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Magnetic promotion of combustion in diffusion flames

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Abstract

When a fuel gas flowed in the direction of a decreasing field strength, inhomogeneous magnetic fields were found to promote combustion in diffusion flames. On the application of a magnetic field gradient ($H(\mathrm{d}H/\mathrm{d}y) = 35\ \mathrm{T}^2/\mathrm{m}$), the flame temperature increased by about 120° and the flame became shorter and more brilliant. Magnetic promotion of combustion was explained by the following two kinds of air flow caused by the magnetic force acting on paramagnetic O_2. The supply of air to the flame front increased because of the magnetic attractive force. Furthermore, magnetic convection occurred along the steepest gradient of the field because χ is linear to p_{O_2}/T^2. The present results suggest the possibility of magnetic control of combustion and air flows (magnetoaerodynamics).

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1. Introduction

Though combustion is well known to be influenced by electric fields [1], few studies have been done about the effect of static magnetic fields on combustion [1–3]. As exceptional cases, there has been some work on the deflection of a flame in a magnetic field. In 1847, Faraday applied a vertical magnetic field gradient to a flame on a wax taper, observed its tendency to form an equatorial disk and concluded that the flame was diamagnetic [1, 2]. Furthermore, Mayo has found a candle flame to be turned horizontally into the region of lower magnetic intensity [1, 3]. In both cases, diffusion flames showed a tendency to be deflected toward a lower field. According to Cozen et al., the magnetic deflection of diffusion flames was explained by the pressure difference acting on the flame gas caused by a magnetic field [1, 4]. As far we know, there has been little work done beyond such observation of a more qualitative kind.

On the other hand, magnetic field gradient has been shown to have a considerable effect on advancing gas streams in air. Faraday found that diamagnetic gases such as nitrogen and hydrogen made a detour around the magnetic poles in air [1, 2]. On the other hand, gas mixtures which contain more oxygen gas than air were observed to be attracted toward stronger magnetic fields [5]. Recently, these magnetic behaviors of the gas mixture were explained by the magnetic force acting on paramagnetic oxygen gas [6]. The magnetic force per unit volume is shown as follows:

$$F = \tfrac{1}{2}\, p_{O_2} \chi_{O_2}\, \mathrm{grad}\, \boldsymbol{H}^2 . \qquad (1)$$

Here, χ_{O_2} refers to the magnetic susceptibility of O_2 gas (1.5×10^{-7} emu/ml), and p_{O_2} is its partial pressure. $\boldsymbol{H}$ is the magnetic field strength. For example, the force acting on air is calculated to be about 1.5 dyn/ml under one dimensional magnetic field gradient ($H = 1$ T, $\mathrm{d}H/\mathrm{d}y = 0.5$ T/cm).

These magnetically induced gas flows are expected to affect combustion in diffusion flames [7]. Since oxygen gas is supplied from the surrounding air, the buoyant convective flow plays an important role to support combustion. Diffusive transport rates are 10–50-fold slower than the buoyant convective transport rates. Therefore, diffusion flames cannot continue combustion under microgravity [8]. The purpose of the present paper is to

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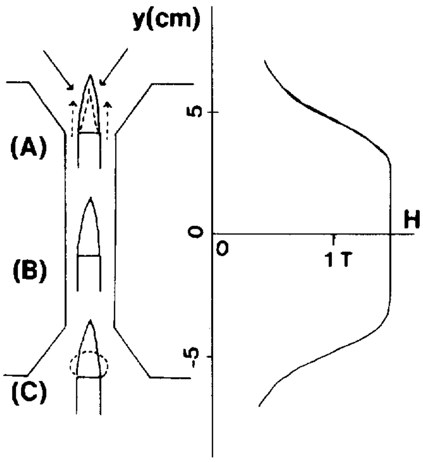


Fig. 1. Experimental setup and spatial distribution of magnetic intensity along the y-axis at the highest current through the magnet.

report magnetic promotion of combustion in diffusion flames and clarify the mechanism.

2. Experimental

Fig. 1 illustrates the experimental setup. The gap of the electromagnet (IDX Corp., ISM-130WV) was 2 cm. The spatial distribution of the magnetic intensity along a vertical y-axis is also shown at the maximum current through the magnet. A homogeneous magnetic field (1.5 T) was generated in the central area, while an inhomogeneous magnetic field with a gradient of about 0.3–0.4 T/cm existed in the region, $6 > y > 3.5$ cm and $-6 < y < -3.5$ cm.

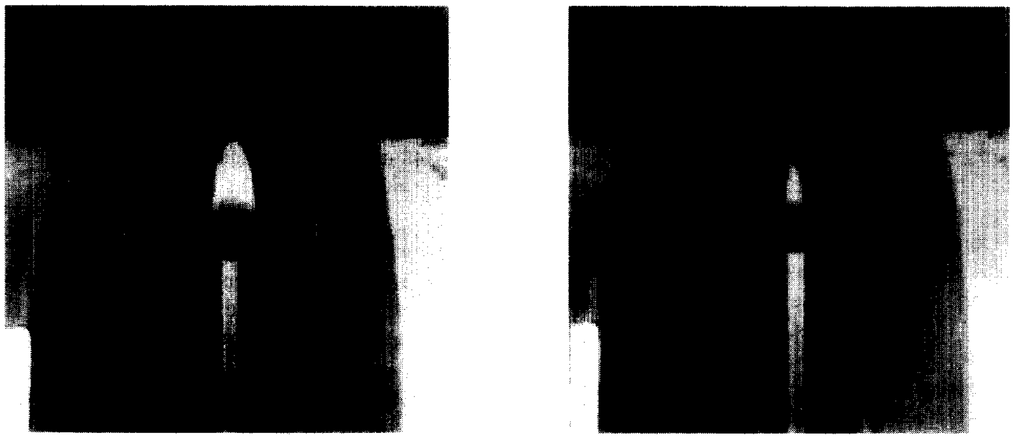
Methane gas (150 ml/min) flowed along the y-axis through a glass pipe (inner diameter 0.8 cm). A circular cone flame was observed at the top of the pipe, as shown by a solid line. The head of the pipe was set 4 cm (A) above the center of the pole and 1 cm (B) and 6 cm (C) below it, as shown in Fig. 1.

The effect of inhomogeneous magnetic fields was studied by measuring the flame temperature and observing the shape and color of the flame. The flame temperature was measured with a thermometer (Advantest Ltd., TR2114). A thermocouple (Pt–Rh) was placed 1 cm above the burner head. The picture of the flame was recorded by a videocamera (SONY, CCD-TR75).

3. Results

In the previous studies by Faraday et al. [1–3], fuel gas always flowed toward a stronger magnetic field and the flame was deflected toward a weaker field. Fig. 1(C) corresponded to this case, and the flame became an equatorial disk, as shown by a dotted line.

On the other hand, in the present study, we set the flame at the position (A) and fuel gas flowed in the reverse direction. The flame became shorter, sharper and more brilliant immediately after applying the magnetic field, as shown by a dotted line in Fig. 1(A), and returned to the original state after the cutoff. Fig. 2 also shows the



without a magnetic field **with a magnetic field**

Fig. 2. Comparison of diffusion flames without and with an inhomogeneous magnetic field (35 T^2/m).

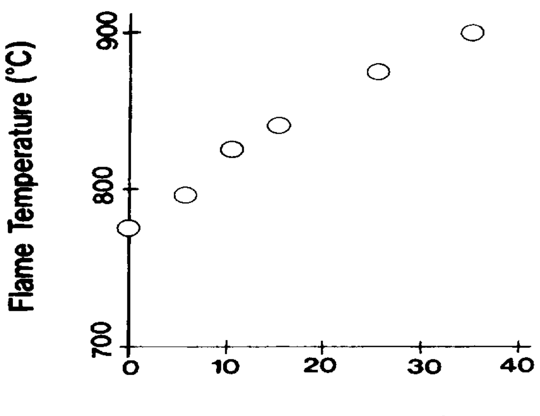


Fig. 3. The effect of magnetic field gradients on the flame temperature.

comparison of the diffusion flames with and without magnetic field. The flame was distorted toward a stronger field, in the opposite direction to that of the magnetic deflection previously reported [1–3].

The flame temperature increased rapidly when the field was turned on, and returned to the original value when it was turned off. Fig. 3 shows the dependence of the flame temperature on the product of the magnetic field intensity (H) and its gradient ($\mathrm{d}H/\mathrm{d}y$) 1 cm above the burner head. The flame temperature increased with increasing the value of $H(\mathrm{d}H/\mathrm{d}y)$, and rose by about 120 °C at the maximum.

For comparison, when the flame was set in a homogeneous magnetic field, 1.5 T (Fig. 1(B)), no magnetically induced change was observed in the flame.

4. Discussion and conclusion

These experimental results indicate that a magnetic field gradient affects combustion considerably. Magnetic promotion of combustion was found when fuel gas flowed in the direction of a decreasing field strength. Then, the flame was distorted toward a higher field.

In the previous studies, the flames were reported to be deflected into the region of lower magnetic field intensity [1–3]. Therefore, the theory explaining the flame deflection [4] cannot be applied to the present case.

Magnetic promotion of combustion was found in diffusion or partially premixed flames, but not in premixed ones. This fact suggests the importance of air flows.

We explained magnetic promotion of combustion by considering air flows under magnetic field gradients. In the experimental setup (Fig. 1(A)), air was magnetically attracted along the steepest gradient, as indicated by a solid arrow, and supplied to the flame front. For example, when air is attracted from 0 to 1 T, the final velocity is calculated by using the energy conservation equation:

$$\tfrac{1}{2}\chi H^2 = \tfrac{1}{2}\rho v^2, \qquad (2)$$

where ρ is air density. The velocity at the flame front (v) is calculated to be about 48 cm/s, which is three orders larger than the rate of diffusion.

Furthermore, magnetic convective air flow occurred along the y-axis as indicated by a dotted arrow because the volume magnetic susceptibility of air, χ, is linear to p_{O_2}/T^2.

These two kinds of magnetically induced air flows are considered to promote combustion in diffusion flames in Fig. 1(A). Recently these magnetically induced air flows were found to support combustion in microgravity where diffusion flames could not continue combustion [9].

The magnetic deflection (Fig. 1(C)) can be explained similarly. Then, magnetic field gradient prohibited convective air flow and suppressed combustion.

In conclusion, magnetically induced air flows were found to promote combustion in diffusion flames. The present study suggests the possibility of magnetic control of combustion and air flows (magnetoaerodynamics).

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