the magnet bore were tested: one at z=-170 mm in the positive magnetic gradient (upward increasing magnetic induction) and one at z=+70 mm in the negative magnetic gradient as specified in Fig. 2. The two burner positions inside the air gap do not provide similar flame conditions at zero magnetic field due to steric consideration. Magnetic effects are then deduced from comparison of measurements performed in the two positions both without and with applied magnetic field.

A high-speed digital camera at a framing rate of 100 Hz provides 8-bit black and white images (1024x1024 pixels²). A Nikkon 105 mm f/2.8 lens mounted on the camera focuses on the axis of the burner giving a scale of 0.2 mm² area x 5mm in depth par pixel. Flame images have been recorded in two sets of recording conditions: a first set (fixed exposure time of 5 ms) to identify the geometric characteristics of the flame: length, lift height, pinch elevation, and a second set for the luminosity measurements. In order to compare from one experiment to another the recording parameters have been kept constant in the first set all along the different films. In the second set the camera parameters (exposure time and lens aperture) are adjusted in order to avoid saturation. The recording parameters are only kept constant for a given set of injection parameters allowing to compare luminosity of images that have been taken in identical conditions.

For each experimental condition (air injection velocity, magnetic gradient), flame length (Lf), lift height (lift) and luminosity (lum) were determined from image analysis.

Along with the flame flickering phenomena (characterized by oscillations of the flame tip), in given conditions, the flame may break repeatedly in two combustion parts (flame pinch off) as illustrated by the images in Figure 3. In these cases, two flame lengths are defined (Fig 3): the length of the main flame part is called Lf and the total flame length including the two combustion parts is called Lf pinch. The flame lift corresponds to the position of the first luminous pixel and the flame lengths are determined on the flame axis by the detection of the position of the last pixel above a given threshold value.

A luminosity parameter was defined as the sum of the luminosity value of each pixel of a specified image area.

Oscillation frequencies of the flame tip were determined by two separate methods. The first method is based on the time dependent variation of the flame length measured through image analysis and the second one is using a thermocouple. The temperature signal was time recorded using a type K thermocouple of 60 µm diameter (of less than 33 ms response time) 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 from the two sets of data. Data obtained by thermocouple and by image analysis have given the same results of frequency with extremely limited discrepancy less than 0.5 % error. The use of a thermocouple is then a robust way of measurement of the flickering phenomena in systems without optic access.

# 3 Results and discussion

Experimental results are reported on Fig. 4 to 6. Figure 4 presents the variation of the mean visible flame length (Lf and Lf pinch) and mean visible flame lift height (lift) with the air inlet velocity for the two cases of positive and negative magnetic gradients. Comparison with experiments at zero magnetic gradient shows that when the flame is lifted above the burner tip, the lift height is decreased (resp. increased) by the action of a positive (rep. negative) magnetic gradient. Variations of the flame edge position are explained by 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 magnitude of the magnetic effect on the lift height varies with the variation of the flame edge position inside the bore. Small value of the magnetic force in front of the edge leads to a small variation except when the lift height is high enough (at higher air velocity) to position the flame edge in front of a stronger magnetic gradient.

Average flame lengths are reported Figure 4. The main flame length is found to be decreased by the application of a magnetic gradient either positive or negative whereas the mean total flame length including the pinch off is higher in flames under magnetic gradient than in their counterparts without magnetic field. Interestingly, at high air coflow velocity where a lifted flame develops far above the burner, oscillation and pinch off of the flame tip are still observed. Whereas the difference between the main flame length and the total flame length (Lf pinch) is small without magnetic action, it is highly influenced by the magnetic force.

Influence of positive and negative magnetic gradients on the time-variation of the two parts of the flame length is illustrated Fig. 5 for the case of no air coflow (Uair=0). The periodic variation of the flame length is illustrated showing both the flame flickering and the pinch off characteristics. If the magnetic force appears to increase the amplitude of variation of the main flame length, its main action is to trigger and to enhance the development of the flame pinch off. It is the difference between the main flame length (Lf) and the pinched flame length (Lf pinch) which evidences the action of the magnetic convection in the air aside the flame. In the positive magnetic gradient, the buoyancy convection is slowed down by the magnetic force. The variation is of about 85 mm from the lower flame length  to the higher flame tip position including the flame pocket tip position in the conditions reported Fig.5. In the negative magnetic gradient, the amplitude of variation is enhanced (about 145 mm Fig. 5). Buoyancy added to magnetic force increase air convection leading to a stronger upward displacement of the detached burning pocket.

Figure 5 shows also the shift of flickering frequency by comparing the curves with and without MF in time.

The magnetic effect on the flame flickering frequency is confirmed Fig. 6 which reports the variation of flickering frequency versus the air coflow exit velocity. At zero magnetic field, the flickering frequency is observed to increase with Uair as predicted by Gohari Darabkhani (2011). The frequency is observed to be reduced in the positive magnetic gradient and increased in the negative one; the magnitude of the effect being related to the relative vertical position of the flame to the maximum of the magnetic gradient as detailed in Gillon et al. (2015). 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, burner at z=-170 mm, the upward magnetic force is opposed to gravity, the effective gravity is reduced and it leads to a reduced convection in air along the flame. In the negative magnetic gradient burner at z=+70 mm, the downward magnetic force adds to gravity to drive a stronger convective motion in air at the flame tip corresponding to an enhanced effective gravity. Results obtained in the negative magnetic gradient present the same evolution of the flickering frequency that has been obtained by Sato et al. (2000) for flickering flames in increased gravity.

To take into account both gravity and magnetic force in convection, a modified gravity factor g* is defined following Eq. (2) as detailed in the analysis of Khaldi et *al*. (2005) .

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

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

Without magnetic field G+1 and g*=g whereas in the positive (resp. negative) gradient G=0.86 (resp. G=1.21). Following Sato'sanalysis (2000), the new gravity factor is introduced in a modified Froude number Fr* defined as:

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

Figure 7 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. Figure 7 is inspired from the correlation presented in Arai et al. (1999). Arai  et al. obtained a variation of Strouhal versus Froude as $St=Fr^{-0.57}$ based on the flickering frequency of a methane flame burning in ambient air. In their case, the Strouhal and Froude numbers are based on the mean fuel exit velocity. The graph presented fig.7 is using a similar analysis, the Strouhal and Froude numbers being based on the mean air velocity. As the frequency is shown to depend on the co flow velocity (cf fig. 6), the variation of St with Fr is expected to be different. The results are interesting as it appears that $St=Fr^{0.34}$ when no MF is applied and that $St= Fr^{0.23\ \text{to}\ 0.45}$ when the magnetic field is applied: variation which corresponds to enhanced and reduced convection. when the magnetic effect is introduced in the definition of the Froude number.

Figure 8 reports the percentage of variation of the natural flame luminosity when submitted to a magnetic field gradient compared to the case without magnetic field fixed at zero. In the positive magnetic gradient, in an upward increasing magnetic field, the flames are found to be more luminous whereas in the negative magnetic gradient flames are less luminous than the flame without magnetic field application.

In the hypothesis of a correlation between soot production and natural flame luminosity the observed increase of luminosity in the positive magnetic gradient is in agreement with the trends obtained by Jocher at al. (2015) that have observed an increase of soot volume fraction of an ethylene steady flame in an upward increasing magnetic field. This effect can be attributed to various magnetic effects: one is the complementary supply of oxygen that leads to an increase of the flame temperature; a second is the reduced convection in the side air that contributes also to an increased flame temperature and the decreased flickering frequency evidencing a reduced effective buoyancy coupled can be related to an increased residence time of the soot particles inside the flame. 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 Conclusion

The average 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 time-variation of soot production in flickering flames has then to be performed.

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**Figure captions**

Figure 1: Schematic of the experimental set-up and burner geometry.Insert is a cross-section of the burner tip.

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

Figure 3: Flame images at $U_{air}$=0 for the two burner positions.

Figure 4: Average flame lift height (lift) and flame lengths (Lf and Lf pinch) 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 1 s for $U_{air}$=0 at the two positions of the burner in the magnetic bore a) z= -170 mm b) z=+70 mm

Figure 6: Flickering frequency versus air injection velocity without (no MF) and with magnetic gradient (MF) in the two burner positions.

Figure 7: Relation between the Strouhal number and the inverse Froude number without and with positive (-170mm) and negative (+70 mm) magnetic gradients.

Figure 8: Visible flame luminosity variation without (no MF) and with magnetic gradient (MF) in the two burner positions versus air injection velocity.

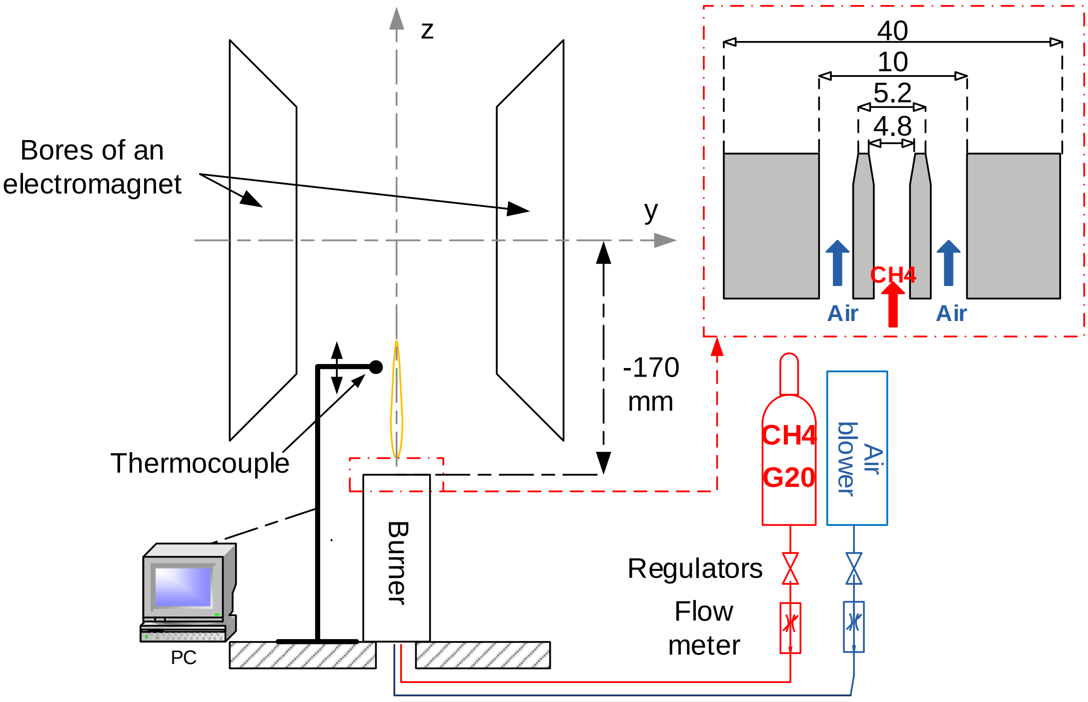

z
y
Bores of an electromagnet
Thermocouple
-170 mm
Burner
PC
40
10
5.2
4.8
CH4
Air
Air
CH4
G20
Air blower
Regulators
Flow meter

Figure 1

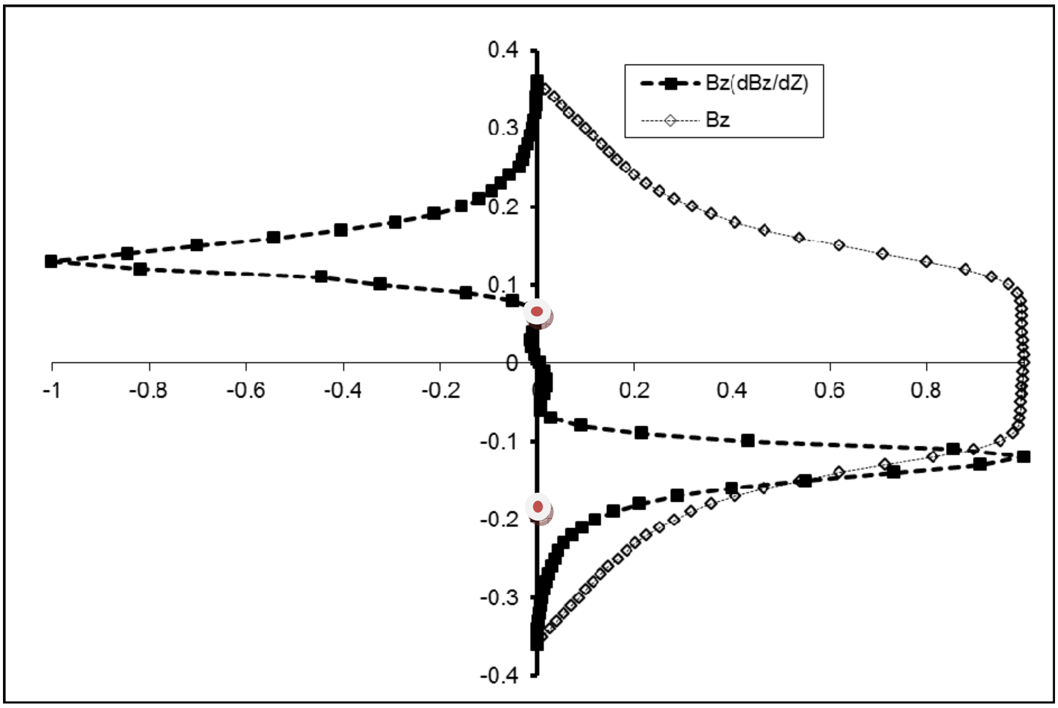
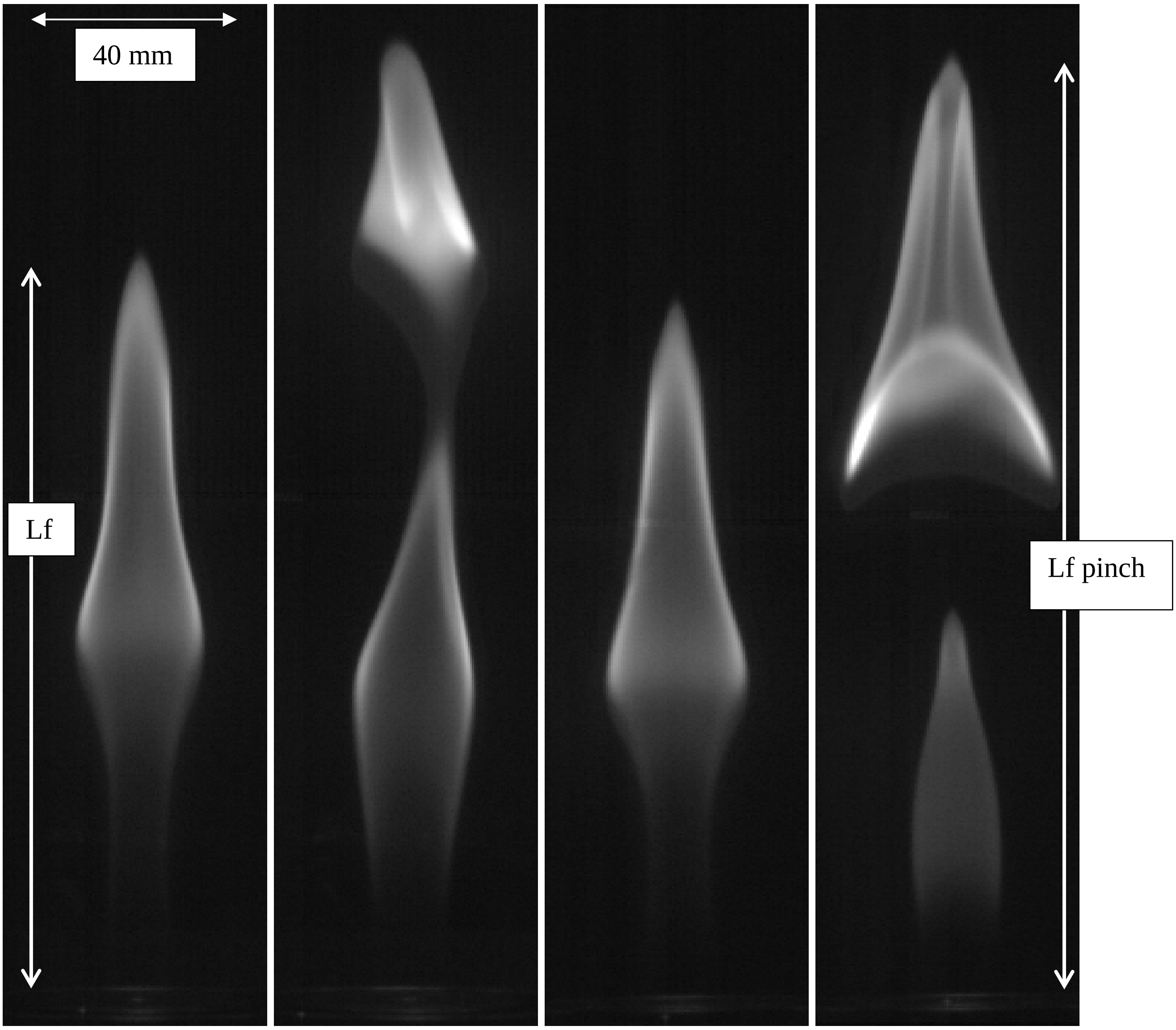
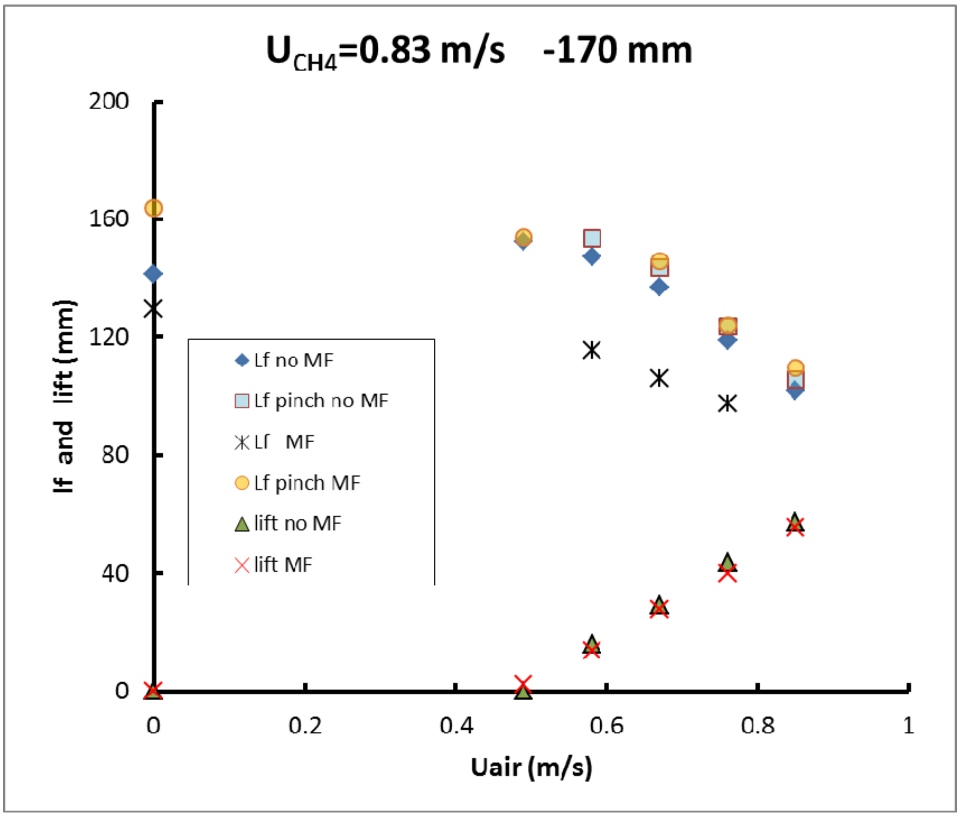



Figure 2

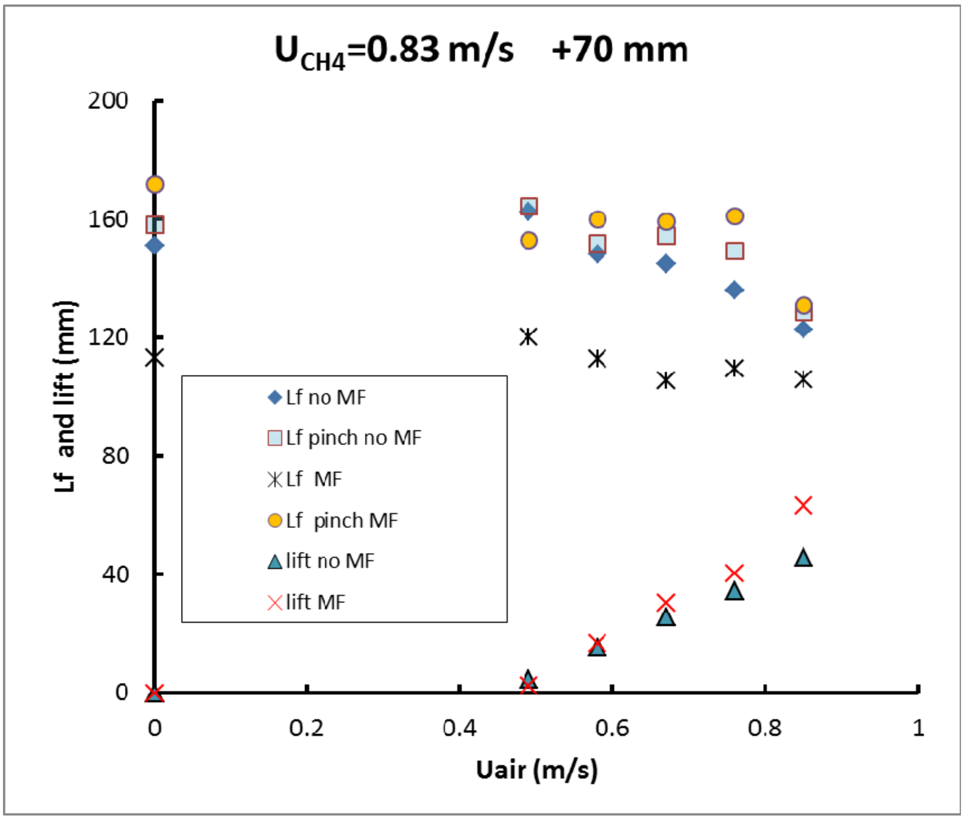



-170 no MF    -170 MF    +70 no MF    +70 MF

Figure 3



$U_{CH4}$=0.83 m/s -170 mm
lf and lift (mm)
Uair (m/s)
Lf no MF
Lf pinch no MF
Lf MF
Lf pinch MF
lift no MF
lift MF
200
160
120
80
40
0
0
0.2
0.4
0.6
0.8
1

$U_{CH4}$=0.83 m/s +70 mm
Lf and lift (mm)
Uair (m/s)
Lf no MF
Lf pinch no MF
Lf MF
Lf pinch MF
lift no MF
lift MF
200
160
120
80
40
0
0
0.2
0.4
0.6
0.8
1


Figure 4

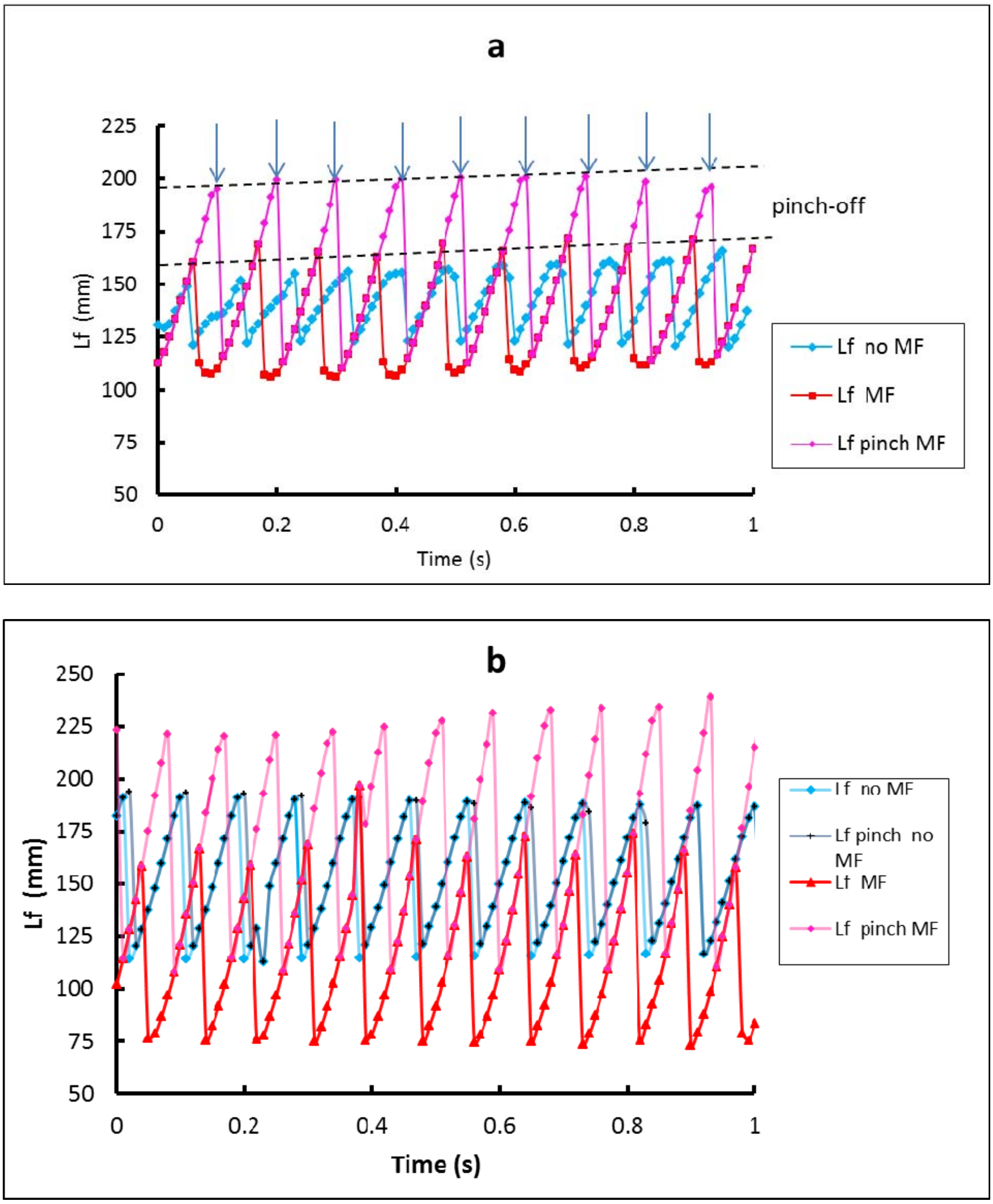
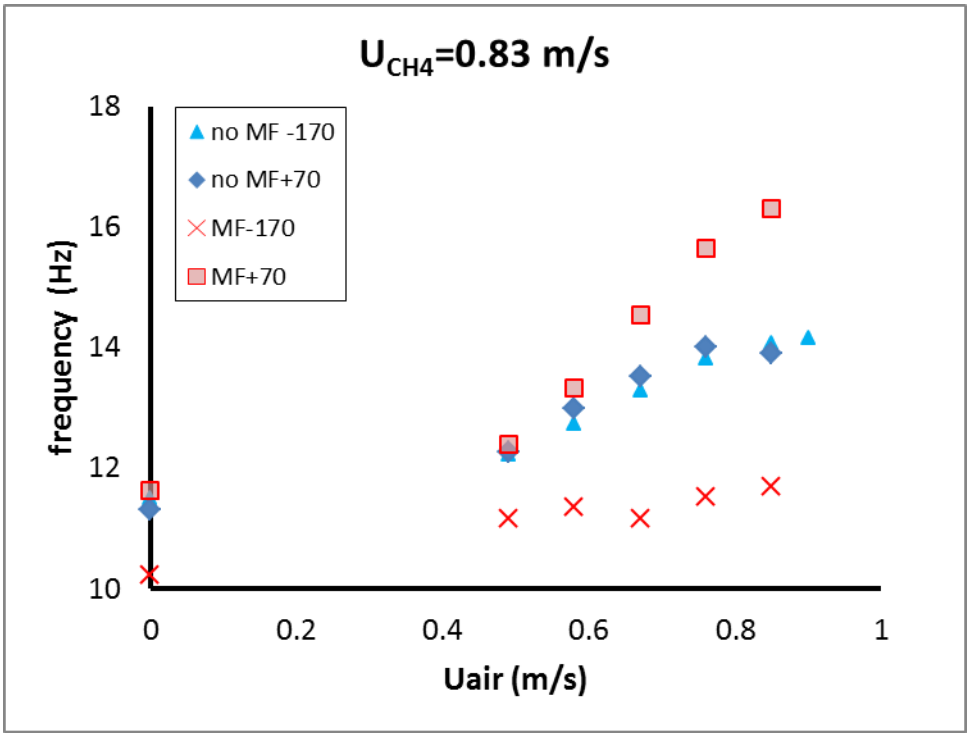

a
225
200
175
150
125
100
75
50
Lf (mm)
0
0.2
0.4
0.6
0.8
1
Time (s)
pinch-off
Lf no MF
Lf MF
Lf pinch MF
b
250
225
200
175
150
125
100
75
50
Lf (mm)
0
0.2
0.4
0.6
0.8
1
Time (s)
Lf no MF
Lf pinch no MF
Lf MF
Lf pinch MF

Figure 5



$U_{CH4}$=0.83 m/s
18
16
14
12
10
0
0.2
0.4
0.6
0.8
1
frequency (Hz)
Uair (m/s)
no MF -170
no MF+70
MF-170
MF+70


Figure 6

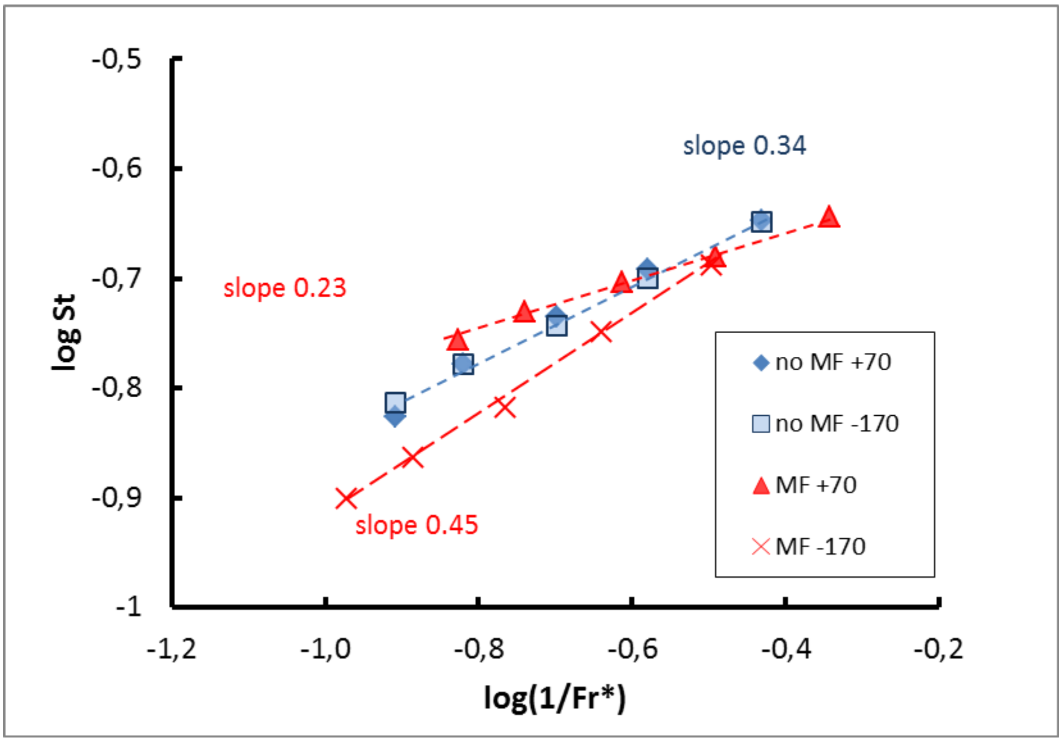
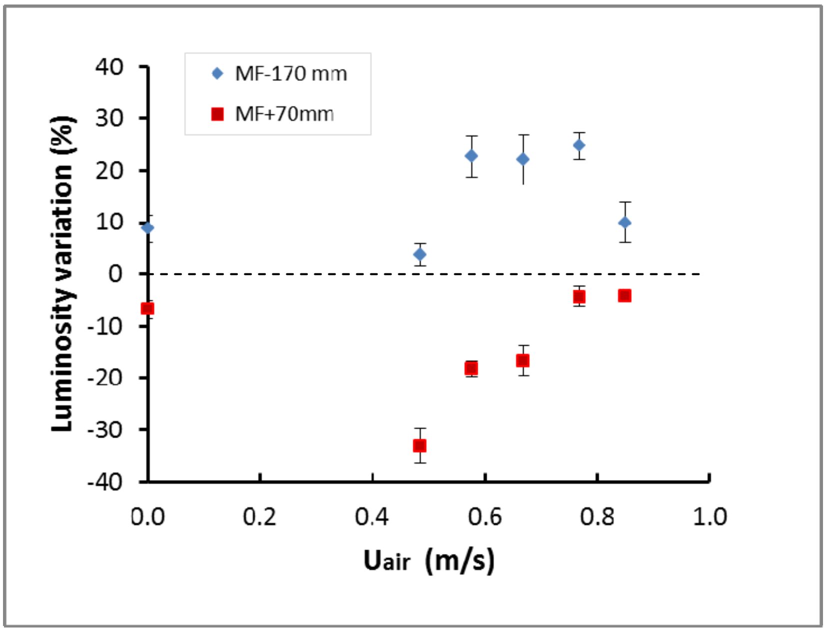

-0,5
-0,6
-0,7
-0,8
-0,9
-1
log St
slope 0.34
slope 0.23
slope 0.45
no MF +70
no MF -170
MF +70
MF -170
-1,2
-1,0
-0,8
-0,6
-0,4
-0,2
log(1/Fr*)

Figure 7



MF-170 mm
MF+70mm
Luminosity variation (%)
40
30
20
10
0
-10
-20
-30
-40
0.0
0.2
0.4
0.6
0.8
1.0
Uair (m/s)


Figure 8