HOLOGRAPHIC INTERFEROMETRY AND LAMINAR JET DIFFUSION FLAMES IN THE PRESENCE OF NON-UNIFORM MAGNETIC FIELDS

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INTRODUCTION

Magnetic fields impact combustion processes in a manner analogous to that of buoyancy i.e., as a body force. It is well known that in a terrestrial environment buoyancy is one of the principal transport mechanisms associated with diffusion flame behavior. Unfortunately, in a terrestrial environment it is difficult if not impossible to isolate flame behavior due magnetic fields from the behavior associated with buoyancy. A micro-, or reduced, gravity environment is ideally suited for studying the impact of magnetic fields on diffusion flames due to the decreased impact of buoyancy on flame behavior.

For over one hundred years now it has been recognized that magnetic fields can be used to affect the behavior of diffusion flames [1]. While early efforts considered this interaction to be due to the interaction between magnetic fields and ions in the flame, it is now accepted that the principal interaction is due to the paramagnetic and diamagnetic behavior of the constituent gases [2]. Atoms with no permanent magnetic dipole moment exhibit diamagnetic behavior i.e., the interaction between the atomic magnetic dipole moments within an atom results in a zero net magnetic dipole moment. When a magnetic field is applied, the orbital behavior of the electrons is changed such that a net magnetic dipole moment exists. As a result of Lenz' law, the resulting net dipole moment opposes the applied field and thus a diamagnetic materials exhibits a weak repulsion to an applied magnetic field. Note that diamagnetic behavior is present in all materials but is weak compared to paramagnetic behavior. Materials such as oxygen, whose atoms possess permanent magnetic dipole moments, exhibit paramagnetic behavior. For paramagnetic materials, the magnetic dipole moments are randomly oriented when not in the presence of a magnetic field. When a magnetic field is applied, the dipoles line up with the magnetic field and thus a weak attraction to an applied magnetic field is produced. This attraction must compete with the randomizing effect of thermal motion. The magnetic susceptibility, χ, defined as the ratio of the magnetization vector to the magnetic field strength, for a paramagnetic gas is given by the Curie-Weiss law. The Curie-Weiss law is $\chi = C/(T-\theta)$ where C and θ are material dependent constants and T is the temperature. For a diamagnetic gas, the susceptibility is independent of temperature. The magnetic susceptibility is $O(10^{-6})$ and $O(-10^{-9})$ for paramagnetic and diamagnetic gases, respectively. The force per unit volume, F, exerted on a paramagnetic or diamagnetic gas by the applied magnetic field is

$$F = \mu_o \chi H \frac{\partial H}{\partial z} \tag{1}$$

where μ_o is the permeability of free space and H is the magnetic field strength. An order of magnitude analysis shows that, under certain conditions, the forces associated with an applied magnetic field can be comparable to those associated with buoyancy [3].

The purpose of this investigation is to better understand the behavior of laminar diffusion flames in the presence of non-uniform magnetic fields and the impact that paramagnetism and diamagnetism have with regard to transport phenomena in the vicinity of such flames. This will be accomplished by experimentally observing, in an environment where buoyant forces are negligible, the effect of non-uniform magnetic fields on diffusion flame characteristics and on the associated temperature fields. A significant aspect of the experimental effort is the development of holographic interferometry as a microgravity combustion diagnostics tool.

MAGNETOCOMBUSTION

From a thermodynamic point of view, early work involving chemical reactions and magnetic fields predicted that prohibitively large magnetic field strengths would be required to produce a significant interaction [4,5]. These conclusions were based upon order-of-magnitude estimates and did not account for the highly nonlinear nature of chemical reactions. Recently there has been a renewed effort to develop the equations needed to analyze the thermodynamic interaction between chemical reactions and magnetic fields [6-9]. Using a chemical equilibrium model that included a magnetic field contribution, Baker and Saito [10] were able to show that a uniform magnetic field can affect equilibrium combustion behavior at extremely elevated temperatures. In prior experimental investigations of magnetocombustion behavior, the temperature of the flames has not been large enough to produce a significant magnetic field interaction for uniform magnetic fields. Non-uniform fields have been shown to produce significant magnetic field/flame interaction for several cases [11-24].

HOLOGRAPHIC INTERFEROMETRY

Holographic interferometry (HI) is non-intrusive visualization technique that can be used to detect changes in velocity, density, temperature, or species concentration. HI has already been successfully used to examine combustion behavior and a few of the papers involving HI are presented in the Reference section of this paper [25-28]. HI possesses several desirable characteristics that make it ideally suited to micro-, or reduced, gravity combustion research. Because HI measures only relative changes in the object wave, high quality optics such as those used in traditional interferometry are not needed thus decreasing the cost of the experimental apparatus. Holographic interferometry also does not have the power requirements of techniques such as laser-induced fluorescence. For the investigation discussed here, holographic interferometry measurements will use the fact that the refractive index of a gas is temperature dependent. Once a relation between the refractive index and the temperature is developed, the temperature at any given location near the flame can be determined by examining the fringe pattern in relation to a point of known temperature. The difficulty in obtaining quantitative temperature measurements of magnetocombustion phenomena is that the system does not consist of a homogeneous mixture of gases. In the planned effort, holographic interferometry will be used to qualitatively examine the temperature distribution of the gases surrounding the flame.

TECHNICAL APPROACH

An experimental test cell is being built that will be capable of producing both optical images and holographic interferograms of laminar jet diffusion flames in the presence of non-uniform magnetic fields. At the time of writing, the holographic interferometer is being constructed. Optical images have been obtained of slot diffusion flames and this data has been used to examine the impact of non-uniform magnetic fields on laminar flame height. Figure 1 is an example of the typical results obtained during the initial investigation. Note that the flames produced during this initial investigation have inner burner port widths of $O(0.5mm)$. A non-uniform magnetic field was produced using cast iron prisms attached to a neodymium iron boron (NdFeB) magnet. For the current experimental configuration, a maximum magnetic induction of 1.00 Tesla and a maximum magnetic induction gradient of approximately 100 Tesla/m was used. When such a non-uniform magnetic field was applied to the diffusion flame; the flame does not attach to the wall, the flame height was decreased, and the sooting characteristics of the flame were changed.

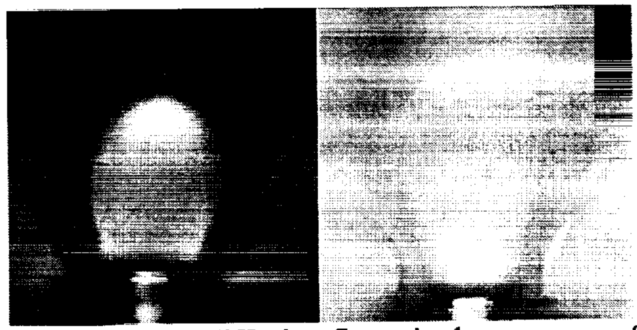

Figure 1: Slot diffusion flame in the presence of a magnetic field (left) and with no applied magnetic field (right).

Once the holographic interferometer is fully operational, temperature data will be gathered in the vicinity of the flame both with and without an applied magnetic field. The temperature data will be examined to determine if oxygen is being concentrated in the vicinity of the flame. As one would expect, if oxygen is being concentrated in the vicinity of the flame, the flame temperature will increase. After the data from the terrestrial investigation has been fully analyzed, a test cell will be designed for use in a reduced-gravity carrier. As with the terrestrial investigation, the reduced-gravity test cell will employ both holographic interferometry and optical images. The reduced-gravity investigation will examine the behavior of laminar jet diffusion flames as a function of the type of fuel, the fuel flow rate, the burner port geometry, peak magnetic field strength, and the magnetic field gradient. Empirical correlations will be developed for flame height as a function of the above-mentioned variables and these correlations will be compared to mathematical models of magnetocombustion behavior. The effectiveness of holographic interferometry as a microgravity combustion diagnostic tool will also be evaluated. If the results of this investigation show that holographic interferometry is a viable tool for microgravity combustion research, a preliminary effort will be undertaken to examine the use of holographic interferometry for species measurements in a reduced gravity. Such quantitative information would significantly enhance magnetocombustion research as well as microgravity combustion research in general.

CONCLUDING REMARKS

Magnetic fields are known to affect combustion behavior and in a terrestrial environment buoyancy effects cannot be fully isolated from the effects of magnetic fields. Initial results indicate that non-uniform magnetic fields produced using permanent magnets do change diffusion flame characteristics even in a terrestrial gravitational field. The planned investigation will attempt to isolate magnetic field effects by examining the behavior in a reduced gravity environment. Holographic interferometry will be used to examine temperature behavior in the vicinity of the flames. Examining the temperature field is important because it is believed that magnetic fields can be used as a means of achieving an oxygen-enhanced combustion environment. For the flames being considered, oxygen is the only major constituent gas that is paramagnetic. Recall that paramagnetic gases are attracted to a magnetic field. For specific magnetic field configurations, it should be possible to concentrate oxygen in the vicinity of the flame. Oxygen-enhanced combustion has many desirable characteristics. For example, oxygen-enhanced combustion is known to produce increased flame temperatures, flammability limits, thermal efficiency, and flame stability. This list is only a partial listing of the effects of increased oxygen concentration on combustion. The potential for the development of oxygen-enhanced combustion technologies through the use of magnetic fields is one of the primary motivating factors of this investigation.

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