International Scientific Colloquium
**Modelling for Material Processing**
Riga, September 16-17, 2010

# Effects of Magnetic Field on Swirling Flame

## I. Barmina, M. Zake

### Abstract

Magnetic-field-induced variations of swirl flame velocity, temperature, composition and combustion efficiency profiles at different stages of swirl flame formation are experimentally studied by varying the magnetic field strength. The results show that the magnetic field-enhanced mass transfer of paramagnetic and diamagnetic flame species significantly disturbs the axial and tangential velocity and composition profiles, promoting combustion reactions along the outside part of the reaction zone with its radial expansion. Based on the experimental results, a mechanism of gradient magnetic field effect on the swirl flame behaviour is discussed by considering the impact of a non-uniform upstream increasing magnetic field on the physical transport behaviour of flame species near the flame recirculation zone and on the combustion characteristics of the swirling flame flow.

### Introduction

Over the last years an increasing interest to an ability to provide different types of combustion control with application of external forces (electric, magnetic) to the flame has been observed. Many researches on the relation between combustion and magnetic fields have taken place [1-4] providing the detailed study of the effects of gradient magnetic field on the diffusion flame emission, flame shape, luminosity and size, which are accepted as a result of the paramagnetic and diamagnetic properties of the flame species. The results of these studies have shown that paramagnetic flame species, predominately, oxygen, are drawn towards higher magnetic field strengths, while diamagnetic substances such as nitrogen, carbon dioxide and most of hydrocarbon fuels are repelled by stronger magnetic fields, so providing the local variations of the flame composition and combustion characteristics. In fact, the magnetic field effect on paramagnetic species is about three orders of magnitude larger than the magnetic effect on diamagnetic species. Hence, under conditions, when the flame is subjected to the influence of magnetic force, the dominant field effect on the flame can be related to the field-enhanced mass transfer of paramagnetic flame species.

In addition to the effect of gradient magnetic field on the mass transfer of paramagnetic and diamagnetic flame species, with subsequent variations of the combustion characteristics, the magnetic field also can directly influence the chemical reactions between free radicals or molecules, which, possessing an odd number of electrons, can be viewed as "molecular magnets" [5] with opposite or parallel spin orientation. An external field under the given conditions slows down reactions, which require a change of spin. As a consequence, less radicals can change their spin, and free radicals live longer and their overall concentration increases when a field is applied, decreasing the rate of the reactions [5].

So far, the investigations of magnetic field effects on the flames are focused mostly on the interaction between the non-uniform magnetic field and laminar diffusion flames, for which the dominant factors, influencing combustion, are the physical processes of diffusion and mixing. The focus of the current study is to understand the mechanism of interaction between the swirling flame and the gradient magnetic field of moderate strength, which can cause greater entrainment of the oxidizer into the flame reaction zone, thus completing the fuel burnout. In particular, the recent study refers to the experimental research of the magnetic field-induced variations of the swirling flame velocity, temperature and composition profiles with account for the magnetic field effect on paramagnetic and diamagnetic behaviour of the swirling flame flow. Actually, the usefulness of magnetic field effects on the swirling flame behaviour has been investigated and analyzed.

## 1. Experimental Set-up

The digital image of the experimental device for experimental study of the magnetic field effects on the swirling propane flame flow is shown in Fig. 1. The main components of the experimental device are: a swirl burner with radial propane supply and tangential air supply into the burner (1), a sectioned stainless steel channel with inner diameter of 40 mm and total length up to 300 mm, downstream of which the swirling flow field is developing (2), and two coils of an electromagnet (3), which induce a non-uniform downstream decreasing magnetic field (Fig. 1). The propane burner is placed between the coils of the electromagnet that for the given field configuration promotes a reverse axial mass transfer of paramagnetic oxygen up to the burner outlet. The magnetic field effect on the propane burnout was studied experimentally at a slight excess of propane supply at the burner outlet ($\alpha \approx 0.9$), determining fuel-rich conditions downstream the flame axis ($R < 10$ mm) at the initial stage of the swirl flame formation ($L/D \approx 1.5$-$2$) with a pronounced air excess along the outside part of the flame reaction zone ($R > 10$ mm). The magnetic field effect on the swirling flame dynamics, temperature and composition profiles for the given combustion conditions was investigated using the diagnostic sections with orifices (4), which allow to insert diagnostic tools (thermocouples, gas sampling probes and Pitot tube) into the swirling flame channel flow for local measurements of the flame temperature, composition and flow velocity compounds at different stages of the swirl flame formation.

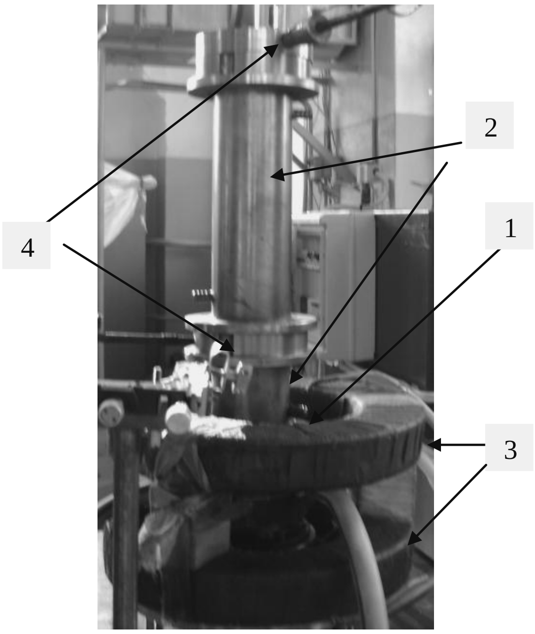


Fig. 1. The digital image of the experimental device: 1 - propane burner, 2 -channel sections, 3 – electromagnet, 4 - diagnostic sections with probes

The magnetic field effect on the formation of flame velocity and composition profiles was measured by a gas analyzer Testo 350 XL equipped with a Pitot tube and gas sampling probes. The flame temperature profiles were measured using Pt/Pt-Rh thermocouples and a data recording system PC-20TR. Mass flow controllers, calibrated for propane and air supply, were used to measure the rate of radial propane and swirling air supply into the burner. Propane can be supplied into the burner at a rate of 0.6-0.8 l/min, while the swirling air flow at a rate 14-18 l/min.

To evaluate the magnetic force, acting on the swirling flow field, the axial distribution of magnetic field intensity (B, T) was measured as a function of the flame centerline position from the burner outlet and as a function of the applied electric current (I) using a gaussmeter with a transverse probe. The minimum value of magnetic induction close to the burner outlet (L = 10 mm) was 0.02 T for I = 5 A, while the maximum value of magnetic induction used in this study was about 0.092 T for I = 30 A, providing a net mean axial magnetic field gradient downstream the flame axis (dB/dz) in a range of 0.09-0.37 T/m. The radial variations of the magnetic field induction over the water-cooled channel do not exceed 2% and can be neglected.

## 2. Results and Discussion

The effect of the gradient magnetic field on the swirling combustion was investigated experimentally using a partially premixed strongly swirled propane/air flame with a high swirl number $\boldsymbol{S} = 2/3v_{tg}/v_{ax} \approx 2.5\text{-}3$ of the burner outlet flow, resulting in the formation of a recirculation zone close to the burner outlet. The balance between the axial flow rate and the reverse axial mass transfer of the products under conditions of undisturbed swirling flame flow (B=0) is observed close to L/D ≈ 1.5-2, where the axial flow velocity achieves its minimum value (Fig. 2a).

The investigations of the magnetic field effects on the swirling flame dynamics have shown that the application of a non-uniform downstream decreasing magnetic field to the swirling flame channel flow disturbs the shape of the flame velocity profiles (Fig. 2a) with a direct influence on the average values of the axial and tangential flow velocity compounds (Fig. 2b) and residence time of reactions ($t \approx L/v_{av}$).

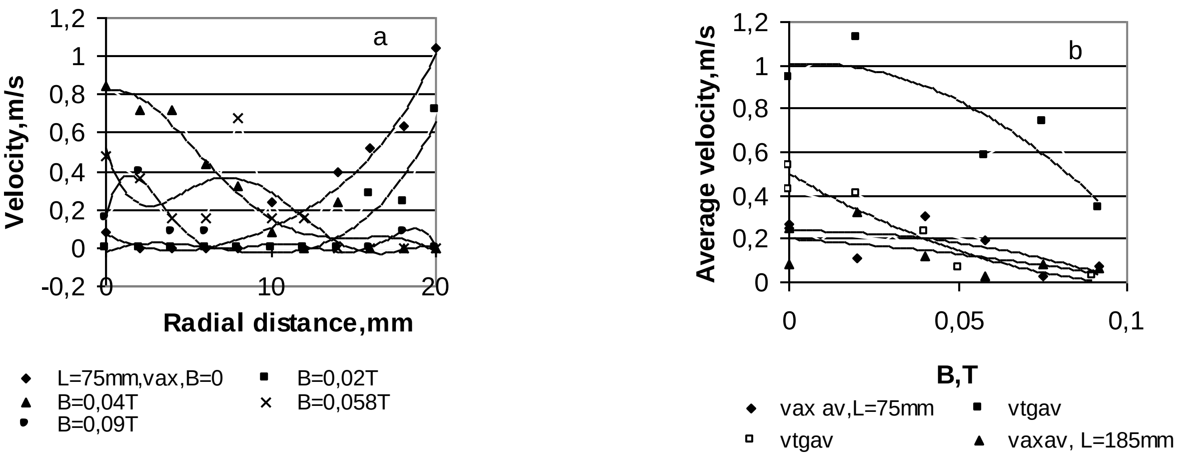


Fig. 2. Magnetic field effect on the formation of axial flame velocity profiles (a) and average values of the flame velocity compounds at different stages of the swirl flame formation (b)

As it follows from Fig. 2a, the dominant field-induced variations of the axial flame velocity profiles are detected close to the channel walls (R > 10 mm), where the field-induced reverse axial motion of the flame species (paramagnetic oxygen) results in a decrease of the axial flame velocity along the outside part of the flame reaction zone with subsequent increase of the axial flame velocity and radial expansion of the flame velocity profiles. The field-induced variations of average values of the flame velocity compounds indicate that the magnetic force acts like magnetic pressure, which gradually slows down the flame downstream motion during the primary stage of the swirl flame formation, increasing the residence time of reactions from 0.3 $s^{-1}$ for B = 0 up to 0.8 $s^{-1}$ for B = 0.092 T. The magnetic force, acting on the paramagnetic flame species under such conditions, can be approximately estimated with account for the volume magnetic susceptibility ($\chi_{ox}$) of paramagnetic oxygen, magnetic field induction ($B$) and magnetic field gradient, developing along the flame axis ($dB/dz$) [1-4]:

$$F_{mag} = \frac{1}{2}\frac{\chi_{ox}}{\mu_o} B \frac{dB}{dz}, \qquad (1)$$

with $\mu_0$ being the permeability of free space.

With the cold airflow (300 K) conditions and given magnetic field configuration, the magnetic field-induced body force close to the burner outlet can be varied in a range of 0.003-0.05 N/$m^3$. In accordance with the Curie's law, the magnetic susceptibility of paramagnetic gaseous compounds ($\chi_{ox}$) is proportional to their density and inversely proportional to the temperature and can be expressed as:

$$\chi_{ox} = \frac{C}{T}, \qquad (2)$$

where the Curie's constant C in (2) depends on the number of magnetic moments $N$ and, under the given combustion conditions, on the volume fraction of the paramagnetic flame species (free oxygen) [4].

Considering that the magnetic susceptibility of paramagnetic gaseous compounds ($\chi_{ox}$) depends on the flame temperature and volume fraction of free oxygen ($N_{ox}$), the magnetic force, acting on the swirling flame channel flow, can be approximately expressed linearly dependent on the local volume fraction of free oxygen and inversely dependent on the local flame temperature:

$$F_{mag} \approx \frac{1}{2}\frac{N_{ox}\mu^2}{\mu_0 k_B T} B \frac{dB}{dz}. \qquad (3)$$

According to (3), the magnetic force, acting on the swirling flame flow, approaches its peak value close to the outside part of the swirling flame flow, where the flame temperature decreases from 1200-1300 K for R ≈ 0 below 600-700 K close to the channel walls (R = 20 mm), while the volume fraction of free oxygen increases from 3-4% close to the flame centerline up to 19-20% along the outside part of the flame reaction zone (R ≈ 2 0mm), determining the field-induced variations of the shape of the flame velocity profiles (Fig. 2a). As a result of the magnetic field-enhanced reverse axial mass transfer of paramagnetic oxygen and field-enhanced mixing of the flame compounds that disturbs the flow dynamics, interrelated variations of the combustion characteristics are observed. Local measurements of the flame composition at different stages of the swirl flame formation confirm the field-enhanced mixing of the flame compounds with radial expansion of the flame reaction zone and field-enhanced increase of the combustion efficiency along the airside part of the reaction zone (Fig. 3).

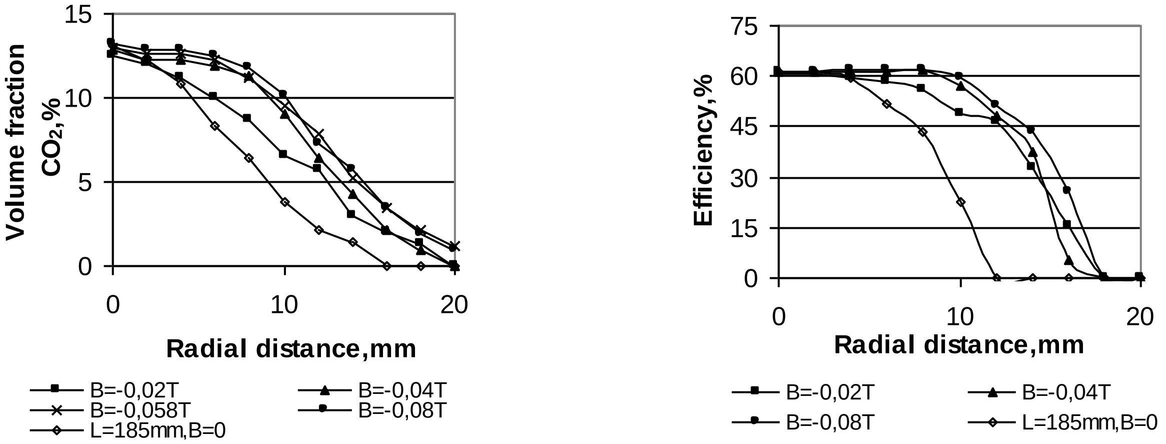


Fig. 3. Magnetic field effect on the shape of composition profiles of the main product ($CO_2$) and combustion efficiency of the swirl flame reaction zone (L/D ≈ 4.5)

Moreover, estimations of the magnetic field effect on the average values of the volume fraction of $CO_2$,, mass fraction of NO, CO and temperature of the flame reaction zone have shown that the field-induced variations of the residence time of reactions and the enhanced mixing of the flame compounds promote a correlating increase of the average values of the flame temperature, volume and mass fraction of the main products by increasing the magnetic field induction, while decreasing the average value of the CO mass fraction in the flame reaction zone (Fig. 4).

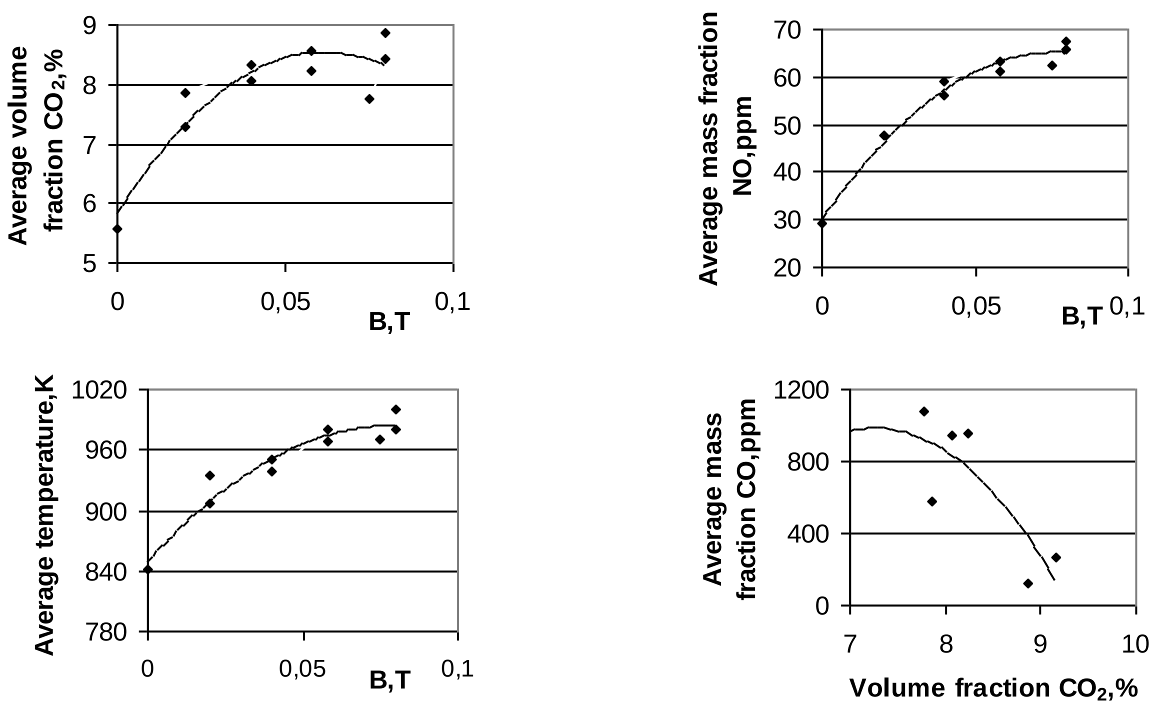


Fig. 4. Magnetic field effect on the average values of the main products and average temperature with correlation between the average mass fraction of CO and volume fraction of $CO_2$

Finally, it should be noted that under the given combustion conditions no direct magnetic field effect on the reaction rates for the main products $CO_2$, NO was observed. Assuming that the rate constants of the reactions, determining the formation of main products (NO, $CO_2$), can by expressed from the Arrhenius law with a strong temperature dependence of the reaction rates: $k = A*\exp(E_a/RT)$ and the constant activation energy $E_a$ of reactions ($A$ is the pre-exponential factor), the Arrhenius plot of lnNO and $\ln CO_2$ can be expressed linearly dependent on 1/T. A similar approximation of the field-induced variations of average values of NO and $CO_2$ confirms the linear dependence on 1/T with a significant temperature affect on the formation of the main products and constant activation energy of reactions with no magnetic field effect on the activation energy of the reactions.

## Conclusions

In view of all the above results, the effect of the gradient magnetic field on the swirling flame flow formation is initiated by the field-induced upstream mass transfer of paramagnetic oxygen with interrelated variations of the flame dynamics, temperature and composition profiles.

The dominant feature of the field effect on the flow dynamics is the reduction of the average values of the flow velocity compounds with a correlating increase of the residence time of reactions.

The field-enhanced axial upstream mass transfer of free oxygen along the outside part of the flame reaction zone (R > 10 mm) with flow reversing downstream the flame core (R < 10 mm) promotes the enhanced mixing of the flame compounds with radial expansion of the flame reaction zone and a correlating increase of the flame temperature, combustion efficiency and average values of the main products. Hence, the field effect on the flame formation can be used to provide additional control of the flame dynamics with direct impact on the fuel combustion. There has been found no evidence of magnetic field effect on the activation energy of reactions.

## References


[1] Wakayama, N. I.: *Magnetic Promotion of Combustion in Diffusion Flames*. Physica B. National Institute of Advanced Industrial Science and Technology, Japan, Vol. 216, 1996, pp. 403-405.

[2] Aoki, T.: *Radicals' Emissions and Butane Diffusion Flames Exposed to Upward Decreasing Magnetic Fields*. Japanese Journal of Applied Physics. Vol. 28, 1989, pp. 776-785.

[3] Baker, J., Calvert, M. E.: *A Study of the Characteristics of Slotted Laminar Jet Diffusion Flames in the Presence of Non-uniform Magnetic Fields*. Combustion and Flame, Elsevier, Vol. 133, 2003, pp. 345-357.

[4] Swaminathan, S.: *Effects of Magnetic Field on Micro Flames*. Thesis, Louisiana State University, USA, 2005, pp. 117.

[5] Scaiano, J.C.: *Control of chemical Reactions with Magnetic Fields*,. Department of Chemistry, Interscientia, Vol. 1, 1996, No. 1, University of Ottawa, Ottawa, Ontario, K1N 6N5.
http://www.uottawa.ca/publications/interscientia/inter.1/magnetic.html


## Authors


Dr. Sci. ing. Barmina, Inesa
Dr. Phys. Zake, Maija
Institute of Physics
University of Latvia
32 Miera str., Salaspils, LV-2169, Latvia
E-mail: barmina@sal.lv
mzfi@sal.lv