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Combustion and Flame 133 (2003) 345–357

Combustion and Flame

A study of the characteristics of slotted laminar jet diffusion flames in the presence of non-uniform magnetic fields

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Received 21 June 2002; received in revised form 27 January 2003; accepted 30 January 2003

Abstract

The behavior of laminar jet diffusion flames in the presence of non-uniform magnetic fields has been investigated and the results of this experimental study are presented. It has long been recognized that magnetic fields can influence the behavior of laminar diffusion flames as a result of the paramagnetic and diamagnetic properties of the constituent gases. Using a magnet assembly consisting of neodymium iron boron magnets and gray steel prisms, a non-uniform upward decreasing magnetic field was applied to a laminar jet diffusion flame produced using a slotted burner port. The experimental results show that under certain conditions the application of the magnetic field decreased the flame height, prevented the flame from attaching to the prisms, increased the intensity of the flame, decreased the flow rate for which visible soot inception occurred, and increased the flow rate below which the flame extinguished. It was also observed that the degree to which these phenomena occur is proportional to the product of the magnetic induction times the gradient of the magnetic induction. A discussion as to the reasons for these observations is provided. In addition to traditionally defined dimensionless parameters, the previously defined magnetic Grashof number, the magnetic Froude number, and the ratio of the gravitationally induced buoyancy forces to the magnetically induced body forces are identified as key parameters for determining when a magnetic field will affect diffusion flame behavior. Using these dimensionless parameters, the experimental data was cast in a form that clearly indicated the universal nature of diffusion flame behavior in a non-uniform upward decreasing magnetic field. A power law curve fit to the dimensionless data is presented and discussed.

Keywords: Jet diffusion flames; Magnetic fields

1. Introduction

Magnetic fields are known to affect flame behavior as a result of the paramagnetic and diamagnetic behavior of the constituent gases. Paramagnetic behavior is observed in materials with atoms that possess a permanent dipole moment. In the presence of a non-uniform magnetic field, these dipole moments align with the field and thus paramagnetic materials are drawn toward the direction of increasing magnetic field strength. The magnetic susceptibility, the ratio of the magnetization to the magnetic field strength [1], is the parameter that characterizes this behavior. Since the magnetic forces associated with the dipole moments in a paramagnetic material must compete with the randomizing effects of temperature, the magnetic susceptibility for a paramagnetic material is a function of temperature. Materials with no

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0010-2180/03/$ – see front matter
doi:10.1016/S0010-2180(03)00021-X

Nomenclature

a	mean buoyant acceleration
AMF	applied magnetic field
b	burner port width
B	magnetic induction
BP	burner port
d	minimum distance between prisms
d_{BP}	outer width of slot burner port
D	mass diffusivity
Fr	Froude number
Fr_m	magnetic Froude number
g	acceleration due to gravity
Gr	Grashof number
Gr_m	magnetic Grashof number
h	burner port length
I	ratio of the actual initial momentum to that for uniform flow
L_f	flame height
M	magnetic field configuration
$NAMF$	no applied magnetic field
N_d	flow obstruction parameter
N_{gm}	ratio of buoyancy to magnetic forces
R^2	coefficient of determination
Re	Reynolds number
t	burner port wall thickness
T	temperature
v_F	mean burner port exit velocity
Y_F	fuel mass fraction
z	distance above burner port exit
μ_0	permeability of free space
ν	kinematic viscosity
ρ	density
χ	magnetic susceptibility
Subscripts	
f	flame
F	fuel
OX	oxidizer
$stoic$	stoichiometric conditions

permanent atomic dipole moments exhibit diamagnetic behavior. When a non-uniform magnetic field is applied to a diamagnetic material, the atoms of the material develop a net dipole moment. This induced dipole moment opposes the applied field and thus a diamagnetic material experiences a weak repulsion to the applied magnetic field. All materials, to some degree, experience diamagnetic behavior. For materials whose atoms possess permanent dipole moments, the associated paramagnetic forces are typically orders of magnitude larger and the diamagnetic behavior for these materials is thus negligible [2]. Note that the magnetic susceptibility for a diamagnetic material is not a function of temperature. Note also that the magnetic susceptibility for a diamagnetic material is negative in sign while a paramagnetic material has a positive magnetic susceptibility. Oxygen is the principal paramagnetic material associated with diffusion flames with most hydrocarbon fuels, nitrogen, elemental carbon, carbon monoxide, and carbon dioxide being the principal diamagnetic species.

In this paper, a laminar diffusion flame produced using a slotted burner port in the presence of a non-uniform upward decreasing magnetic field was used to gain insight into magnetocombustion behavior. The specific objectives of study were:

1. Observe diffusion flames produced using slotted burners in the presence of non-uniform magnetic fields and compare these observations to those of similar flames with no applied magnetic field,
2. Identify parameters that may be used to characterize regimes where the presence of magnetic fields can significantly influence flame behavior, and
3. Develop an empirical correlation which may be used to predict the height of diffusion flames in the presence of a non-uniform upward decreasing magnetic field.

2. Literature review

The fact that magnetic fields can influence the behavior of flames was first recognized over one hundred and fifty years ago. In 1847, Michael Faraday [3] observed that the presence of strong, non-uniform magnet fields caused candle flames to deflect. He also observed that the flames were more luminous when placed within the magnetic field. He theorized that the changes were due to the presence of “magnetic” and “diamagnetic” gases in the flames. von Engel and Cozens [4] used a model based upon electromagnetic theory to show that the interaction between magnetic fields and the charged ions within flames was insufficient to cause experimentally observed flame behavior. The changes in experimentally observed flame behavior were attributed to a pressure difference caused by the differing magnetic permeabilities.

A renewed period of research into the impact of magnetic fields on combustion behavior began in the 1980s. Hayashi [5] investigated magnetic field effects on the emission intensities of some intermediate species in oxygen-propane and oxygen-hydrogen combustion. He found that the presence of a uniform magnetic field caused a noticeable increase in the emission intensity of the OH* radical, with the emission intensity increasing with magnetic field strength. Wakayama, et al. [6] investigated changes in the total emission intensity of sodium D lines in oxygen-hydrogen flames enriched with various sodium salts within magnetic fields. It was found that the total emission intensity significantly increased in the presence of a magnetic field. The relationship between the increased intensities and the combustion conditions was found to be very complex and depended on such factors as the concentration of sodium salts, type of counter ions, and the flow rates of hydrogen and oxygen. The exact mechanisms behind the increases and the magnetic field effects were not identified. Ueno, et al. [7] studied "slow" combustion as an analogy to cellular respiration in biological systems. They found that increases in the applied magnetic field gradient caused a sinusoidal response in the gasoline combustion velocity. For alcohol, it was found that the combustion rates exhibited a minimum at a specific magnetic field strength. Ueno, et al. [8] continued this investigation by conducting experiments under which the combustion temperature and reaction rate were continuously monitored. They observed that both the combustion rate and temperature fluctuated as the magnetic field was varied but that the average combustion temperature was reduced. Ueno and Harada [9] found that the combustion temperature of alcohol in the presence of platinum catalysis decreased by 100–200°C for the range of applied magnetic field gradients considered. The authors also noted changes in temperature as a function of location within the reaction zone for increasing magnetic gradients. To further examine this phenomenon, the behavior of a candle flame in an applied magnetic gradient field was examined. It was noted that the presence of an increasing magnetic gradient caused the flame to deflect in the direction of decreasing magnetic field strength. The authors noted the paramagnetic nature of oxygen and the diamagnetic nature of the combustion products as possible contributors to this behavior. Oxygen, concentrated in the region of highest magnetic field gradient, developed what the authors described as a magnetic pressure that deflected the candle flame and combustion products. In an effort to clarify the behavior observed previously, Ueno and Harada [10] expanded their investigation to first examine flames and then jets of paramagnetic and diamagnetic gases. The authors observed that the magnetic gradient field caused the flame shape to alter in such a way as to minimize exposure to increasing magnetic gradients. The authors concluded that the presence of a strong magnetic field and gradient did not concentrate oxygen near the magnetic poles, but seemed to align the molecules into a "curtain" that reduced the flow of the other gases through the airspace between the magnetic poles. Ueno [11] examined the ability of magnetic fields to quench flames. Using a candle placed between two columnar electromagnets, the combination of magnetic induction/magnetic induction gradient of sufficient strength was found to extinguish the flame shortly after application of the field. It was also indicated that the oxygen and nitrogen were not separated by the magnetic field. Rather, than concentrating the oxygen molecules and dispersing the nitrogen molecules, air was trapped in the region of highest gradient strength. Secondly, the presence of the magnetic field was not found to increase air pressure.

Aoki [12] investigated butane diffusion flames within an upward decreasing magnetic fields generated by electromagnets. He found that the presence of the magnetic field caused an increase in the emission intensities of radical OH*, CH* and C2* transitions. He also observed that the magnetic gradient field caused the flame temperature to increase. Aoki determined that the Lorentz force induced by the presence of charged particles in the flames was insufficient to cause any appreciable flame deformation within the magnetic field. Aoki [13] also investigated butane diffusion flames in upward increasing magnetic fields. He observed that the upward increasing magnetic field caused the combustion processes within the flame to invert. Physically, the flame shape was compressed into a mushroom shape by the application of an upward increasing magnetic field. Aoki [14] investigated butane diffusion flames exposed to a uniform magnetic field. He found that the flame dimensions increased, while the combustion temperature, soot formation and emission intensities of OH*, CH*, and C2* radicals decreased for increasing magnetic field strength. It was also found that a sufficiently strong field could effectively block the flow, causing the flame to be extinguished. In a related work, Aoki [15] investigated butane combustion encircled by magnetic gradient fields. Under specific conditions, he found that the diffusion flame would ultimately extinguish, and then a bluish ring flame would appear for strong gradient fields. Wakayama [16] investigated the behavior of methane premixed and diffusion flames within gradient magnetic fields. It was found that when the flame was placed in a region of decreasing magnetic field strength, the flame shape became elongated and slender. It was also observed that the temperature and luminosity of the flame increased with increasing gradient strength. When the flame was moved into a region of increasing magnetic field strength, the flame shape was observed to become short and thick. When the flame was exposed to a homogeneous field, the flame did not appear to be affected. Wakayama attributed these effects to the paramagnetic nature of oxygen, and the diamagnetic nature of the combustion products. Wakayama [17] investigated the influence of magnetic gradient fields on partially premixed and diffusion flames in air. The author found that the combustion rate of diffusion flames in decreasing magnetic fields increased with increasing magnetic field intensity while the magnetic fields had little effect on the partially premixed flames. Wakayama found that combustion was promoted in regions of increasing magnetic gradients for geometries where magnetic blocking was negligible. No effect was observed for flames under a uniform magnetic field. The observed phenomena indicated that the flow of oxygen into regions of increasing strength was the most dominant factor in affecting the combustion behavior of diffusion flames.

Wakayama et al. [18] investigated the magnetic support of combustion using butane diffusion flames in microgravity. The experimental investigation was conducted in a 10-second drop tower for flames within a decreasing magnetic field. The results of these tests were compared to microgravity diffusion flames with no applied magnetic field. The investigators found that the presence of the magnetic gradient field induced convection within the flame similar to that induced by buoyancy effects. This magnetically induced convection elongated the flame shape, as opposed to the spherical flame shapes normally seen under microgravity conditions. The flames within magnetic fields settled down after an initial transition period and remained highly luminous, while the normal flames decreased in luminosity and ultimately extinguished. Fujita et al. [19] extended Wakayama's microgravity research to include flames in increasing magnetic fields. Again, experimental investigations were conducted in a 10-second drop tower. The authors found that the presence of an increasing magnetic field caused the diffusion flame to invert. Diffusion flames at the center of the magnetic field elongated into a long, slender flame. It was also observed that the magnetically induced buoyancy forces associated with the flame could sustain the flame for longer periods under microgravity than otherwise possible. Fujita et al. [20] varied the intensity of the magnetic field surrounding a propane diffusion flame in a microgravity environment. A critical value of the magnetic field intensity above which diffusion flames would burn steadily under microgravity was observed. The authors also identified a parameter similar to the Grashof number that could be used to identify when magnetically induced convection would occur. They found that increases in the magnetic field intensity and the oxygen concentration caused a decrease in the flames "redness," indicating an increase in flame temperature. The authors were able to correlate the behavior with a new parameter, $F[O_2]$. This parameter is defined as the product of the strength of the magnetically induced convection, and the oxygen concentration.

3. Experimental approach

Figure 1 is a schematic representation of the burner port/magnetic prism assembly. Propane (99.5% purity) was used as the fuel. A mass flow controller, calibrated for propane, was used to measure the fuel flow rate. The fuel flow rate was regulated using a metering valve. Two neodymium-iron-boron (NdFeB) magnets were used to provide the magnetic field. A triangular prism made of gray steel was attached to each of the permanent magnets to shape the magnetic field. Note that the NdFeB magnets are not shown in Fig. 1. The poles of the magnets were aligned in the attracting position. The magnet/prism assembly was mounted to a vertical linear translation device that allowed the apex of the prisms to be positioned at the top of the burner. The magnet/prism assembly was positioned so that the burner was centered in the space between the two prism apexes. Four slot burners were formed from 1/8 inch drawn brass tubing with the respective port dimensions given in Table 1. The test cell portion of the apparatus was contained within a screened-in cage to reduce air currents that could influence the flame behavior. The magnetic field induction was measured as a function of centerline position between the prisms using a gaussmeter with a transverse probe attached to a vertical linear translation device. Optical images of the flames were captured using a 35 mm single lens reflex (SLR) camera back with a 65 mm f/2.8 1-5x macro lens.

The flame image photos were developed and digitized into JPEG image files. The flame images were processed to obtain flame shapes by the use of Tracker [21]. It has been previously shown that the blue luminous flame sheet dimensions agrees favorably with the stoichiometric flame dimensions [22,23]. The green flame sheet dimensions were used instead of the blue due to the large contrast between the flame profiles and the background observed for this filtering method.

The measurement uncertainty for the mass flow meter was ± 0.3 cm^3/min. The uncertainty in the magnetic field measurement was 2% of the reading. The uncertainty in the flame height measurements

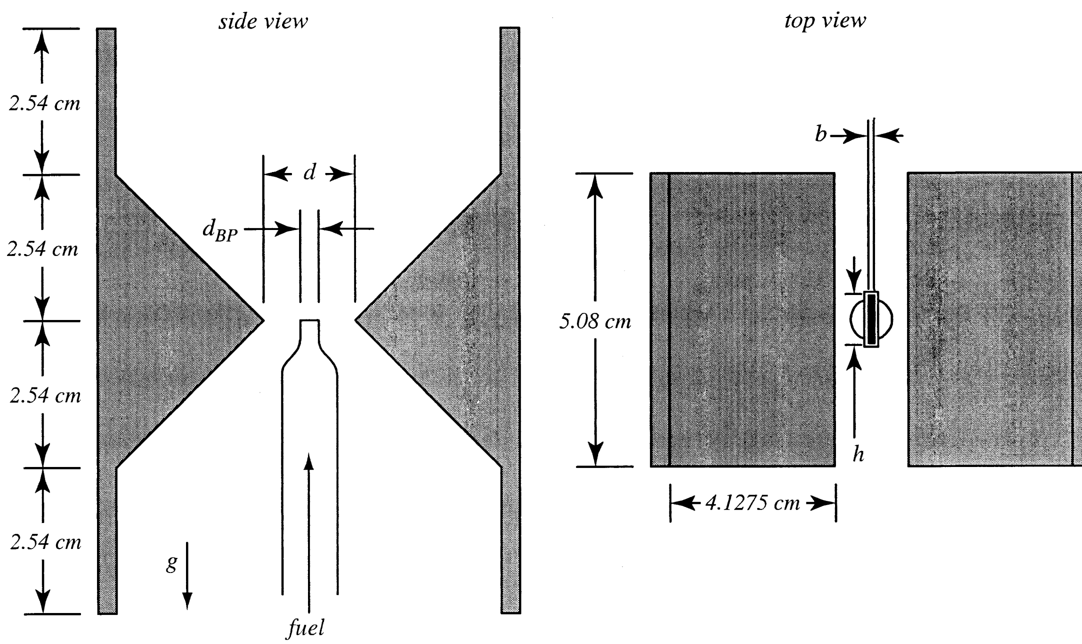

Fig. 1. A schematic diagram of the burner port/magnetic prism assembly.

were ±0.0111 mm. The uncertainty in the burner port length measurements was ±0.005 mm while the uncertainty in the burner port width measurements was ±0.0005 mm.

4. Scaling analysis

In Fujita, et al. [20], a magnetic Grashof number was defined to identify the regime where fluid motion due to the presence of a magnetic field would occur. The magnetic Grashof number was defined as the ratio of magnetobuoyancy forces to viscous forces i.e.,

$$Gr_M = \frac{(\chi_f - \chi_{OX})\, B\, \frac{dB}{dz}\, L_f^3}{\mu_0 \rho \nu^2} \cong -\frac{\chi_{OX} B\, \frac{dB}{dz}\, L_f^3}{\mu_0 \rho \nu^2} \quad (1)$$

Note that the above equation differs from that appearing in Fujita, et al. [20] in that the characteristic length has been changed from the flame width to the flame height and a change of variables has been made to cast the expression in terms of the magnetic induction rather than the magnetic field strength. The reason for the first change is to account for the fact that the magnetobuoyancy forces should accelerate the flow along the length of the flame and thus the flame height is a more appropriate characteristic length. The reason for the second change is simply for convenience as the magnetic induction was measured during the course of this investigation. Eq. (1) also provides an approximation for the magnetic susceptibility as a result of the fact that magnetic susceptibility of oxygen is two orders of magnitude greater than that of the fuel (or the major product species) at room temperature. Fujita, et al., [20] concluded that in a manner similar to buoyancy induced flow as a result of the acceleration due to gravity, the presence of a magnetic field should induce flow for a value of the magnetic Grashof number on the order of 10^2–10^3. For flames with a magnetic Grashof number greater than the critical value, flames were observed to burn brighter and the tips of the flames were observed to close with increasing magnetic field intensity. Both of these observations were attributed to the increased motion due to the application of a non-uniform upward decreasing magnetic field.

For jet diffusion flames, one must account for both the acceleration due to a buoyancy force (whether that associated with a magnetic or gravitational

Table 1
Burner port dimensions

Burner	BP1	BP2	BP3	BP4
b (mm)	0.508	0.254	0.762	0.102
h (mm)	3.350	3.550	3.390	3.820
t (mm)	0.260	0.260	0.260	0.260

field) and the forces associated with the forced motion due to the gas issuing from the burner port. For slotted flames in a terrestrial gravitational field Roper showed that, depending upon the magnitude of the Froude number, slot diffusion flames may either be buoyancy-controlled ($Fr \ll 1$), momentum controlled ($Fr \gg 1$), or transitional ($Fr \approx 1$) [24,25]. Recall that the Froude number is defined as [26]

$$Fr = \frac{(\nu_F I Y_{F,stoic})^2}{\alpha L_f} \tag{2}$$

where it has been assumed that the mean buoyant acceleration may be determine following Roper [24] as

$$a \cong 0.6g\left(\frac{T_f}{T_{OX}} - 1\right) \tag{3}$$

To compare the orders of magnitude of the magnetically generated buoyancy forces to the momentum forces, one may define the magnetic Froude number as

$$Fr_m = \frac{\rho\mu_0(\nu_F I Y_{F,stoci})^2}{(\chi_f - \chi_{OX})\, B\, \dfrac{dB}{dz}\, L_f} \cong -\frac{\rho\mu_0(\nu_F I Y_{F,stoic})^2}{\chi_{OX} B\, \dfrac{dB}{dz}\, L_f} = \frac{Re^2}{Gr_m} \tag{4}$$

Note that in the above definitions, the $F[O_2]$ parameter used by Fujita et al. [20] to correlate the oxygen concentration is implicitly included by introducing the stoichiometric fuel mass fraction term. Note also that by defining the Reynolds number as

$$Re = \frac{\nu_F I Y_{F,stoic} L_f}{\nu} \tag{5}$$

it is possible to cast the magnetic Froude number as the ratio of the Reynolds number squared to the magnetic Grashof number. In this manner, it is again reasonable to compare the magnetically induced behavior to that associated with a gravitationally generated buoyancy induced flow. For combined free and forced convection heat transfer, it has been established that for $Gr/Re^2 \ll 1$ free convection is negligible relative to forced convection [27]. Similarly, for $Gr/Re^2 \gg 1$ forced convection is negligible and if $Gr/Re^2 \approx 1$ then the heat transfer must be considered a combination of the two mechanisms [27]. As a rule of thumb, if $Gr/Re^2 > 10$, then buoyancy induced flow may be assumed to be the dominant heat transfer mechanism [28]. As previously mentioned, Fujita, et al. [20] concluded that the same scaling should hold for both gravitationally generated flows and magnetically generated flows. Following the same line of reasoning, the scaling for mixed free and forced convection should be similar to that for jet diffusion flames in the presence of non-uniform magnetic fields. In this manner, for $Fr_m < 0.1$, the behavior of the flame should be dominated by the magnetic field interaction. One interesting point to note is that for gravitationally generated buoyancy, when the buoyancy forces are in the same direction as the forced flow, the heat transfer is enhanced and when the buoyancy forces are in opposition to the forced flow the heat transfer is diminished. In the case of a jet diffusion flame in the presence of a non-uniform upward decreasing magnetic field, the magnetic field should generate a flow of oxygen that opposes the magnetically induced flow of the fuel and product species. As previously discussed, since the order of magnitude of the magnetic susceptibility for oxygen is two orders of magnitude greater than that of the fuel and product species, the effects associated with oxygen transport should dominate the transport associated with the diamagnetic species.

The ratio of the body forces associated with gravity to those associated with the application of the non-uniform magnetic field may be determined by examining the ratio of the magnetic Froude number to the traditionally defined Froude number

$$N_{gm} = \frac{Fr_m}{Fr} = -\frac{\rho\mu_0 a}{\chi_{OX} B\, \dfrac{dB}{dz}} \tag{6}$$

As in Eqs. (1) and (4), Eq. (6) has been written using an approximation for the magnetic susceptibility.

Finally, in this investigation the maximum magnetic induction was changed by moving the magnetic prisms inward or outward relative to the burner port. To account for this change, a flow obstruction parameter was defined as

$$N_d = \frac{d - d_{BP}}{d} \tag{7}$$

Eq. (7) is simply a statement of the fact that as the spacing between the magnetic prisms increases, the physical presence of the magnetic prisms will have a decreased impact on the flow field in the vicinity of the flame. As the spacing between the magnetic prisms tends toward infinity, the flow obstruction parameter will tend toward unity.

5. Results and discussions

Figure 2 is a plot of the three magnetic field configuration examined in this investigation. Note that in this investigation, the burner port exit was located at the origin along the vertical axis. Table 2

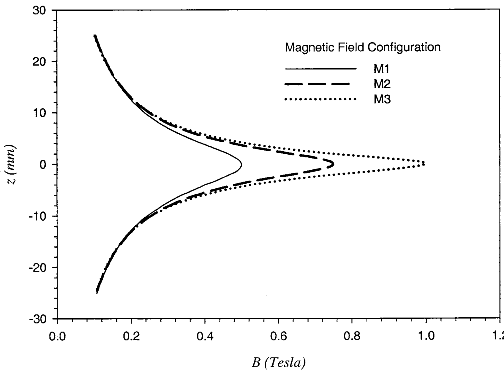

Fig. 2. A plot of the three magnetic field distributions.

provide information on the maximum magnetic induction, the gradient of the magnetic induction, and minimum distance between the prisms for a specific magnetic field configuration. Since the flame heights were typically on the order of 5 mm or less and a linear curve fit of the magnetic field data in this range yielded a coefficient of determination greater than 0.97 for all three magnetic configurations, it was assumed that the magnetic field was a linearly decreasing function of height above the burner port exit. The horizontal variation of the magnetic field exhibited a typical variation of ±0.009 T with a 95% confidence interval. The greatest variation in the measurements occurred near the edges of the prism apexes, with the variation decreasing near the center of the region between the apexes. The size of the magnetic probe relative to the space between the prism apexes prevented a more accurate measurement of the variation in the magnetic field as a function of the horizontal distance between the prisms.

Figure 3 provides images of typical flames observed when applying the M1, M2, and M3 magnetic field configurations. For the M1 configuration, there are no significant differences between the flames with an applied magnetic field and with no applied magnetic field. For the M2 configuration, there were no discernible differences between flames with an applied magnetic field compared to those with no applied magnetic field for the smaller fuel flow rates. For the larger flow rates, a small but distinct decrease in flame height was observed. This trend was more pronounced for the M3 magnetic field configuration. For the M3 configuration, the application of a non-uniform upward decreasing magnetic field significantly decreased the flame height.

Table 2
Magnetic field configuration

Magnetic Field	M1	M2	M3
$B_{\max}$ (*Tesla*)	0.500	0.75	1.00
dB/dz (*Tesla/m*)	−29	−72	−120
d (*mm*)	8.59	4.78	2.87

As can also be seen in Fig. 3, the application of a non-uniform upward decreasing magnetic field produced an increase in the intensity of the flame. This increase in intensity was proportional to the product of the maximum magnetic induction times the gradient of the magnetic induction. Also, note that the flames with no applied magnetic field appear more diffuse than the flames in the presence of the non-uniform upward decreasing magnetic field. The most significant change observed to occur as a result of applying a non-uniform upward decreasing magnetic field was the fact that for the M3 magnetic field configuration, the flame clearly elongates relative to the flame with no applied magnetic field. The flame sheet produced when no magnetic field was applied spanned nearly the entire width of the space between the prisms and attached to the prism walls. When the M3 magnetic field configuration was applied, the flame did not attach to the prism and behaved almost as if the prisms were not present. It was also noted that the application of the non-uniform upward decreasing magnetic field decreased the flame's stand-off distance relative to flames with no applied magnetic field. The explanation for the above observations may be found in the transport characteristics of the oxygen in the vicinity of the flame. The oxygen, a paramagnetic material, is drawn to the region where the product of the magnetic induction times the gradient of the magnetic induction is a maximum i.e., at the point of minimum distance between the prism which happens to also be at the burner port exit. Since the jet is issuing fuel into the center of the region, the oxygen is drawn down the sides of the prisms. This has the effect of increasing the oxygen concentration along the edges of and at the base of the flame. The increased oxygen concentration enhances combustion at the base of the flame thereby producing a smaller, more intense flame. Since the fuel is burning at an elevated temperature the quenching distance is decreased relative to a flame with no applied magnetic field.

Prism spacing was also observed to affect flame height. When no magnetic field was applied but the prisms were placed in the same exact physical location corresponding to the M1 and M2 configurations, i.e., the same gap distance *d*, the flame height increased faster as a function of flow rate for the gap distance corresponding to the M2 configuration than it did for the M1 configuration. A similar trend was observed between the M2 and M3 configuration gap distances. Again, these observations were made with

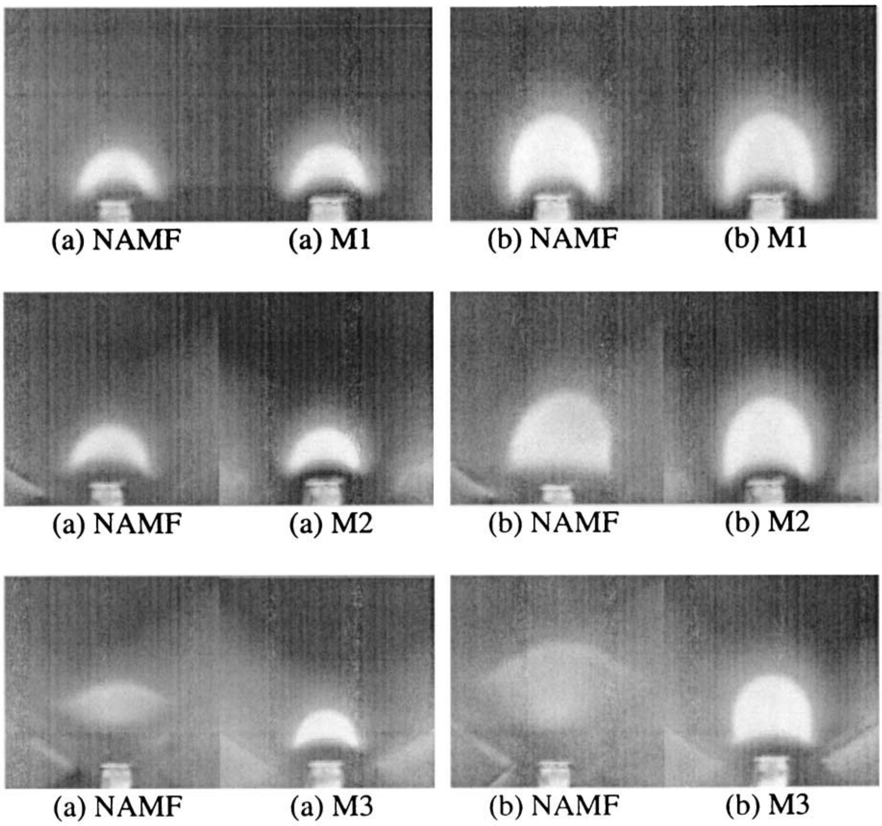

Fig. 3. Flames produced using burner BP1 with no applied magnetic field (NAMF) and with magnetic field configurations M1, M2, or M3 at a flow rate of (a) 4 cm^3/min and (b) 6.4 cm^3/min.

no applied magnetic field as verified by direct measurement. The conclusion is that the physical presence of the prisms has an impact of flame height. The prism effect also influenced the flame heights when a magnetic field was applied. The application of the magnetic field seemed, however, to decrease the effect that the prism spacing had on flame height. In general, when the magnetic field was applied the change in flame height associated with the prism spacing was on the order of 0.1 mm or less while for the case of no applied magnetic field the change in flame height was on the order of 0.4 to 0.8 mm. This indicates that the paramagnetic/diamagnetic interaction in the vicinity of the flame somewhat counteracts the effect of physically changing the location of the prisms.

Table 3 shows the average fuel flow rate at the near extinction point for both the case of an applied magnetic field (AMF) and of no applied magnetic field (NAMF). The near extinction point was defined as the point where any decrease in the flow rate resulted in the extinction of the flame. There were no

Table 3
Average fuel flow rate (in cm^3/min) at near extinction point

	M1		M2		M3	
	AMF	NAMF	AMF	NAMF	AMF	NAMF
BP1	2.5	2.5	2.7	2.5	2.9	2.7
BP2	2.7	2.7	3.0	2.7	3.3	2.9
BP3	2.5	2.5	2.6	2.5	2.7	2.9
BP4	2.6	2.6	2.8	2.6	3.3	2.8

Table 4
Average fuel flow rate (in cm^3/min) at visible soot inception

	M1		M2		M3	
	AMF	NAMF	AMF	NAMF	AMF	NAMF
BP1	7.4	7.4	7.7	9.4	9.7	10.7
BP2	7.9	7.5	7.7	9.9	10.4	12.0
BP3	7.6	7.4	7.7	9.6	9.1	11.0
BP4	7.5	7.4	8.0	10.0	9.9	12.1

discernible differences in the near extinction fuel flow rate between the NAMF and the M1 AMF conditions. The near extinction flow rates increased by 0.1–0.3 cm^3/min for the M2 AMF conditions relative to the NAMF cases. For the M3 AMF conditions, the minimum flow rates increased by 0.1–0.5 cm^3/min relative to the NAMF cases. The influence of magnetic fields on near extinction point flow rates was expected due to the paramagnetic nature of oxygen. It has been previously mentioned that the oxygen is drawn down the sides of the prisms to the base of the flame. The magnetically induced transport of oxygen down the sides of the prism will cool the prisms near the base of the flame. The decrease in prism temperature associated with the magnetically induced flow of oxygen is believed to be responsible for the increase in flow rate for the near extinction point. For the physical prism spacing associated with the M3 magnetic configuration but with no applied magnetic field, there was an increase in the flow rate corresponding to the near extinction point for all burner ports relative to the other prism spacings. The reason for this is believed to be the result of heat transfer from the flame to the prisms extinguishing the flame for lower flow rates. As the prisms were moved closer together this phenomena became more pronounced.

Table 4 shows the flow rates corresponding to the soot inception point defined as the point where the orange glow of soot formation was first observed in the flames by the unaided human eye. For the M1 magnetic field configuration, the difference in the flow rates between the AMF and the NAMF cases varied by 0–0.4 cm^3/min, with no particular bias indicated by the data in terms of the application of a magnetic field. For the M2 configuration, the decrease in the visible soot inception point varied from 1.7–2.2 cm^3/min with the application of the magnetic field. For the M3 configuration, the decrease ranged between 1.1–2.2 cm^3/min. It may also be noted that the minimum fuel flow rates required for soot formation increased with decreasing prism spacing for both the AMF and NAMF cases. The application of the non-uniform upward decreasing magnetic field was observed to not only change the soot inception flow rate but also the structure of the soot cap. For the case of NAMF, the soot cap appeared to be diffusely distributed across the top of the flames. When the non-uniform upward decreasing magnetic field was applied, the soot cap was concentrated at the upper portion of the flame primarily at the centerline above the burner exit. The reduction in fuel flow rate for soot formation and the change in the behavior of the soot cap in the presence of magnetic fields may be understood by considering the physical processes associated with the paramagnetic and diamagnetic nature of the constituent gases. The fact that oxygen is paramagnetic, and thus attracted to the magnetic field, while all the other major species present are diamagnetic, and are thus repelled by the magnetic field, is the key to understanding the observed soot formation behavior. The paramagnetic/diamagnetic properties of the constituent gases will tend to decrease diffusion in the radial direction above the burner port. This will decrease the amount of oxygen available to oxidize carbon and thus decrease the flow rate at which soot forms. It has previously been noted that oxygen is drawn down the sides of the prisms toward the region of where the product of the magnetic induction and the gradient of the magnetic induction is maximum. This combined with the fact that the fuel and combustion products are diamagnetic and are thus repelled by the magnetic field concentrates the fuel and combustion products directly above the burner port. This causes soot to preferentially form directly above the burner port.

To examine the physical processes responsible for the flame behavior, the magnitude of the previously defined dimensionless parameters were examined. Table 5 provides a listing of the baseline parameters used during the order of magnitude analysis. Note that the Schmidt number has been assumed to be unity and thus the mass diffusivity is equal to the kinematic viscosity. Table 6 is a list of the range of the dimensionless parameters examined during the course of this investigation. The Reynolds numbers ranged from 0.017 to 1.53 so it may be concluded that the flames were laminar in nature. The flow obstruction parameter ranged from 0.553 to 0.928 so for all the cases considered the physical presence of

Table 5
Baseline parameters for order of magnitude analysis

Parameter	Value
a	23.73 m/s^2
D	7.62×10^{-5} m^2/s
I	1.0
T_f	1500 K
T_∞	298.15 K
$Y_{F,stoic}$	0.0601
μ_0	1.26×10^{-6} $kg \cdot m/s^2 \cdot A^2$
χ_{OX}	2.0×10^{-6}
ρ	0.4 kg/m^3

the prisms would have at least some impact on flame behavior. The experimentally examined Froude numbers were on the order of 10^{-5} to 10^{-3}. From this it can be concluded that, ignoring the effects of an applied magnetic field, the flames would be buoyancy-controlled and the flame height would be inversely proportional to the gravitational acceleration raised to the 1/3 power. The experimentally observed magnetic Froude numbers were on the order of 10^{-6} to 10^{-3}. From the discussion in the Scaling Analysis section, this would indicate that the flames were magnetically controlled relative to the inertia effects as the magnetic Froude number is much less than 10. While it would have been beneficial to examine flames with magnetic Froude numbers of order ten or greater, limitation associated with the experimental diagnostics prevented such an examination. Recall that the flame height was determined from an examination of the luminous region of the flame, that this method of determining flame height is not valid for sooting flames, and in this study flames were examined for flow rates at or below the soot inception point. This was the reason for the limits on the magnetic Froude number. From Table VI one can see that the magnetic Grashof number ranged from 19.9 to 9,200. As one would expect, the smallest values of

Table VI
Range of dimensionless parameters examined

	M1			
	BP1	BP2	BP3	BP4
Gr_m	23.1–314	23.1–285	24.7–273	19.9–267
N_d	0.880	0.910	0.851	0.928
N_{gm}	0.411	0.411	0.411	0.411
Fr	6.00×10^{-5} –2.74×10^{-4}	2.64×10^{-4} –1.12×10^{-5}	2.62×10^{-5} –1.25×10^{-4}	1.23×10^{-3} –5.74×10^{-3}
Fr_m	2.47×10^{-5} –1.13×10^{-4}	1.09×10^{-4} –4.61×10^{-4}	1.08×10^{-5} –5.14×10^{-5}	5.06×10^{-4} –2.36×10^{-3}
Re	0.0256–0.188	0.0522–0.361	0.0170–0.117	0.111–0.750
	M2			
	BP1	BP2	BP3	BP4
Gr_m	97.6–1274	89.6–1212	100–1519	83.8–1388
N_d	0.785	0.838	0.732	0.870
N_{gm}	0.110	0.110	0.110	0.110
Fr	7.06×10^{-5} –2.95×10^{-4}	2.86×10^{-4} –1.08×10^{-3}	2.92×10^{-5} –1.22×10^{-4}	1.57×10^{-3} –5.80×10^{-3}
Fr_m	7.79×10^{-6} –3.25×10^{-5}	3.16×10^{-5} –1.19×10^{-4}	3.23×10^{-6} –1.35×10^{-5}	1.73×10^{-4} –6.41×10^{-4}
Re	0.0288–0.204	0.0568–0.364	0.0185–0.139	0.124–0.926
	M3			
	BP1	BP2	BP3	BP4
Gr_m	240–6278	240–9200	216–5892	263–7257
N_d	0.642	0.730	0.553	0.783
N_{gm}	0.050	0.050	0.050	0.050
Fr	7.48×10^{-5} –3.66×10^{-4}	3.20×10^{-4} –1.37×10^{-3}	2.89×10^{-5} –1.41×10^{-4}	1.91×10^{-3} –6.78×10^{-3}
Fr_m	3.72×10^{-6} –1.82×10^{-5}	1.59×10^{-6} –6.82×10^{-5}	1.43×10^{-6} –7.02×10^{-6}	9.51×10^{-5} –3.37×10^{-4}
Re	0.0320–0.327	0.0688–0.773	0.0190–0.202	0.159–1.53

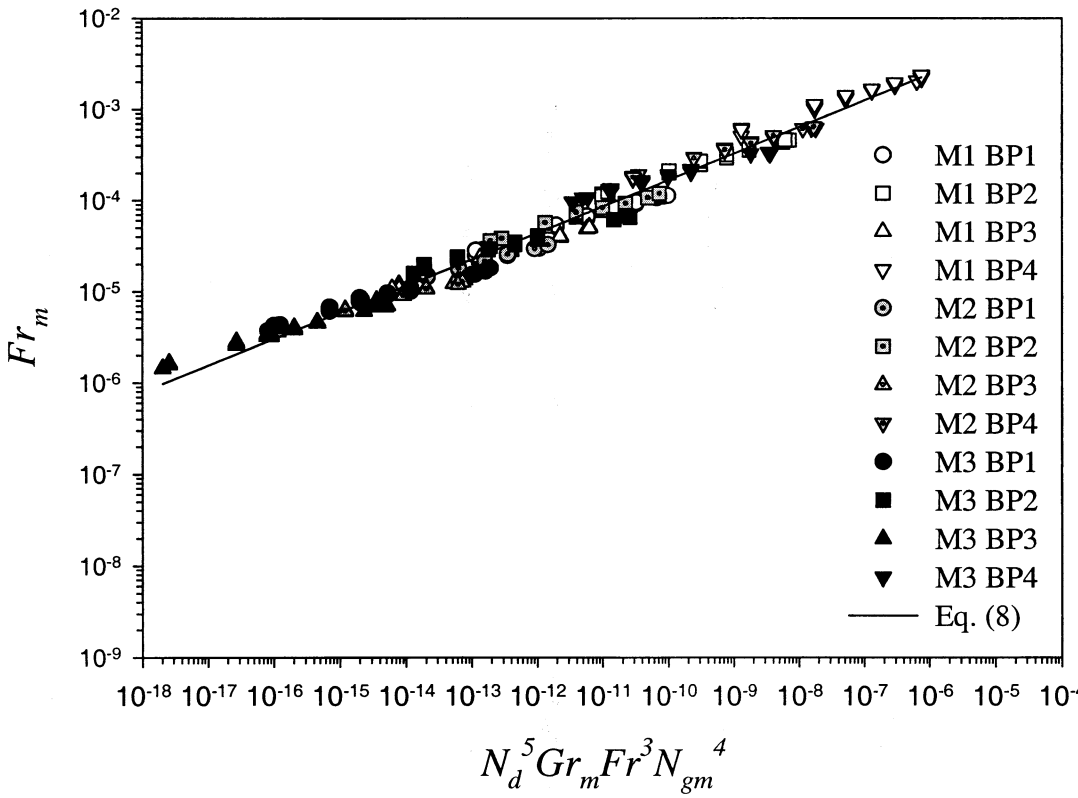

Fig. 4. An empirical correlation of the dimensionless flame height in the presence of a non-uniform upward decreasing magnetic field.

the magnetic Grashof number correspond to the M1 magnetic field configuration and the largest values correspond to the M3 configuration. According to Fujita et al. [20], magnetically induced flows should begin to have an impact for the M2 and M3 magnetic field configurations and this was experimentally observed. Given that, in the absence of a magnetic field, the flame would be considered buoyancy-controlled, the range of the ratio of gravitational to magnetic body forces is of considerable importance when examining flame behavior. As can be seen from the table, N_{gm} ranges from a value of 0.050 to a value of 0.411. An examination of Fr_m, Gr_m, and N_{gm} shows that the flames examined in this study span a range over which the flames transition from buoyancy-controlled to magnetic field-controlled. As one would expect, for jet diffusion flames in the presence of both a non-uniform upward decreasing magnetic field and a terrestrial gravitational field, an examination of more than just one of the previously defined dimensionless parameters is needed to fully characterize the regimes associated with the experimentally observed flame behavior.

While previous magnetocombustion research has provided a wealth of information regarding magnetic field interactions, models have yet to be developed for predicting fundamental diffusion flame parameters such as flame height. Figure 4 provides a plot of the experimentally observed flame height data cast in terms of the dimensionless parameters discussed above. As can be seen from the plot, the experimental data collapsed to a single curve using the dimensionless groups identified on the plot. A power law curve fit was used to obtain the following empirical correlation for flame height in the presence of a non-uniform upward decreasing magnetic field

$$Fr_m = 0.1346X^{0.2906} \tag{8}$$

where $X = N_d^5 Gr_m Fr^3 N_{gm}^4$. The coefficient of determination for the power law curve fit was calculated to be 0.9816. The dimensionless group on the right hand side of Eq. (8) includes the effect of magnetically induced buoyancy, gravitationally induced buoyancy, diffusion, and inertia as well as the effects associated with the physical presence of the prisms. Note that despite the fact that the individual dimensionless parameters contain the flame height in their respective definitions, the right hand side of the Eq. (8) is not a function of the flame height. Note also that in Eq. (8) the product of the Froude number cubed and the ratio of the gravitational to magnetically induced body force parameter raised to the fourth power is, as a group, functionally raised to approximately the 0.29 power. Recall that for buoyancy-controlled flames, the flame height is proportional to the gravitational acceleration raised to the $-1/3$ power as predicted by Roper [24,25]. Whether this indicates that the interaction between the magnetically and gravitationally induced flows change the functional dependence of flame height with respect to the gravitational acceleration is not clear. This difference could indicate more a more complex interaction or it could be an artifact of the assumptions with regard to the baseline parameters. From Eq. (8) it can be seen that as the magnitude of the magnetic body force increases, the height of the flame decreases and that as that magnitude of the buoyancy force increases, the height of the flame increases. This behavior is consistent with previously reported flame behavior in upward decreasing magnetic fields.

6. Conclusions

This study has examined the behavior of a slotted diffusion flame in the presence of an upward decreasing magnetic field. Based upon the results of this investigation, the following conclusions have been drawn:

1. When the product of the magnetic induction times the gradient of the magnetic induction is of sufficient magnitude, a non-uniform upward decreasing magnetic field was observed to have a significant impact on laminar diffusion flame behavior. For these conditions, relative to flames with no applied magnetic field, flames were observed to both decrease in height and increase in intensity. It was also observed that the flames did not attach to the prisms under these conditions while flames with no applied magnetic field did attach to the prisms. This behavior was consistent with previously published results.
2. In addition to the previously defined magnetic Grashof number, the magnetic Froude number, and the ratio of the magnetic Froude number to the traditionally defined Froude number were identified as dimensionless parameters that can be used to define regimes where non-uniform magnetic fields impact flame behavior. The experimentally observed behavior was in general agreement with the behavior expected when considering the magnitude of the dimensionless parameters defined in this study.
3. The average flow rate for which the visible soot inception point decreased and the average flow rate corresponding to the near extinction point increased relative to the flames with no applied magnetic fields for conditions where the non-uniform upward decreasing magnetic field impacted diffusion flame behavior. This behavior was explained by considering the impact a non-uniform upward decreasing magnetic field has on the physical transport behavior of the gases near the flame.
4. The experimental data was cast in terms of the appropriate dimensionless groups and was found to exhibit universal behavior for the conditions examined during the course of this investigation. A curve fit of the data provides an empirical correlation that can be used to predict flame height in a non-uniform upward decreasing magnetic field.

Acknowledgments

This study was supported by the NASA Microgravity Combustion Program (Grant No. NAG3-2560). The authors thank Dr. R. Vander Wal (NASA technical monitor) and Professor K. Saito for their assistance with this project.

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