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Effect of a gradient magnetic field on the combustion reaction of methane in air

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When a fuel gas flows in the direction of a magnetic field of decreasing strength, a combustion reaction is found to be activated. The relationship between the direction of a fuel-gas flow and the steepest gradient of the magnetic field was observed to determine how the reaction was promoted. This magnetic effect has been explained by the movement of the reactants and reaction products caused by gradient magnetic fields. The results suggest that a chemical reaction involving a change in the magnetic susceptibilities of component species can be controlled by application of a gradient magnetic field.

1. Introduction

Certain photochemical processes in liquids are known to be affected by a homogeneous magnetic field, and their mechanisms have been explained by radical-pair theories [1]. Recently, a gradient magnetic field has been found to cause a significant effect in an advancing gas flow and in chemical reactions [2–6].

The present paper reports on the effect of an inhomogeneous magnetic field on the combustion reaction of methane, which contains paramagnetic–diamagnetic transformations; our goal is to study the magnetic effect which is different from that of a homogeneous field.

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 strength is also shown at the maximum current through the magnet (10 A). A homogeneous magnetic field (1.5 T) was generated in the central area, where the diameter was less than 5 cm, while an inhomogeneous magnetic field with a gradient of about 0.3–0.4 T/cm existed in the surrounding region, > 3.5 cm from the center of the pole.

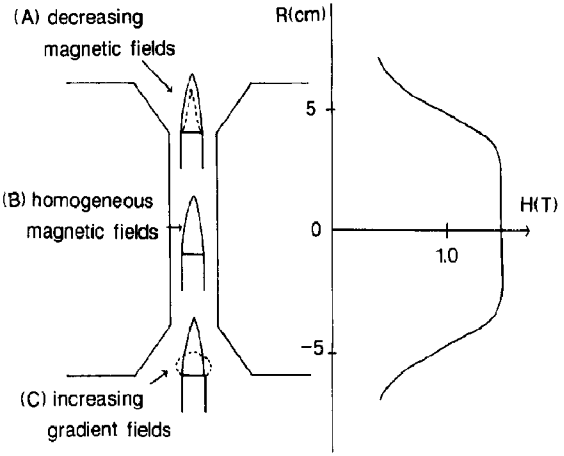

Fig. 1. Experimental setup and spatial distribution of the intensity of a magnetic field at the highest current. The flames with and without a magnetic field are shown by a broken line and a solid one, respectively.

Methane gas or a mixture of methane and air flowed through a glass pipe (inner diameter 0.8 cm). A circular cone flame was observed at the top of the pipe. The head of the pipe was set 4 cm (A) above the center axis of the pole, 1 cm (B) or 6 cm (C) below it, as shown in fig. 1.

The flame temperature was measured by a thermometer (Advantest Ltd., TR2114). A thermocouple (Pt–Rh) was placed 1 cm above the burner head. The flame chemiluminescence was measured by a monochromator (SPEX-500M) and an optical multichannel analyzer (PAR).

3. Results

The combustion reaction was studied under the conditions of decreasing and increasing field gradients and a homogeneous field, and with a partially premixed flame (P; methane: 150 mL/min, air: 400 mL/min) and a diffusion flame (Q; methane: 150 mL/min). Flame P was more convenient for observation because of its stability and stronger chemiluminescence.

When the head of the pipe was set at position (A) in fig. 1, a fuel gas flows in the direction of decreasing field strength (case (A)). In this case, both flames P and Q became shorter and sharper by application of the field, as shown by a broken line.

The temperature of flame P increased rapidly when the field was turned on, and returned to the original value when it was turned off, as shown in fig. 2. Furthermore, the flame was observed to become more brilliant immediately after the application of the field and returned to the original state after the cutoff.

Fig. 3(P) shows the dependence of the flame temperature on the product of the magnetic field intensity (H) and its gradient ($\partial H/\partial R$) measured at 5 cm above the center of the pole. The temperature was observed to rise by about 120°C at maximum with increasing value of $H\,\partial H/\partial R$. A similar increase of about 30% at the highest current was also observed in the chemiluminescence from OH ($A\,^2\Sigma^+ \rightarrow X\,^2\Pi(0\text{–}0)$).

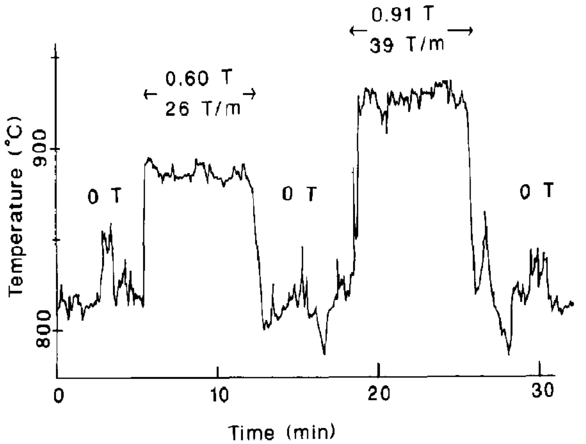

Fig. 2. Effect of a decreasing gradient magnetic field on the temperature of flame P.

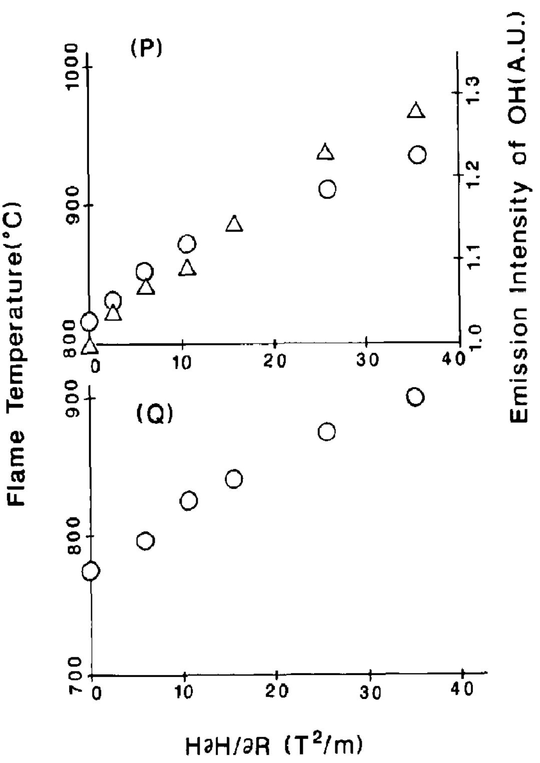

Fig. 3. Dependence of a decreasing gradient field on the flame temperature (O) and chemiluminescence (△). (P): a partially premixed flame; (Q): a diffusion flame.

The magnetically induced enhancement in the flame temperature was also observed in flame Q, as shown in fig. 3(Q). This flame also looked more brilliant after the field was applied. In this case, however, the chemiluminescence was too weak to be measurable. These observations suggest that an application of a decreasing magnetic field promotes a combustion reaction.

Conversely, when the fuel gas was allowed to flow in the direction of an increasing field (fig. 1C), the flame was observed to be flattened and to avoid the field (case (C)). The magnetic field behaved as if it had quenched the combustion reaction. When a fuel gas flowed perpendicular to a gradient field (case (D)), for comparison, the flame was repelled horizontally towards a weaker field.

Finally, when the flame was exposed to a homogeneous field, 1.5 T (fig. 1B), no change was observed in the shape (case (B)). Furthermore, neither the temperature nor the chemiluminescence was affected by the field.

4. Discussion and conclusion

These experimental results show that a gradient magnetic field, but not a homogeneous one, causes a significant effect in a combustion reaction. The reaction is promoted when a fuel gas flows in the direction of a decreasing gradient field. On the other hand, it is quenched when a fuel gas flows in the direction of an increasing field. Ueno et al. discovered that the flame escapes from a stronger field (case (C)) and explained it phenomenologically by the effect of a wall of oxygen aligned by a magnetic field pressing back the flame [2,3]. However, this explanation is not applicable to other cases.

Here, we propose a mechanism which can explain all of these observed magnetic effects (A)–(D) systematically. Paramagnetic oxygen gas is known to be attracted towards a stronger field, while the reaction products and fuel vapors are diamagnetic and always flow towards a weaker field [4,5]. The magnetic force F in a magnetic field gradient [7] is given by

$$F=(\chi-\chi_0)H\,\partial H/\partial R\,, \qquad (1)$$

where χ and χ_0 denote the volume magnetic susceptibilities of the flame and air, respectively. The susceptibility of the gas group is mainly determined by the partial pressure of oxygen, which is paramagnetic. For example, the force acting on flame Q is calculated to be about 1 dyn/cm^3 in case (A) or (C). The dependence of the magnetically induced changes on $H\,\partial H/\partial R$ in fig. 3 suggests that the force due to the gradient field affects the reaction.

Furthermore, a combustion reaction in a diffusion flame occurs in the reaction zone between the fuel gas and air which is as thin as about 0.01 cm at atmospheric pressures [8]. Therefore, when the combustion proceeds in the direction of a decreasing magnetic field (case (A)), the supply of air and the fuel gas to a reaction zone should increase. Furthermore, the reaction products, carbon dioxide and water molecules, are rejected efficiently from the reaction zone. Accordingly, it is expected that a combustion in a diffusion flame Q is activated by the application of a decreasing magnetic field. A similar explanation is also applicable to a partially premixed flame P, because most oxygen gas is supplied from the surrounding air.

Reverse effects are expected when an increasing magnetic field is applied (case (C)), where an increasing field behaved as if it quenched the reaction. The case (D), where the fuel gas flows perpendicular to the steepest gradient of the field, can also be explained similarly. Finally, no effect is expected in a homogeneous field (case (B)).

In summary, we have observed the relationship between the direction of the fuel-gas flow and the steepest gradient of the field to determine the behavior of the magnetic effect, and clarified the mechanism. The observation suggests the possibility that a chemical reaction involving a change in the magnetic susceptibilities of component species can be controlled by the application of an inhomogeneous magnetic field.

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