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Basi teoriche a dimostrazione della possibilità di controllare la combustione con dispositivi a campi magnetici ed elettromagnetici:

Review sulla letteratura esistente

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Il secolo appena trascorso è stato il testimone dello svilupparsi di tecnologie correlate alla produzione di campi magnetici.

In questi ultimi 25 anni molta attenzione da parte del mondo scientifico è stata volta allo studio degli effetti dei campi magnetici sulla salute dell'uomo, senza per altro arrivare a delle conclusioni definitive.

Se da una parte c'è chi sostiene che la esposizione a campi magnetici può interferire con la attività biologica delle cellule, dando luogo all'insorgere di patologie, altri si schierano a paladini della innocuità di tali campi. Tra i due litiganti c'è addirittura chi pretende di utilizzare tali campi alla stregua di farmaci per il trattamento di fratture ossee e problemi neuro motori.

Da un punto di vista logico, non è per nulla illogico, che tra cellule umane e campi elettro-magnetici ci possa essere incompatibilità elettromagnetica, visto che la attività elettrica è caratteristica peculiare di molte cellule del nostro corpo. Da questo punto di vista quindi, non è improbabile che in un prossimo futuro si possano impiegare campi magnetici in medicina alla stregua di farmaci.

Che però un campo magnetico possa essere usato per combattere l'inquinamento atmosferico o per risolvere (per lo meno in parte) l'atavico bisogno di carburanti, questo però, a veramente sconvolto il modo scientifico e non solo.

Certo ne Maxwell e tanto meno Hertz, Righi o Marconi pensavano che oltre a far viaggiare le informazioni, tali campi, potessero anche servire a far muovere automobili!

Negli ultimi anni sono infatti apparsi sul mercato dispositivi magnetici, decantati essere in grado, di abbattere la produzione di gas serra prodotti dalla combustione di combustibili liquidi o gassosi e di conseguenza, di produrre un risparmio energetico.

A fronte di tanta bestemmia si è sollevato lo sdegno di un esercito di scienziati e tecnici che con un termine poco elegante americano, hanno definito i produttori di tali congegni, come produttori di "bull shet" ovvero escrementi di toro.

Quando però si va a studiare l'argomento più a fondo, ci si accorge della esistenza di una buona quantità di letteratura tecnico scientifica, pubblicata su riviste internazionali con peer review, a supporto della possibilità , che un campo magnetico possa interferire con la combustione di combustibili sia liquidi che gassosi.

Mentre l'effetto di un campo elettrico sulla combustione di un combustibile è un fenomeno noto solo dagli anni sessanta (Lowton et al) l'effetto di un campo magnetico è noto sin dal 1846, ovvero sin da quando Faraday notò che una fiamma, quando era prodotta in un campo magnetico, era più luminosa che in assenza del campo medesimo. Ovviamente Faraday, ne dedusse che nella fiamma ci potessero essere particelle che in grado di interagire con il campo magnetico ed a ragione di ciò la temperatura della fiamma era maggiore con una maggiore intensità luminosa della fiamma stessa. Molto tempo dopo Von Enghel and Cozens nel 1964 dimostrarono che il fenomeno osservato da Faraday poteva essere attribuito a gas paramagnetici presenti nella atmosfera in cui la combustione del combustibile avveniva.

Negli ultimi venti, anni Ueno, Mizutani, Wakayama, Fujita ed altri, hanno dimostrato come un campo magnetico non omogeneo possa interferire con le reazioni chimiche tipiche della combustione e nel trasporto dei gas. La velocità di trasposrto di alcuni gas è ostacolata da campi magnetici mentre quella di altri ne risulta favorita (Ueno, Wakayama, Fujita)(figura seguente).

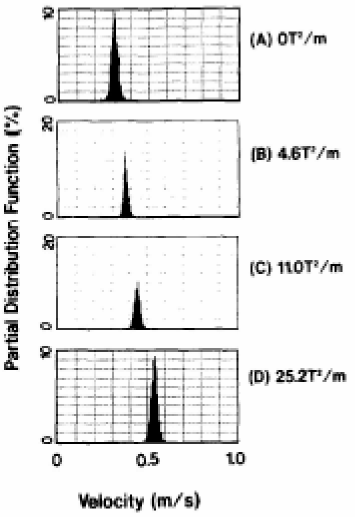

Fig. 2. Partial distribution function (PDF) of O_2 gas velocity under various gradient magnetic fields when O_2 gas flowed toward a stronger field. The average velocity, the standard deviation, and the intensity of turbulence are as follows: (a) 31.1 cm/s, 1.96 cm/s, 6.29%; (b) 37.6 cm/s, 1.32 cm/s, 3.50%; (c) 44.7 cm/s, 1.80 cm/s, 4.02%; (d) 54.0 cm/s, 1.80 cm/s, 3.32%.

Tra le varie teorie sviluppate, è di particolare interesse per spiegare come la combustione di un combustible, possa essere resa più efficace in presenza di un campo magnetico è quella che vede l'atmosfera come composta da una miscela di gas di cui alcuni paramagnetici (ossigeno) e altri diamagnetici (anidride carbonica, azoto…). Hueno e Arada suggeriscono che l'ossigeno (figura seguente)

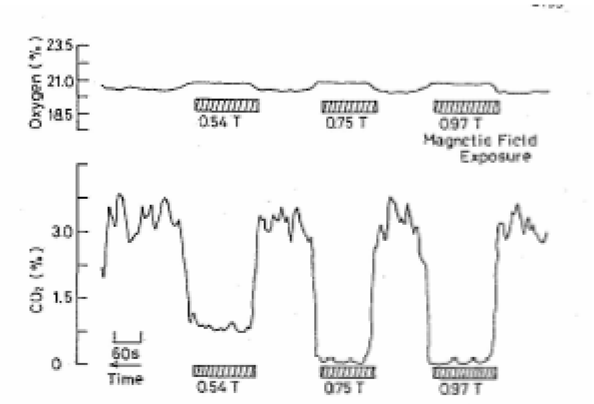

Fig.4 Gas-flow changes during magnetic field exposures when carbon dioxide is supplied. The flow of carbon dioxide is blocked by magnetic fields.

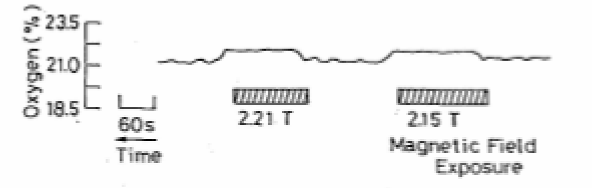

Fig.5 Gas-flow changes during magnetic field exposures when oxygen gas is supplied.

potesse venire a concentrarsi tra i poli del magnete tra cui avveniva la combustione aumentandone l'efficienza. Nel 1985 Ueno in uno studio sulla combustione di combustibili liquidi, tra cui la benzina (vedi figura seguente),

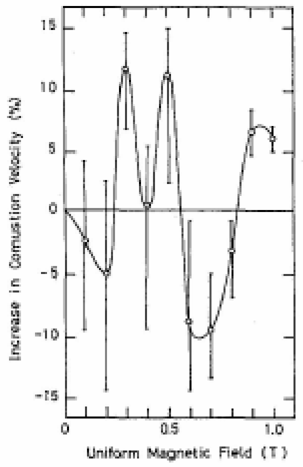

Fig.3 The effect of uniform magnetic fields on the combustion velocity of gasoline.

in presenza di forti campi magnetici statici, concludeva che la presenza di campi statici di valore predeterminato inducesse un maggiore efficienza nella combustione del combustibile.

Dagli studi prodotti in trenta anni di ricerche e per altro mai confutati, salvo l'ignoranza dello scrivente, si può dedurre che è possibile controllare la combustione applicando un campo magnetico statico di appropriata intensità, vettore e gradiente e che quindi in condizioni particolarmente controllate la combustione possa avvenire più efficacemente e quindi (vedi figura)

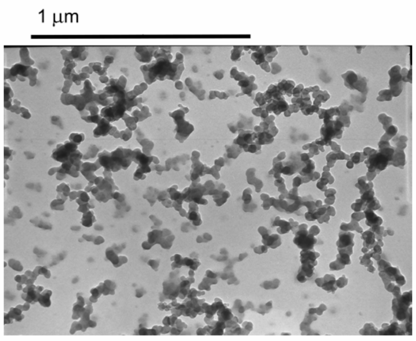

Fig. 5.16a: Soot samples collected at flame tip for a case of no magnetic field

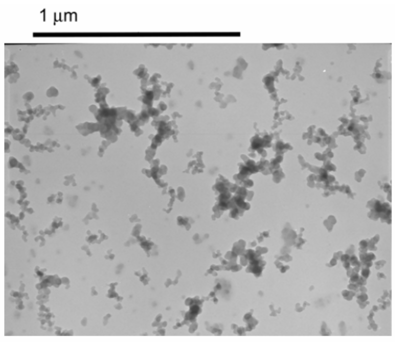

Fig. 5.16b: Soot samples collected at flame tip for a case of vertically decreasing magnetic field (B_c =2.77 KGs)

con un minore apporto di prodotti dovuti a cattiva combustione, nell’atmosfera .

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Seguono prime pagine della letteratura più importante La letteratura completa è fornita in Power Point

Dynamic Behavior of Gas Flow in Gradient Magnetic Fields

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***Abstract* — The present study focuses on the mechanism of the formation of the "magnetic curtain" which appears in an air atmosphere under gradient magnetic fields. It is assumed that the magnetic curtain is a wall of air produced by the interaction of gradient magnetic fields with paramagnetic oxygen. Gas flow experiments in magnetic fields were carried out. The gas flow was clearly blocked by magnetic fields at 120 T^2/m. A model based on molecular dynamics was proposed to explain the experimental results. Trajectories of gas flows were calculated, and the threshold value of magnetic field strength needed to block nitrogen gas flow was obtained.**

I. INTRODUCTION

We have observed a phenomenon in which candle flames are pressed down by magnetic fields of high intensities [1]. We have also observed a phenomenon in which the flow of gases such as carbon dioxide and oxygen is blocked by magnetic fields [2]. A model called a "magnetic curtain" has been introduced to explain these phenomena.

It is assumed that the magnetic curtain is a wall of air caused by magnetic fields. We have demonstrated that a candle flame can be smothered by a magnetic field [3]. The interception of oxygen by the magnetic curtain quenches flames. Gas flow experiments in air and nitrogen atmosphere have shown that oxygen as a paramagnetic molecule has an important role in formation of the magnetic curtain [4]. This study focuses on the mechanism of the magnetic curtain. The magnetic curtain is simulated on the basis of molecular dynamics.

To verify the validity of the model, the magnetic curtain is produced by an 8-T superconducting magnet and gas pressure in the bore of the magnet is measured by a manometer.

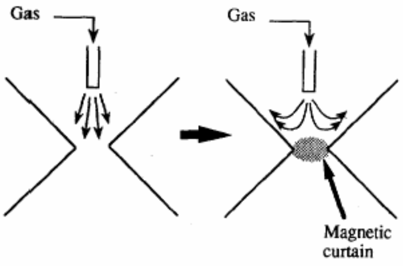

Fig. 1. Formation of the magnetic curtain.

II. GAS FLOW EXPERIMENTS

We observed the blocking of nitrogen gas flow in an air atmosphere. As shown in Fig. 2, flows of nitrogen gas were supplied to the airgap between magnetic poles, and the differential pressure was measured with a manometer. Fig. 3 shows the change of the differential pressure against the magnetic field strength. The gas flow was clearly blocked at about 1 T. The field gradient was about 120 T/m.

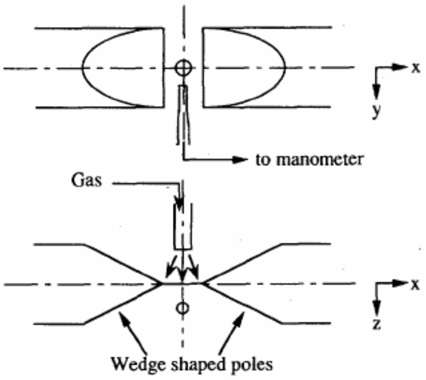

Fig. 2. The apparatus of the gas flow experiment

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Numerical Simulation of Diffusion Flames With and Without Magnetic Field

Shinichi Kinoshita, Toshimi Takagi, Hideki Kotera, and Nobuko I. Wakayama

Abstract—**Numerical computations are made of axisymmetric laminar hydrogen diffusion flames, focusing on the unsteady behavior under microgravity and the effects of magnetic field. In the microgravity without magnetic field, it is revealed that combustion products remain around the diffusion flame because of the lack of convection, and the amount of O_2 diffusion to the flame region becomes retarded. When a gradient magnetic field is added, convection is induced around the diffusion flame by the magnetic field which induces magnetic buoyancy force due to the inhomogeneity of magnetic susceptibility. The flow configuration formed by the magnetic force under microgravity is similar to that under the normal gravity without the magnetic field.**

Index Terms—**Combustion phenomena, laminar diffusion flame, magnetic field, microgravity, numerical simulation.**

I. INTRODUCTION

DIFFUSION flames under microgravity, which has been studied experimentally [1]–[3] and analytically [4], are quite different from those under normal gravity. On the ground, air flow is induced around the flames by buoyancy force with inhomogeneity of density in combustion field and the flame is stably constructed. On the other hand, under microgravity, where buoyancy-induced convection is not available, the diffusion flames expand spherically [1], [2] or extinct [3].

The application of magnetic field was proposed as a possible method to support combustion in microgravity. It is revealed that the diffusion flame with magnetic field can be stabilized even in microgravity as in normal gravity [3], and the fluid flow is driven by magnetic field [5]–[8]. Gas mixture, which contains more oxygen gas than air, were observed to be attracted toward stronger magnetic fields [5], [6], [8], while nitrogen was pushed out toward a weaker field [6], [7]. These effects were explained by the magnetic force acting on paramagnetic oxygen molecules. Considering these phenomena, magnetic field has possibility of the control of flow or combustion, and it is useful that the effects of magnetic field to combustion are quantitatively evaluated.

In the present study, computations are made of axisymmetric laminar jet hydrogen diffusion flames under normal gravity or microgravity taking into account the effect of the magnetic field. The transient diffusion flame under microgravity and the effects of magnetic force are numerically investigated.

II. MAGNETICALLY INDUCED GAS FLOW

Magnetic characteristics of gas molecules are classified in paramagnetic gas and diamagnetic gas. O_2 molecule is a paramagnetic gas. Magnetic susceptibility per unit mass of paramagnetic gas is generally inversely proportional to absolute temperature T, which is called Curie's law [9]. On the other hand, most of gas species except for O_2 are diamagnetic, and its magnetic susceptibility is constant against temperature, and is much smaller than that of paramagnetic gases. It is reasonable to consider that the magnetic susceptibility of the gas mixture in the combustion field approximately depends on partial pressure of O_2 and temperature as following equation.

$$\chi = \chi_{O_2} x_{O_2} \frac{p}{p_0} \frac{T_0^2}{T^2}, \tag{1}$$

where, χ, volumetric magnetic susceptibility of mixture; χ_{O_2}, volumetric magnetic susceptibility of O_2 at standard state; x_{O_2}, volume fraction of O_2; p, pressure; p_0, standard pressure (1 atm); T, temperature; T_0, standard temperature (298 K).

Magnetic body force per unit volume, $\boldsymbol{f}_{\mathrm{m}}$, is generally represented by the following equation [10].

$$\boldsymbol{f}_{\mathrm{m}} = \frac{1}{2}\nabla\left[H^2\rho\left(\frac{\partial\mu}{\partial\rho}\right)_T\right] - \frac{H^2}{2}\nabla\mu - \mu[\boldsymbol{H}\mathrm{rot}\boldsymbol{H}], \tag{2}$$

where, H, magnetic field strength; ρ, density; μ, permeability of gas mixture. Ion density in hydrogen-air flames is about 10^{12} ions/m^3 [11], and its electric charge is the order of 10^{-7} C/m^3. The electric current estimated from the electric charge and the flow velocity is so small that the third term of right hand side of (2) is negligible. There is a following relation between magnetic susceptibility and permeability.

$$\mu = \mu_0\mu_{\mathrm{r}} = \mu_0\left(1 + \chi_{\mathrm{m}}(T)\rho\right), \tag{3}$$

where, μ_0, permeability of free space; μ_{r}, relative permeability; χ_{m}, magnetic susceptibility per unit mass which is $\chi_m = \chi/\rho$. With this relation, (2) is transformed as follows.

$$\boldsymbol{f}_{\mathrm{m}} = \mu_0(\mu_{\mathrm{r}} - 1)H\nabla H = \mu_0\chi H\nabla H. \tag{4}$$

In the magnetic field, the sum of the force by pressure gradient and body force by gravity and magnetic field in vertical direction is represented by the following equation.

$$F_z = -\frac{\partial p}{\partial z} + \mu_0\chi H\frac{\partial H}{\partial z} + \rho g, \tag{5}$$

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"PRETREATMENT" OF A HOMOGENEOUS FUEL–AIR MIXTURE WITH AN ELECTRIC FIELD

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UDC 536.463

Results are shown of a study concerning the effect which "treating" a homogeneous fuel–air mixture with an electric field has on the velocity V of the flame travel through it. Data are presented pertaining to the flame front velocity V and the flame front shape as functions of the electric field intensity E, the field application time t, and the time interval τ between field removal and subsequent ignition.

Among many studies on how to improve the combustion process in engines, of special interest are those concerning the fuel "treatment" with an electric or magnetic field prior to ignition. In the early sixties several types of ionizers were proposed for "treating" liquid fuel with an electromagnetic field [1, 2]. While passing through the ionizer, the fuel is subjected to the effects of an electric discharge and a magnetic field of permanent magnets in a random configuration. According to some studies, the use of an ionizer in the fuel system of internal-combustion engines has improved the maximum engine power by 6–8% and reduced the fuel consumption by 4–9%. Subsequently, an attempt was made to improve the combustion of gasoline by applying to it an electric field prior to ignition [4]. The cylinder with gasoline is subjected to an electric field. The gasoline is then ignited, after the voltage has been removed. The subsequent combustion rate depends on the "treatment" time.

The purpose of our study was to establish whether the combustion rate of a homogeneous fuel–air mixture would increase under the influence of an electric field and, in the affirmative case, how the velocity of flame travel would depend on the field intensity and on the time through which the field had been applied to a combustible mixture. Of interest was also to estimate the time through which a combustible mixture would retain its thus acquired characteristics.

The tests were performed in a tube with a square cross section 3.6×3.6 cm^2 and 66.5 cm long, made of grade AG-4s glass plastic. The electric field was generated between two brass plates 45×4.5 cm^2 each, mounted in the tube 6 cm apart. A high negative voltage was applied to the upper plate, while the lower plate was grounded. The maximum field intensity was 10 kV/cm. As the combustible mixture we used one containing 10% methane in air. In order to facilitate the analysis of the results, we examined the effect of "pretreatment" on the velocity of uniform flame travel. The test procedure was as follows: the tube, closed with a flange at one end and by a film on the other, was evacuated with a suction pump and then filled with combustible mixture up to atmospheric pressure (the mixture had been prepared and thoroughly stirred in a gas meter). After "treatment" of the mixture with an electric field of intensity E through a period of time t, the voltage was removed and the upper plate was grounded. The film which had covered one end of the tube was cut out. The mixture was then ignited at the open end at a time τ after the upper plate had been grounded. The flame front visually inspected by the Tepler method, was recorded photographically with a model SKS-1 high-speed camera through a window covering the entire tube section over a length of 20 cm.

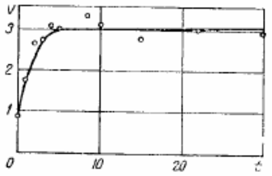

Fig. 1. Flame velocity V (m/sec) as a function of the time t (min).

An analysis of photographic data has shown that "pretreatment" of

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Distribution of Electromagnetic Force in Permanent Magnets

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Abstract - **Two dual formulations are proposed for the calculation of the electromagnetic forces in permanent magnets. The formulations are based on the virtual work principle with the use of nodal elements. Both methods allow the calculation of global force as well as local force densities. These densities depend on the expression of the magnetic energy or co-energy of the magnet. The energies of a permanent magnet are discussed on physical basis.**

Index terms : **local force densities, permanent magnet, virtual work, magnetic energy.**

INTRODUCTION

Two dual formulations are used to calculate electromagnetic forces by the Finite Element Method (FEM). One is based on the vector potential $\boldsymbol{A}$ and the other one is based on the scalar potential Ψ. By the use of the virtual work principle, the electromagnetic force on a magnet is obtained by deriving either the energy ($W=W(\boldsymbol{B})$) or co-energy ($W'=W'(\boldsymbol{H})$) with respect to a virtual displacement, according to the formulation used to solve the FEM problem [1][2][3]. The global force on a magnet is well known and is calculated currently [5][6]. Nevertheless, when mechanical calculation is done, a local distribution of forces is necessary. Though the local force densities obtained directly by the above expressions are not significant. They do not represent the actual interaction force distribution between the magnets. The results depend on the expression of the magnetic energy or co-energy. It is shown that the use of simplified expressions can lead to erroneous results. It is shown also that, with these expressions, the total energy on a magnet is composed of two terms : the intrinsic and the interaction energy. An analysis of the calculated "local force densities" from the above energies is given. The adequacy of the methods is shown as the same results are obtained by the two different approaches.

DESCRIPTION OF THE METHOD

For a permanent magnet, one can define the magnetic induction, in terms of the remanent induction $\boldsymbol{B}_r$ as $\boldsymbol{B}=\mu_0\boldsymbol{H}+\boldsymbol{B}_r$. Considering the relation $\boldsymbol{B}_r=\mu_0\boldsymbol{M}$, where $\boldsymbol{M}$ is the magnetization, the magnetic induction is given by $\boldsymbol{B}=\mu_0(\boldsymbol{H}+\boldsymbol{M})$ [4][6][7]. The electromagnetic force on the magnet can be calculated either with $\boldsymbol{B}_r$ or $\boldsymbol{M}$, according to the formulation used. The formulations to be used are described below.

A - Vector Potential Formulation

The vector potential as used, is defined from the magnetic induction as $\boldsymbol{B}=\boldsymbol{curl}\,\boldsymbol{A}$. By the virtual work principle, the electromagnetic force is calculated in terms of the magnetic energy, which on a permanent magnet is [4][6][7] :

$$W=\frac{1}{2\mu_0}\int_\Omega (B-B_r)(B-B_r)d\Omega \tag{1}$$

In this basis, the electromagnetic force on the magnet is given by $F=-\partial W/\partial s$ at constant flux, which in the direction i is :

$$\begin{aligned}F_i&=-\frac{\partial}{\partial s_i}\left[\frac{1}{2\mu_0}\int_\Omega (B-B_r)(B-B_r)d\Omega\right]\\&=-\frac{1}{2\mu_0}\sum_e\frac{\partial}{\partial s_i}\int_{\Omega_e}(B-B_r)(B-B_r)|G|d\Omega_e\end{aligned} \tag{2}$$

where e stands for the elements of the magnet, μ_0 is the permeability of the air, s_i is the virtual displacement in the direction i, $|G|$ is the determinant of the jacobian matrix and $d\Omega_e=du\,dv\,dw$.

The derivation of (2) for a node k of the magnet results in :

$$\begin{aligned}F_{ik}=-\frac{1}{2\mu_0}\sum_{ek}\int_{\Omega_{ek}}\Bigg[&\frac{\partial B}{\partial s_i}(B-B_r)+(B-B_r)\frac{\partial B}{\partial s_i}+\\&(B-B_r)(B-B_r)|G|^{-1}\frac{\partial|G|}{\partial s_i}\Bigg]d\Omega_{ek}\end{aligned} \tag{3}$$

where $|G|^{-1}$ is the inverse of the jacobian matrix and ek concerns the elements which have in common the node k. The virtual displacement is applied with constant vector potential $\boldsymbol{A}$ which is equivalent to constant flux.

The derivation of $|G|$ with respect to the virtual displacement is given by [1]. To calculate the derivation of B with respect to the displacement s_i, the finite element approximation of nodal unknowns is defined as :

$$A(u,v,w)=\sum_k\alpha_k(u,v,w)A_k \tag{4}$$

where α_k are the nodal shape functions. The magnetic induction B is given by :

$$B=curl\sum_k\alpha_kA_k=\sum_k grad\,\alpha_k\times A_k \tag{5}$$

so, $$B=\sum_k G^{-1}\partial_{uj}\alpha_k\times A_k \tag{6}$$

which gives $$\frac{\partial B}{\partial s_i}=\sum_k\frac{\partial G^{-1}}{\partial s_i}\partial_{uj}\alpha_k\times A_k \tag{7}$$

for the derivation of B. With the identity

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EFFECTS OF MAGNETIC FIELDS ON FLAMES AND GAS FLOW

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Abstract -- Effects of magnetic fields on combustion and gas-flow were studied. Methane, propane and hydrogen gases were burned, and flames of these gases were exposed to gradient magnetic fields up to 1.6 T and 220 T/m. Flames bent so as to escape from magnetic fields of higher intensities. Apart from the combustion experiments, flows of gases such as carbon dioxide and oxygen were exposed to magnetic fields up to 2.2 T and 300 T/m. The flows of these gases with a flow velocity 20-140 ml/min were blocked or modified by the magnetic fields. The changes of flame-shape and gas-flow by magnetic fields are understood to be the result of the role of oxygen. Under the intensities of magnetic fields concerned, oxygen gases as paramagnetic molecules are not concentrated but are aligned so as to make a "wall of oxygen". The wall of oxygen presses back flames and other gases.

INTRODUCTION

Combustion is an oxidation reaction which involves both burning phenomena in the air and cell respiration in the living body. The effects of magnetic fields on combustion of alcohol and hydrocarbons with the aid of platinum catalysis have been studied to simulate in part the oxidation of organic matter in the living body, and it has been found that the combustion velocities and temperature are influenced by magnetic fields [1], [2]. The combustion temperature of alcohol decreased within a range 100-200°C when the combustion site was exposed to gradient magnetic fields in a range 20-200 T/m under 0.5-1.4 T [2]. It has been also observed that candle flames bend so as to escape from magnetic fields of higher intensities when flames are exposed to gradient magnetic fields of the same intensities as used in the case with platinum-catalyzed combustion [2].

Two hypotheses have been introduced in understanding the phenomenon; (1) Behaviors of charged particles in flames as plasma state are influenced by gradient magnetic fields, and (2) Oxygen gases as paramagnetic molecules are concentrated by gradient magnetic fields, and the concentrated oxygen gases exert pressure which tends to press back flames and other gases.

The purpose of the present paper is to clarify the mechanism for the phenomena observed in the combustion and flame experiments. Two different types of experiments are carried out. First, flames of burning gases such as methane and hydrogen gases are exposed to magnetic fields. Second, apart from combustion experiments, flows of gases such as carbon dioxide and oxygen are exposed to magnetic fields.

FLAMES UNDER MAGNETIC FIELDS

Methane, propane and hydrogen gases were burned in an airgap between wedge-shaped poles of electromagnet, and flames were exposed to gradient magnetic fields up to 1.6 T and 220 T/m.

Independent of the fuels, the shapes of flames were dramatically changed by gradient magnetic fields in the same manner as observed in the case of candle experiments.

The results in the case of combustion of hydrogen gases are shown in Fig.1, and Fig.2.

In the experiment in Fig.1, flames were pressed down, and the shape of flames changed like a mushroom. The field intensity at the center of the airgap was 1.5 T, and the gradient was 200 T/m.

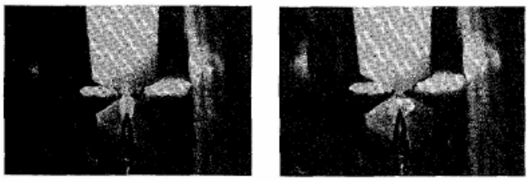
(a) (b)

Fig.1 Flames of hydrogen gas in gradient magnetic fields. (a) Flames before magnetic field exposures. (b) Flames during magnetic field exposures. The flames are pressed down. The field intensity is 1.6 T at the center of the airgap.

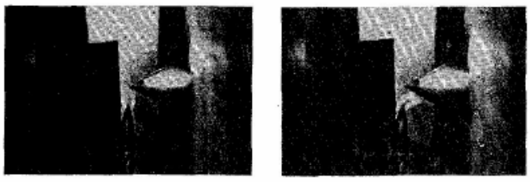
(a) (b)

Fig.2 Flames of hydrogen gas in gradient magnetic fields. (a) Flames before magnetic field exposures. (b) Flames during magnetic field exposures. The flames bend so as to escape from magnetic fields of higher intensities. The field intensity is 1.6 T at the center of the airgap.

In the experiment in Fig.2, a magnetic pole in the left side was turned by 90°, and the flames were exposed to the gradient magnetic fields. The flames bent so as to escape from magnetic fields of higher intensities.

GAS FLOW UNDER MAGNETIC FIELDS

Apart from the combustion experiments, flows of carbon dioxide, oxygen, nitrogen, argon and methane gases were exposed to magnetic fields up to 2.2 T and 300 T/m.

Figure 3 shows the experimental setup. Gases were supplied into the airgap between poles of electromagnet at a flow velocity in a range 20-140 ml/min through a gas-tube with 4 mm in diameter. The gases in the area beneath the outlet of gas-tube were continuously sampled into gas sensors through an inhalation nozzle. Oxygen and carbon dioxide were simultaneously measured.

The flows of these gases were blocked or modified by the magnetic fields.

When carbon dioxide was supplied with a velocity 45 ml/min, the flow pattern was clearly changed by magnetic fields as shown in Fig.4. In this experiment, the airgap was kept 2.5 mm wide, and the outlet of gas tube and the inhalation nozzle were positioned at z=8.0 mm and z=-8.0 mm, respectively.

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COMBUSTION PROCESSES UNDER STRONG DC MAGNETIC FIELDS

Shoogo Ueno, Hiroshi Esaki, and Koosuke Harada

Abstract - The effects of magnetic fields on the combustion velocities of gasoline and alcohol with platinum catalysis were studied. The place of combustion reaction of gasoline on platinum catalyst was exposed to d.c. magnetic fields with field intensities from 0.1 T to 1.0 T. The combustion velocity was influenced by the magnetic fields. The combustion velocity of gasoline decreased in 5 % - 10 % at 0.2 T and 0.6 T, and increased in 5 % - 10 % at 0.3 T, 0.5 T and 1.0 T. To explain the undulant phenomenon in the curve of combustion velocity v.s. magnetic field, various types of alcohol were burned with platinum catalysis under magnetic fields. The magnetic field effect on the combustion velocity of alcohol was observed to show a minimum at a specific magnetic field; -5.3 % at 0.9 T for methanol, -2.3 % at 0.6 T for ethanol, -16.9 % at 0.6 T for n-propanol, and -73.8 % at 0.7 T for n-butanol.

INTRODUCTION

The question of whether magnetic fields affect combustion processes or not is of considerable interest in fuel engineering and in biomagnetics. Combustion is oxidation reaction which involves both burning with flames in the air and cell respiration in the living bodies. In a series of our studies on biological effects of magnetic fields [1], [2], we are investigating the effects of magnetic fields on the reaction rate of slow-velocity types of combustion to simulate partly the oxidation of organic matter in the body. In the present paper, the effects of d.c. magnetic fields on the combustion of gasoline and alcohol with platinum catalysis are studied.

The relationships between combustion and magnetic fields have been partly studied: Hayashi [3] measured an increased flame intensity of OH radical in magnetic fields. Yoshimura [4] and others applied magnetic fields to flowing gasoline in a pipe conducted to an engine, not to the place of combustion. However, no investigations on measurements of combustion velocities of gasoline and alcohol with platinum catalysis under magnetic fields have been reported previously.

METHODS

Oil-fed pocket warmers made by Hakukinkairo Corp., Osaka, Japan, were used in the experiments. The pocket warmer is a kind of portable body warmer which generates heat by oxidation of gasoline with the aid of platinum catalysis. The combustion is not performed by direct burning of liquid gasoline but by surface reaction of gasified gasoline on the platinum catalyst. Therefore, the combustion rate is very slow compared with burning phenomena.

The samples, 65 mm wide, 100 mm high, and 10 mm thick, were positioned in an airgap of an electromagnet 70 mm gap and 240 mm in diameter. Three types of experiments were carried out:

Experiment (a) The combustion place of oxidation reaction was exposed to magnetic fields with low gradients which were obtained by simply positioning samples in the edges of the airgap. Gasoline of 10.0 cc was poured into each sample, and the samples were ignited simultaneously. Two samples were exposed to magnetic fields for 6 hrs. The other two samples were used as the control. The time course of temperature of samples were measured by a thermistor to obtain the combustion time. The combustion time was measured by detecting the time of rapid decrease in sample temperature. The magnetic field effects on the combustion were evaluated by the mean velocity of combustion over the period from ignition to consumption of the fuel. The experiment was repeated four times, replacing samples in turn under diffrent magnetic fields from 0.1 T to 1.0 T. The magnetic field of 0.5 T generates 5 T/m, and the magnetic field of 1.0 T generates 10 T/m in this experiment.

Experiment (b) Evaporating gasoline before combustion reaction was exposed to magnetic fields with different gradients which were generated by a similar technique used in HGMS. That is, a small space between gasoline tank and combustion place of platinum catalysis was packed with ferromagnetic amorphous fibers with different diameter (20 μm, 50 μm, and 125 μm) which were made by UNITIKA Ltd., Kyoto, Japan. Gasoline of 10.0 cc was poured into each sample, and the samples were exposed to a homogeneous magnetic field of 0.75 T, 0.47 T, and 0.23 T for 6 hrs. Gasoline of 5.0 cc was poured into each sample, and the samples were exposed to a homogeneous magnetic field of 1.0 T for 3 hrs. In this case, the gradient field of 5.0×10^4 T/m was generated around the fiber with 20 μm in diameter.

Experiment (c) The place of combustion reaction was exposed to homogeneous magnetic fields with field intensities from 0.1 T to 1.0 T. 13 samples were used. Gasoline of 10.0 cc was poured into each sample, and the samples were ignited simultaneously. 8 samples were exposed to the homogeneous magnetic fields for 6 hrs, and 5 samples were not exposed to magnetic fields. In order to reduce the temperature variation around the samples, the samples located in both edges of the samples were excluded from the data. Therefore, for each magnetic field strength, the average of the data of 6 samples in magnetic fields was compared with the average of 3 samples of control.

RESULTS AND DISCUSSION

Figure 1 shows the results in Experiment (a). The combustion place of gasoline was exposed to 0.1 T - 1.0 T magnetic fields with low gradients (1 T/m - 10 T/m). The combustion velocity decreased at 0.2T,2T/m and 0.6T, 6T/m, and increased at 0.4T,4T/m and 1.0T,10T/m. The undulant phenomenon in the curve of combustion velocity v.s. magnetic field was remarkably observed.

In Experiment (b), the evaporating gasified gasoline was exposed to high gradient magnetic fields, and the combustion place was exposed to homogeneous magnetic fields. The results are shown in Fig. 2. Each curve was obtained by averaging the results of 4 experiments. The combustion velocity increased in proportion to the gradient of the field in the curves of 0.47 T and 1.0 T. The relationship between combustion velocity and homogeneous magnetic field did not show a linear relationship but showed to be undulant.

In order to investigate the effect of uniform magnetic fields on the combustion velocity, Experiment (c) was carried out. The results are shown in Fig. 3. It was observed that the conbustion velocity was influenced also by homogeneous magnetic fields. The combustion velocity of gasoline decreased in 5 % - 10 % at 0.2 T and 0.6 T, and increased in 5 % - 10 % at 0.3 T, 0.5 T and 1.0 T. That is, the undulant phenomenon was observed in the relationship between combustion velocity and uniform magnetic field intensity.

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Simultaneous Alignment and Micropatterning of Organic Crystallites under a Modulated Magnetic Field

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In a previous paper, we reported the micropatterning of magnetically isotropic particles using a microscopically modulated magnetic field. In this paper, we report that the alignment occurs simultaneously if the particles have magnetic anisotropy. An oil-in-water emulsion of *p*-terphenyl or anthracene was subjected to the modulated magnetic field and allowed to evaporate the solvent to obtain a line pattern consisting of the crystallites with alignment. The patterned samples exhibited an emission strongly polarized in the direction of the applied magnetic field that is perpendicular to the patterning lines.

Introduction

In recent years, micropatterning has become a focus of interest in various areas of fabrication, including display units,[1−3] optical information storage, optical switching, diffractive optical elements,[4] miniaturized sensors,[5] biosensors,[6−8] integrated circuits,[9] and photonic crystals.[10] A number of techniques, including photo or electron-beam/ion-beam lithography and microcontact printing techniques,[11−15] have been used to provide two-dimensional patterning.

We have recently developed a novel method of micropatterning feeble magnetic particles.[16] In this method, chemical, physical, or biological modifications of the substrate surface are not required. The substrate surface is exposed to a microscopically modulated magnetic field that traps diamagnetic particles in locations where the field strength is weak. An advantage of this method is that the particle alignment could also be achieved concomitantly if the particles have magnetic anisotropy. By combining these two magnetic effects, it is possible to obtain patterning of particles with alignment.

In many aspects, control of alignment is of great importance. For example, one-dimensional aromatic π-conjugated materials such as *p*-terphenyl (*p*-TP) and anthracene (AT) used in the present study have potential applications in optoelectronic devices, including thin-film transistors and light-emitting diodes.[17−19] The alignment of these molecules is an important factor, since their optical and electrical properties are strongly affected by their alignment. For example, if the long axes of π-conjugated molecules are uniaxially aligned in a film, the resultant emission and absorption will be highly anisotropic because the transition dipole moments lie parallel to the long axis.[20−24]

In this study we demonstrate the simultaneous alignment and line patterning of *p*-TP and AT crystallites on a glass substrate and the resultant patterned and polarized fluorescent emission.

Experimental Section

An anion-type surfactant solution was prepared by mixing sodium dodecylbenzene sulfonate (SDBS, Wako, 2.03 g, 5.9 mmol), sodium dodecyl sulfate (SDS, Wako, 0.20 g, 0.70 mmol), and poly(ethylene oxide) 6000 (PEO, Wako, $M_w = 7{,}500$, 0.2 g) with 5 mL of water under strong agitation. A cation-type surfactant solution was prepared by dissolving hexadecyltrimethylammonium bromide (HDTMAB, Wako, 0.97 g, 2.6 mmol) in 5 mL of water. *p*-TP (Aldrich, 23.5 mg, 0.10 mmol) or AT (Aldrich, 18.0 mg, 0.10 mmol) was dissolved in 50 mL of benzene or toluene solvent to obtain the solutions. A total of 2 mL of the solution of *p*-TP was added to a mixture of 2 mL of water and 0.2−0.4 mL of the anion-type surfactant solution and agitated strongly to prepare the emulsion. A total of 2 mL of the solution of AT was added to a mixture of 2 mL of water and 0.2−0.4 mL of the cation-type surfactant solution and agitated strongly to prepare the emulsion. A total of 50−100 μL of aqueous manganese

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Magnetic Acceleration and Deceleration of O_2 Gas Streams Injected Into Air

Nobuko I. Wakayama

***Abstract*—The study of "magnetoaerodynamics" is important to control air flows. The magnetically induced change in the velocity of O_2 gas streams injected into air was quantitatively studied. Whether O_2 gas flow was magnetically accelerated or decelerated was found to depend on the sign of the magnetic field gradient applied at the O_2 outlet. The magnetically induced change in the velocity $\Delta v = |v_H - v_o|$ was found to increase by increasing the product of the magnetic intensity and its gradient, $H * (dH/dy)$, and lowering the velocity without the fields, v_o. The dynamics of this magnetically induced gas flow was explained by considering the magnetic force acting on the paramagnetic oxygen gas. The calculation shows the most efficient acceleration to occur when $v_o = 0$ cm/s. The result of the present study suggests the possibility of magnetic control of gas streams containing O_2 gas. The necessary conditions are the gradient of the O_2-gas concentration, the low-velocity without fields, v_o, and high quantity of $H * (dH/dy)$.**

I. Introduction

A MAGNETIC field gradient has been shown to have a considerable effect on advancing gas streams in air [1]–[3]. For example, Faraday found that diamagnetic gases such as nitrogen and hydrogen made a detour around the magnetic poles in air [1]. Recently, the qualitative behaviors of magnetically induced gas flows in air were examined by using aqueous mists as a visualization tool [2], [3]. According to these studies, the magnetic behavior of the gas mixture depended on the concentration of the paramagnetic oxygen gas. For exmaple, gas mixtures which contain more oxygen gas than air were observed to be attracted toward stronger magnetic fields [2]. On the other hand, a diamagnetic gas such as nitrogen was repelled by a magnetic field [1]–[4]. Furthermore, these magnetically induced gas flows have been found to promote combustion in diffusion flames where the reaction rate is determined by the supply of air [4], [5].

These magnetically induced gas flows have been explained by the magnetic force acting on the paramagnetic oxygen gas. For a paramagnetic gas, the magnetization M is proportional to the applied field $M = \chi H$, where χ refers to the volume magnetic susceptibility. In a magnetic field gradient, the force per unit volume on the gas is

$$F = \mu_0 M(dH/dy) = \mu_0 \chi H(dH/dy). \qquad (1)$$

The important quantity for the magnetic force is, therefore, the square field gradient. Hereafter, we will express the numerical value of $\mu_0^2 H(dH/dy)$ in units of T^2/m.

Previous studies [1]–[4] suggest that the magnetically induced gas stream occurs when there is the discontinuity in the O_2 concentration. As far as we know, there has been little work beyond such limited qualitative observations. From the point of view of controlling gas flows and combustion reactions, it is important to examine the dynamics of the magnetically induced gas flows having the discontinuity in the O_2 concentration. The purpose of the present paper is to study the quantitative behavior of paramagnetic oxygen gas streams injected into air under gradient magnetic fields. The dynamics of these magnetically induced gas flows will also be clarified.

II. Experimental

A picture of the experimental setup is illustrated in Fig. 1. The spatial distribution of the magnetic intensity is also illustrated in this figure. In case (a), oxygen gas was injected in the direction of the increasing strength of the magnetic field from a pyrex glass tube (I.D. 1.0 cm). On the other hand, in case (b), O_2 gas flowed in the reverse direction. Magnetic field gradients were produced by using an electromagnet (IDX Corp., ISM-130WV).

The velocity of O_2 gas flowing along the y-axis was measured 1 cm beyond the head of the tube (at point P). Aqueous mist was mixed in order to measure the velocity using a fiberoptic laser Doppler velocimeter (Kanomax Co. Ltd., FLV 8853). The measurement time was 100 s.

III. Experimental Results

A. Magnetic Acceleration of O_2 Gas

The velocity of O_2 gas increased when O_2 gas flowed in the direction of increasing magnetic field strength [case (a)]. Fig. 2 shows the partial distribution function (PDF) of the O_2 gas velocity under various nonhomogeneous magnetic fields when the average velocity without the field, v_o, was 31 cm/s. Magnetic acceleration of the O_2 gas flow was clearly found. The average velocity, v_H, increased by increasing the product of the magnetic strength and the gradient applied at the head of the tube. At the highest value available (25.2 T^2/m), the velocity increased about 23 cm/s. The standard deviation was about

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MAGNETIC FIELDS AND EQUILIBRIUM COMBUSTION CHARACTERISTICS

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Abstract

The impact of a uniform magnetic field on equilibrium combustion characteristic has been explored. An expression for the Gibbs free energy that includes a magnetic field contribution has been developed. Using the method of Lagrange multipliers, changes in the Gibbs free energy for a mixture of paramagnetic and diamagnetic ideal gases is minimized. A model reaction of methane in air is used to quantitatively examine the changes in equilibrium compositions in the presence of a uniform magnetic field. Plots are presented showing the equilibrium mole fractions as a function of temperature and magnetic induction for all the product species. In general, the results indicate that within a certain temperature range a magnetic field decreases the mole fraction of major product species and increases the mole fraction of minor product species at a specified temperature. The maximum equilibrium mole fraction of NO; however, was observed to decrease an order of magnitude for an increase in magnetic induction of 0 to 0.04 Tesla.

Nomenclature

a_{ij}	atoms of element *j* in product *i*
B	magnetic induction
b_j	atoms of element *j* in reactants
C_w	Curie-Weiss constant
C	damping constant
F	Lagrange multiplier function
G	Gibbs free energy
$\overline{g}_i^\circ$	molar specific reference Gibbs free energy
H	magnetic field strength
I	enthalpy
M	intensity of magnetization
n	number of moles
n_e	number of constituent elements
n_s	number of product species
n_T	total number of moles
p	pressure
p_i	partial pressure of species *i*
R_u	universal gas constant
S	entropy
T	temperature
U	internal energy
V	volume
y_i	mole fraction of species *i*
θ	Curie-Weiss constant
λ_i	Lagrange multiplier of species *i*
μ_o	permeability of free space
χ	magnetic susceptibility

Superscript

o	reference conditions

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1. Introduction

Since the time of Faraday[8] the impact of magnetic fields on combustion behavior has been recognized. This interaction has primarily been attributed to the diamagnetic and paramagnetic nature of the gases involved in the combustion process. Diamagnetic behavior is observed in gases consisting of atoms with no permanent magnetic dipole moments. In the presence of an external magnetic field, the atoms of a diamagnetic substance develop a net dipole moment. This induced moment opposes the applied field and thus a diamagnetic gas exhibits a weak repulsion to an applied magnetic field. The stronger the external magnetic field, the stronger the repulsion. On the other hand, a paramagnetic gas is a gas consisting of atoms with at least one unpaired electron and thus the atoms exhibit permanent dipole moments. In the absence of a magnetic field the magnetic dipole moments of a

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Influence of Four Kinds of Gradient Magnetic Fields on Hydrogen–Oxygen Flame

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To explore the possibility of flame control by magnetic force, the influence of four kinds of gradient magnetic fields on OH density distribution in a hydrogen–oxygen jet diffusion flame was investigated by numerically solving the equations of reactive gasdynamics and magnetism. Vertically decreasing (case 1), vertically increasing (case 2), horizontally decreasing (case 3), and horizontally increasing (case 4) gradients of magnetic field were considered as model configurations. According to the numerical analysis, because the mass density and the magnetic susceptibility of O_2 gas are much higher than those of other chemical species, the surrounding air containing a lot of O_2 gas is strongly influenced by the magnetic force, and the magnetically induced airflow changes the OH distribution in the flame indirectly. The direction and magnitude of the OH density change significantly depends on the configurations of the gradient magnetic field. Specifically, in cases 1, 3, and 4, the OH distribution migrated to the inside of the flame, but in case 2, it moved toward the outside. However, when the horizontally decreasing gradient of the magnetic field was set up near the burner outlet, as in case 3, the OH density change becomes largest among those in the four cases.

Nomenclature

B = magnetic flux density, T
c_p = specific heat capacity under constant pressure, J/(kg · K)
D_i = mass diffusivity of species i, m^2/s
$\boldsymbol{F}_i$ = magnetic force per unit volume acting on species i, N/m^3
$\boldsymbol{f}_i$ = external body force per unit mass acting on species i, N/kg
$\boldsymbol{g}$ = gravitational force per unit mass, N/kg
g_L = Lande's g factor
h = Planck constant, J · s
h_i = enthalpy of species i, J/kg
k = Boltzmann constant, J/K
m = molecular weight of mixture gas, kg/mol
m_i = molecular weight of species i, kg/mol
N = total number of species i,
N_A = Avogadro number, /mol
p = gas pressure, Pa
R = universal gas constant, J/K · mol
r = radial distance in cylindrical coordinate system, m
S_i = total electron spin momentum of species i
T = absolute temperature, K
t = time, s
u = radial component of mean velocity vector of mixture gas, m/s
$\boldsymbol{V}_i$ = diffusive velocity vector of species i, m/s
v = axial component of mean velocity vector of mixture gas, m/s
$\boldsymbol{v}$ = mean velocity vector of mixture gas, m/s
w_i = production rate of species i, $kg/m^3 \cdot s$
Y_i = mass fraction of species i
z = axial distance in cylindrical coordinate system, m
θ = azimuthal angle in cylindrical coordinate system, rad
λ = thermal conductivity, J/K · m · s
μ = gas viscosity, Pa · s
μ_B = Bohr magneton, J/T
μ_0 = magnetic permeability of vacuum, H/m
ρ = mass density of mixture gas, kg/m^3
ρ_i = mass density of species i, kg/m^3
χ_i = magnetic susceptibility per unit mass of species i, /kg

Introduction

SINCE Faraday (1791–1867), it has been well known that combustion flames are affected by magnetic fields. In general, the effects of the magnetic fields on flames can be categorized into two types. One of the magnetic effects is caused by the Lorentz force acting on charged particles in flames, that is, ions and electrons, and it has been studied by a large number of researchers in conjunction with applications to the magnetohydrodynamic power generation, etc. According to Lawton and Weinberg[1] and Weinberg,[2] however, the number densities of ions and electrons is less than $10^{14}/m^3$ in a hydrogen flame, even when a small amount of propane is added to enhance the ionization. Compared with the number densities of ions and electrons, the number densities of molecules, radicals, and atoms in the flame are on the order of $10^{24}/m^3$. Thus, the amount of ionic species is negligibly small, and the influence of the Lorentz force on ordinary hydrogen flames can be ignored.

There is another magnetic effect due to the magnetic force, that is, the magnetic pressure, acting on nonconductive and paramagnetic chemical species in flames, for example, OH radicals and O_2 molecules, etc. The magnetic force per unit volume acting on species i, $\boldsymbol{F}_i$, is expressed by the following equation[3]:

$$\boldsymbol{F}_i = (1/2\mu_0)\rho Y_i \chi_i \nabla(B^2) \tag{1}$$

that is, the magnetic force is essentially in proportion to the mass density ρY_i and the magnetic susceptibility χ_i of the ith chemical species and the gradient of the square of magnetic flux density $\nabla(B^2)$. In Refs. 4–8, it is reported that this magnetic force changes the shape and the temperature of flames. In Refs. 6–8, the magnetic support techniques of the flames in microgravity environments is discussed. However, the mechanism of such a magnetic effect and its applications to flame control techniques are still under discussion.

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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).

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:

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

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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Thermal convection control by gradient magnetic field

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A new technique to control thermal convection has been demonstrated by utilizing a gradient magnetic field. When the center of the superconducting magnet was fixed below the center of the heating region, the thermal convection flow was accelerated. In contrast, the convection flow was suppressed when the field center was fixed above the heating center, and under certain conditions, a reverse direction of flow was observed. The control of the flow was made possible by the experimental procedure, in which a downward flow was induced when the magnetic field was applied prior to the heating, and an upward flow was observed under the reverse procedure. These phenomena can be understood by taking account of the balance between the thermal driving force and the magnetic force acting on the air. A detailed analysis was made by examination of the temperature distribution in the observed system. The results suggest the possibility of using a gradient magnetic field for controlling thermal convection without any mechanical driving parts.

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I. INTRODUCTION

Magnetic convection occurs if the magnetic field gradient and magnetic susceptibility gradient coexist in the same direction. The magnetic susceptibility gradient can be created by nonuniformity of density or temperature. It has been reported that magnetic convection was induced in a horizontal direction by partial heating of the space.[1] Nonuniformity of temperature makes a magnetic susceptibility gradient of air due to the paramagnetic property of oxygen, creating a net airflow. The convection change by an electromagnet was examined.[2] We demonstrated that it is possible to produce a large-volume ‘‘magnetothermal wind’’ in an open space along the horizontal bore of a superconducting magnet.[3] The procedure was based on the imbalance of the magnetic force made by asymmetrical heating.

Thermal convection occurs in a vertical direction because of the temperature gradient. Based on the abovementioned mechanism, by applying a steep gradient magnetic field to a vertical heating system, it may be possible to control thermal convection. In this report, we introduce a new method for controlling thermal convection by making use of a gradient magnetic field.

II. THEORY AND EXPERIMENT

The principle of magnetothermal wind is explained as follows and is shown in Fig. 1. The volume magnetic susceptibility of air $\chi(T)$ decreases with temperature as

$$\chi(T)=\chi_{293.15}\left(\frac{293.15}{T}\right)^2, \quad (1)$$

where x$_{293.15}$ is the magnetic susceptibility of air at room
temperature 10.38310$_{26}$, and the magnetic force *f* exerted
on the unit volume of air is expressed by the following equation:

*f*5
x~*T*!
m$_0$
B
dB
dx
, ~2!

FIG. 1. Diagram illustrating the principle of magnetothermal wind.

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where m$_0$ is the permeability of the vacuum, *B* is the magnetic field intensity, and *dB*/*dx* is the magnetic field gradient.

Under the magnetic field configuration shown in Fig. 1, the air is attracted toward the center because the magnetic susceptibility of air consists mainly of paramagnetic oxygen. However, wind cannot be created magnetically since the magnetic force balances on both sides of the magnetic field in a uniform temperature field. When one part of the magnetic field is heated, a differential pressure to flow air is produced because of the imbalance of the magnetic force in the magnetic field. In addition, the direction is such that hot air is expelled from the magnetic field. In the vertical direction, the heating air generates a thermal convection, i.e., an upward flow in the heater tube. By applying a high- and steep-gradient magnetic field in such a system, it is possible to control the thermal convection. Considering the direction of the magnetothermal wind, it seems possible to accelerate the upward thermal convection by means of applying a magnetic field below the heating region. On the other hand, a reversal of the upward flow may occur when a magnetic field is applied above the heating region. Therefore, it was ascertained that a magnetic field is applicable for controlling thermal convection.

The schematic diagram of the experimental setup is shown in Fig. 2. The ceramic tube, around which a resistive heater was wound, was put in the 100 mm, room-temperature bore of a superconducting magnet. Its inner diameter was 16310$_{23}$ m, and the length was 0.93 m. The output of the heater was fixed at 164 W. The magnetic field *B* and the product of the field and its gradient *BdB*/*dx* distributions are shown in Fig. 3. Under such a magnetic field configuration, a magnetic field 10 T was applied at various positions around the heating region.

III. RESULTS AND DISCUSSION

The temperature distribution with a zero magnetic field is presented in Fig. 4. In this figure, plus means upward. It is understood that a hot upward airflow was created; the temperature distribution showed the heat was carried toward the right-hand side, i.e., upward. The velocity of this upward flow was about 0.94 m/s, according to the calculation of the density based on the temperature distribution. Assuming Hargen-poiseuille viscous flow, the equation of the average velocity is expressed as

n5
D*Pr*$_2$
8 h*L*
, ~3!

where *r* is the radius of the tube 8.0310$_{23}$ m, *L* is the length of the tube 0.93 m, D*P* is the pressure difference at both ends of the tube, and η is the viscosity. The temperature dependence of the viscosity of air is given as

$$\eta(T) = \eta_{RT}\left(\frac{293.15+C}{T+C}\right)\left(\frac{T}{293.15}\right)^{3/2}, \quad (4)$$

where C is Sutherland’s constant ($C_{air}=117$) and η_{RT} is the viscosity at room temperature 18.2×10^{-6} Pa s. $\Delta P_{thermal}$ is obtained by considering the balance between the density outside the tube and the average density along the measured region.

After applying a magnetic field to the heating system with its center at the position from heating center by 0, ±30, ±60 mm, the measured temperature distributions were shown in Fig. 5. In this figure, z is the distance from the magnetic field center. By comparing these figures and Fig. 4, the direction of flow is understood. When the magnetic field was applied below the heating center, the flow was accelerated. When it was applied above the heating center, the flow was suppressed and a downward flow was observed. Based on these temperature distributions, we calculated the magnetic force from Eq. (1), viscosity from Eq. (4), and the density at each point. $\Delta P_{magnetic}$ was calculated by numerically integrating the magnetic force. $\Delta P_{thermal}$, $\Delta P_{magnetic}$, and the velocities of the flow in each case were calculated by Eq. (3) and are given in Table I. In this table, the ratio between the differential pressure of the magnetothermal wind and thermal convection is shown. It is understood that the magnetic-induced airflow is strong enough to control the thermal convection in 10 T field. In each case, the flow is several meters per second.

FIG. 2. Diagram of the experimental setup for controlling thermal convection.

FIG. 3. Distributions of the magnetic field B and the index of the magnetic force BdB/dx of the superconducting magnet.

FIG. 4. Temperature distribution of the air in the tube with zero field with distance from heating center.

Furthermore, it is expected that it may be possible to control the flow by applying the magnetic field before and/or after heating. In the experiment mentioned above, the air was heated after applying the magnetic field. In order to evaluate the effects of this experimental procedure, a magnetic field was applied after heating. Figure 6 shows the temperature distribution when the magnetic field center was raised 30 mm above the heating center. This procedure causes the upward flow to continue. This phenomenon was observed when the centers of heating and the magnetic field were close to each other. When the magnetic field center was quite far above the heating center, the previously formed upward airflow was gradually changed into a downward flow with the increase of magnetic field. It seemed that there was a critical field center position at which the direction of the flow was reversed. Therefore, we determined at what position the flow changed, considering the temperature distribution at the zero field. According to our calculations, it was expected that the change would occur when the magnetic field center was 130 mm above the heating center. In order to confirm this, the magnetic field center was moved toward the upper part of the heating region. At first an upward flow was made by heating the zero field, and the applied magnetic field center was moved upward in the heating region. The upward flow changed to a downward flow when the field center was about 100 mm above the heating center. The difference between the calculation and the measurement can be explained by considering the experimental situation. In the experiment, the previously formed upward flow was somewhat suppressed because the magnetic field was applied above the heating region. As a result, the change occurred before reaching the calculated position of 130 mm.

IV. CONCLUSION

A new technique to utilize a gradient magnetic field to control thermal convection has been studied. It is shown that the acceleration or the suppression of thermal convection has been made possible by an experimental setting and procedure. The magnetic-induced airflow shown in this study is fairly large in volume and has no mechanically driven parts. Therefore, using this technique, it is possible to control thermal convection on an industrial scale. Recently the bore of superconducting magnets has become quite large; therefore, this phenomenon will be of importance in heat treatment processes.

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FIG. 5. Temperature distributions of the air in the tube under the magnetic field, with the heating center at 260 ~a!, 230 ~b!, 0 ~c!, 30 ~d!, and 60 mm ~e! from the field center.

TABLE I. The values of differential pressure induced thermally, DP_{thermal}, and induced magnetically, DP_{magnetic}, and the resultant average velocity v.

	DP_{therm} ~Pa!	DP_{magn} ~Pa!	v ~m/s!
0 T	2.73	0	0.94
10 T, z~mm!			
260	2.38	28.32	21.93
230	2.54	25.35	20.90
0	1.93	5.03	2.44
30	1.82	8.95	3.46
60	1.79	11.98	4.71

FIG. 6. Temperature distributions when the magnetic field center was 30 mm above the heating center; ~s! is the temperature distribution under magnetic field applied before heating and ~ h! is that after heating.

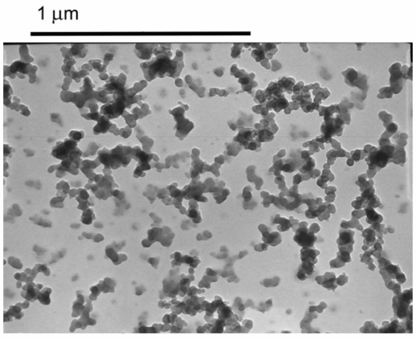

Fig. 5.16a: Soot samples collected at flame tip for a case of no magnetic field

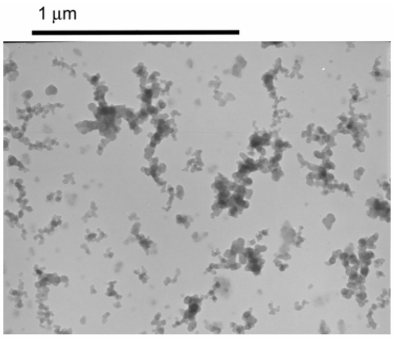

Fig. 5.16b: Soot samples collected at flame tip for a case of vertically decreasing magnetic field (B_c =2.77 KGs)