MODELS AND EXPERIMENTS OF LAMINAR DIFFUSION FLAMES IN NON-UNIFORM MAGNETIC FIELDS

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INTRODUCTION

Non-uniform magnetic fields affect laminar diffusion flames as a result of the paramagnetic and diamagnetic properties of the products and reactants. Paramagnetism is the weak attraction to a magnetic field a material exhibits as a result of permanent magnetic dipole moments in the atoms of the material. Diamagnetism is the weak repulsion to a magnetic field exhibited by a material due to the lack of permanent magnetic dipole moments in the atoms of a material. The forces associated with paramagnetic and diamagnetism are several orders of magnitude less than the forces associated with the more familiar ferromagnetism. A typical example of a paramagnetic gas is oxygen while hydrocarbon fuels and products of combustion are almost always diamagnetic. The fact that magnets can affect flame behavior has been recognized for more than one hundred years. Early speculation was that such behavior was due to the magnetic interaction with the ionized gases associated with a flame. Using a scaling analysis, it was later shown that for laminar diffusion flames the magnetic field/ionized gas interaction was insignificant to the paramagnetic and diamagnetic influences.

In this effort, the focus has been on examining laminar diffusion slot flames in the presence of non-uniform upward decreasing magnetic fields produced using permanent magnets. The principal reason for choosing slot flames was mathematical models of such flames show an explicit dependence on gravitational body forces, in the buoyancy-controlled regime, and an applied magnetic field would also impose a body force. In addition, the behavior of such flames was more easily visualized while maintaining the symmetry of the two-dimensional problem whereas it would have been impossible to obtain a symmetric magnetic field around a circular flame and still visually record the flame height and shape along the burner axis. The motivation for choosing permanent magnets to produce the magnetic fields was the assumption that space-related technologies based on the knowledge gained during this investigation would more likely involve permanent magnets as opposed to electromagnets. While no analysis has been done here to quantify the impact that an electric field, associated with an electromagnetic, would have relative to the paramagnetic and diamagnetic interactions, by using permanent magnets this potential effect was completely eliminated and thus paramagnetic and diamagnetic effects were isolated.

MATHEMATICAL MODELING RESULTS

A modification of Roper's slot flame model [1] was used to develop an expression for the magnetically controlled flame height. To include the influence of a non-uniform magnetic field in Roper's formulation, the expression for the axial velocity must be modified. Assuming a magnetic field that is a linear function of the distance above the burner port, the expression for the axial velocity, v_z, is

$$v_z^2 = v_{fO}\left(1 + \frac{2}{Fr}\frac{z}{L_f} + \frac{1}{Fr_m}\left(\frac{\Delta B}{B_o}\right)\frac{z^2}{L_f^2} + \frac{1}{Fr_m}\frac{z}{L_f}\right)^{1/2} \tag{1}$$

where v_{fO} is the initial speed of the fuel leaving the burner, z is the distance above the burner exit, L_f is the flame height, and $\Delta B / B_o$ is the change in the magnetic induction along the length of the flame divided by the initial magnetic induction at the burner exit. In addition, definitions of the Froude number and the magnetic Froude number used in the above expression may be found in a recent paper by Baker and Calvert [2]. For a magnetically controlled flame, the first two terms in the above expression may be dropped. The resulting expression for the magnetically-controlled flame height requires the solution to a nonlinear algebraic equation. Under the assumption that $\Delta B / B_o \ll 1$, a closed form solution is possible. As one would expect, this expression for a flame in the magnetically-controlled regime is similar to Roper's expression for a buoyancy-controlled flame, with the forces associated with gravity replaced by the forces associated with the magnetic field. While the closed form expression does provide insight into the fundamental relationships between the various dimensionless parameters, the associated assumption regarding the shape of the magnetic field does limit its practical value. At the time of writing, flame height information has been generated using solutions to the full nonlinear equation and a mathematical model for magnetically-controlled flame shape is been developed.

EXPERIMENTAL METHODS AND RESULTS

The initial experimental component of the Magnetically-Assisted Combustion Experiment (MACE) program examined, in a laboratory environment, the behavior of very small diffusion flames not exposed to an applied magnetic field [3]. The reason for this was that such flames, while in the buoyancy-controlled regime as defined by Roper, exhibit behavior qualitatively similar to microgravity flames. A scaling analysis conducted as part of this investigation provided insight into the role axial diffusion plays in determining slot flame height for these micro-flames and showed that micro-flames were not dynamically similar to microgravity flames. The initial microgravity results for slot flames with no applied magnetic fields were obtained through participation in the NASA Reduced Gravity Student Flight Opportunities Program. Examining laminar slot diffusion flames in both reduced gravity and in elevated gravity showed the Roper's expression for buoyancy-controlled flame height did, in fact, predict the flame heights for the conditions examined [4]. These initial investigations have laid the groundwork for the reduced gravity experiments involving laminar diffusion flames in non-uniform magnetic fields that are to be conducted in July 2003.

In parallel to the above investigations, a laboratory-based investigation of laminar diffusion flames in the presence of non-uniform upward decreasing magnetic fields has been conducted and experimental correlations of flame behavior have been developed [2,5]. This component of the MACE program also provided information as to the appropriate dimensionless parameters for a study of the impact magnetic fields have on diffusion flame behavior. During the past year, a holographic interferometer has been used to examine the temperature field in the vicinity of the flames exposed to non-uniform magnetic fields. Figure 1 provides a schematic diagram of the

holographic interferometry test cell. The two-exposure holographic interferometry technique provides images showing fringe patters that are directly related to temperature variations. For the present study, these fringe patters are only qualitative in nature due to the fact that the exact spatial concentration distribution of the product and reactant species is not known. This technique does provide qualitative information, however. Figure 2 shows sample results of optical flame images, holographic interferograms, and the temperature fields produced using the holographic interferograms. A preliminary examination of the holographic interferometry data indicated that that application of a non-uniform upward decreasing magnetic field decreased the maximum flame temperature with only a few exceptions [6]. This was somewhat unexpected as previous researchers have generally reported an increase in flame temperature, although there have been reports of investigations where the flame temperature decreased with the application of a non-uniform magnetic field. The exact reason for this unexpected behavior has yet to be resolved. It could be possible that, as a result of the geometric configuration of the magnetic prisms, a magnetic curtain was formed reducing the amount of oxygen available to the flame. Note also that the variation in the magnetic field was accomplished by moving the prisms in or out relative to the burner. The close proximity of the prisms would serve as a heat sink and thus could also be responsible for the observed temperature decreases. Additional investigation into this behavior is on-going.

CONCLUSIONS

The Magnetically-Assisted Combustion Experiment (MACE) program is examining the fundamental interaction between non-uniform magnetic fields and laminar diffusion flames. Both mathematical and experimental models have been constructed as part of the investigation thus far. Holographic interferometry has been used to examine the temperature field in the vicinity of the flame and has produced some unexpected results. Reduced gravity data has provided insight into the behavior of laminar slot flames when no magnetic field is applied and this information is being used to guide upcoming reduced gravity experiments involving an applied non-uniform magnetic field.

ACKNOWLEDGEMENTS

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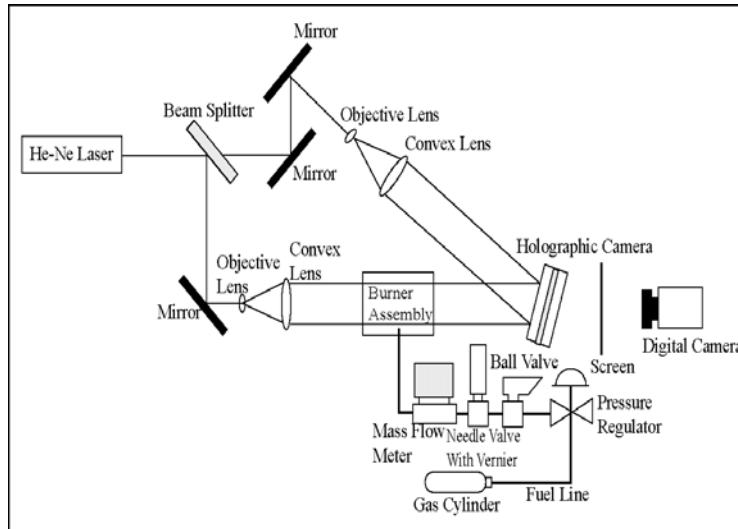
Figure 1: A shematic diagram of the holographic interferometer test cell.

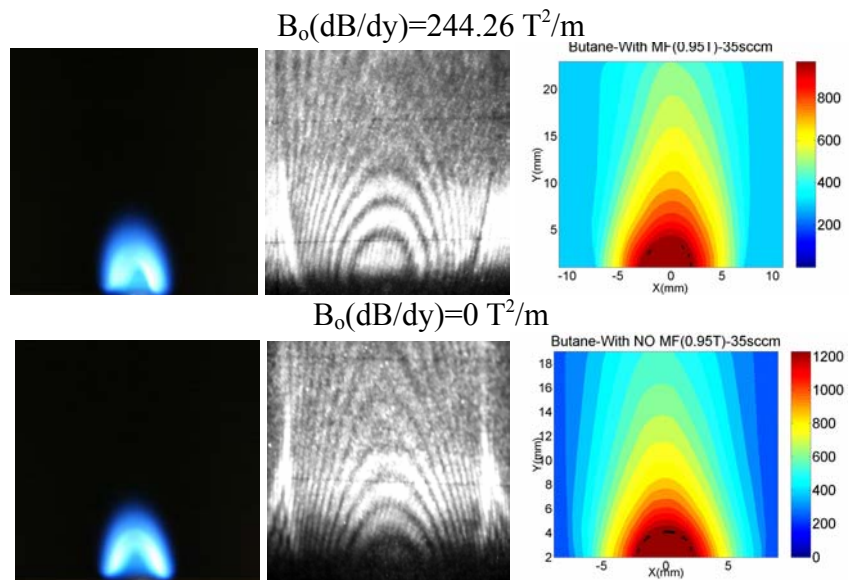$B_o(dB/dy) = 244.26$ T^2/m

$B_o(dB/dy) = 0$ T^2/m

Figure 2: Sample butane flame data obtained from (left to right) : visual images, holographic interferograms, and temperature contours. The flow rate for both cases is 35 cm^3/min.