AN EXPERIMENTAL AND THEORETICAL STUDY OF RADIATIVE EXTINCTION OF DIFFUSION FLAMES

N93-20191

Arvind Atreya, Indrek Wichman, Mark Guenther,
Anjan Ray, and Sanjay Agrawal
Department of Mechanical Engineering
Michigan State University
East Lansing, Michigan 48824

INTRODUCTION

In a recent paper on "Observations of candle flames under various atmospheres in microgravity" by Ross et al. (ref. 1), it was found that for the same atmosphere, the burning rate per unit wick surface area and the flame temperature were considerably reduced in microgravity as compared with normal gravity. Also, the flame (spherical in microgravity) was much thicker and further removed from the wick. It thus appears that the flame becomes "weaker" in microgravity due to the absence of buoyancy generated flow which serves to transport the oxidizer to the combustion zone and remove the hot combustion products from it. The buoyant flow, which may be characterized by the strain rate, assists the diffusion process to execute these essential functions for the survival of the flame. Thus, the diffusion flame is "weak" at very low strain rates and as the strain rate increases the flame is initially "strengthened" and eventually it may be "blown out". The computed flammability boundaries of T'ien (ref. 2) show that such a reversal in material flammability occurs at strain rates around 5 sec^{-1}.

At very low or zero strain rates, flame radiation is expected to considerably affect this "weak" diffusion flame because: (i) the concentration of combustion products which participate in gas radiation is high in the flame zone, and (ii) low strain rates provide sufficient residence time for substantial amounts of soot to form which is usually responsible for a major portion of the radiative heat loss. We anticipate that flame radiation will eventually extinguish this flame. Thus, the objective of this project is to perform an experimental and theoretical investigation of radiation-induced extinction of diffusion flames under microgravity conditions. This is important for spacecraft fire safety.

PROJECT DESCRIPTION:

For the experimental and theoretical investigation of radiation-induced extinction two simple geometries are chosen: [Note: this project started in April 1991]

(i) *A spherical diffusion flame supported by a low heat capacity porous gas burner*: This is considered suitable for the μg experiments and modeling because all the soot formed is trapped between the burner and the high temperature reaction zone. Here, flame radiation will be enhanced by soot oxidation which will occur as soot crosses the high temperature reaction zone. To examine the radiative extinction limit, the following parameters will be varied: (i) Fuel type (chemical structure) and concentration; (ii) Ambient oxygen concentration; (iii) Fuel injection velocity; (iv) Ambient pressure. Temperature and radiation measurements made under these conditions will then enable us to understand the radiative extinction phenomenon. These experiments will soon begin in the NASA Lewis 2.2 sec μg drop tower. A schematic of the test apparatus for these experiments is shown in Figure 1a and 1b.

(ii) *An axis-symmetric low strain rate counterflow diffusion flame:* This geometry is adopted for the ground-based experiments and modeling because it provides a constant strain rate flow field which is one-dimensional in temperature and species concentrations. The strain rate is directly related to the imposed flow velocity and the one-dimensionality of this flame simplifies experimental measurements and analysis. Also, there are no solid boundaries which may quench the flame prior to extinction caused by low or high strain rates. Experiments on counterflow diffusion flames are currently being performed to determine the soot particle formation and oxidation rates. Two types of flames are being investigated: (a) A low strain rate diffusion flame which lies on the oxidizer side of the stagnation plane. Here, as shown in Figures 2a and 2b, all the soot produced is convected away from the flame toward the stagnation plane. (b) A low strain rate diffusion flame which lies on the fuel side of the stagnation plane. Here, as shown in Figures 3a and 3b, all the soot produced is convected into the diffusion flame. This enhances flame radiation as the soot is oxidized. This geometry is especially relevant to the μg experiments described above. The results of the ground-based experiments are being used in a transient model to predict the radiative extinction limit and the conditions under which it occurs.

PROGRESS TO DATE

Although this project started in April 1991, we have made considerable progress on the following items:

μg experiments: The test apparatus has been designed to produce a spherical diffusion flame using a low heat capacity spherical burner constructed from porous alumina. A schematic of this apparatus is shown in Figure 1a. It consists of a drop frame that contains the test chamber, ignition system, batteries, electrical control system, and high-speed motion-picture camera. The diffusion flame is supported by the burner inside a cylindrical test chamber. This test chamber can be evacuated and filled with any desired gas mixture from below atmospheric pressure to 5 atm. A 5" clear lexan window enables the camera to photograph the spherical diffusion flame. The fuel flow system, shown in Figure 1b, consists of a fuel supply line from the gas cylinder that is controlled by a metering valve and turned on and off with a solenoid valve. The porous, spherical burner and other drop rig apparatus components have been successfully tested in normal gravity conditions. Microgravity testing will begin early in September and will continue through December of 1994.

1-g experiments: The supporting ground-based experiments have already started. Figures 2(a,b) and 3(a,b) show the two types of flames being investigated. Since the flame on the fuel side of the stagnation plane is directly related to the spherical microgravity flame, it is being investigated first. Figure 4 shows the measured soot volume fraction and the temperature distribution inside this flame. The fuel and oxidizer concentrations and the strain rate for this flame are 22.9%, 32.6% and 8 sec^{-1} respectively. Figure 5 shows the measured concentrations of stable gases inside this flame. It is extremely interesting to note that only CO and H_2 exist after the luminous flame zone. These are later burned in the blue flame above the luminous flame. Also, the CO concentration is greater than 2% and is substantially larger than the corresponding flame on the oxidizer side of the stagnation plane. This may be an important source of CO in building fires.

Theoretical investigation: To investigate the extinction limits of diffusion flames, the work of Linan (ref. 3 & 4) was reviewed and the simple case of a one-dimensional, diffusion flame with flame radiation is being examined. This model corresponds to the ground-based experiments described above. As a first step we have assumed zero gravity, no convection, constant properties, one-step irreversible reaction and unity Lewis number. These equations are being numerically integrated to examine the conditions under which radiation-induced extinction occurs. The soot formation and oxidation rates will be obtained from the counterflow diffusion flame experiments.

FUTURE PLANS

In the near future we plan to focus our attention on the following items:

1. Perform microgravity experiments on spherical diffusion flames for different fuels and under various atmospheres.

2. Continue our work on supporting ground-based experiments at low strain rates to quantify soot formation and oxidation rates and flame radiation for the same fuels and atmospheres used in the μg experiments.

3. Complete our theoretical model for zero strain rate (no flow) flames in microgravity and identify conditions under which radiation-induced extinction occurs.

4. To analyze the experimental results and develop an appropriate theoretical model for spherical diffusion flames with flame radiation.

REFERENCES

1. *Ross, H. D., Sotos, R. G. and T'ien, J. S.*, Combustion Science and Technology, Vol. 75, pp. 155-160, 1991.
2. *T'ien, J. S.*, Combustion and Flame, Vol. 80, pp. 355-357, 1990.
3. *Linan, A.*, Acta Astronautica, Vol. 1, pp. 1007-1039, 1974.
4. *Linan, A., Crespo, A.*, Combustion Science and Technology, Vol. 14, pp. 95-117.

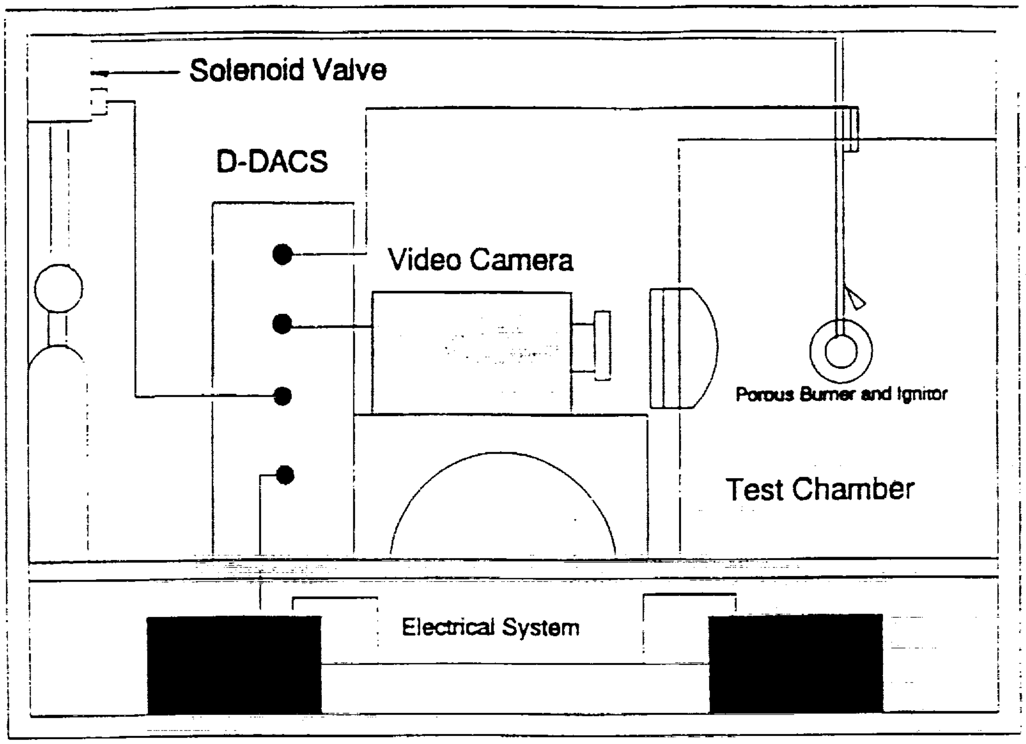

Fig. 1a. Drop Rig Apparatus

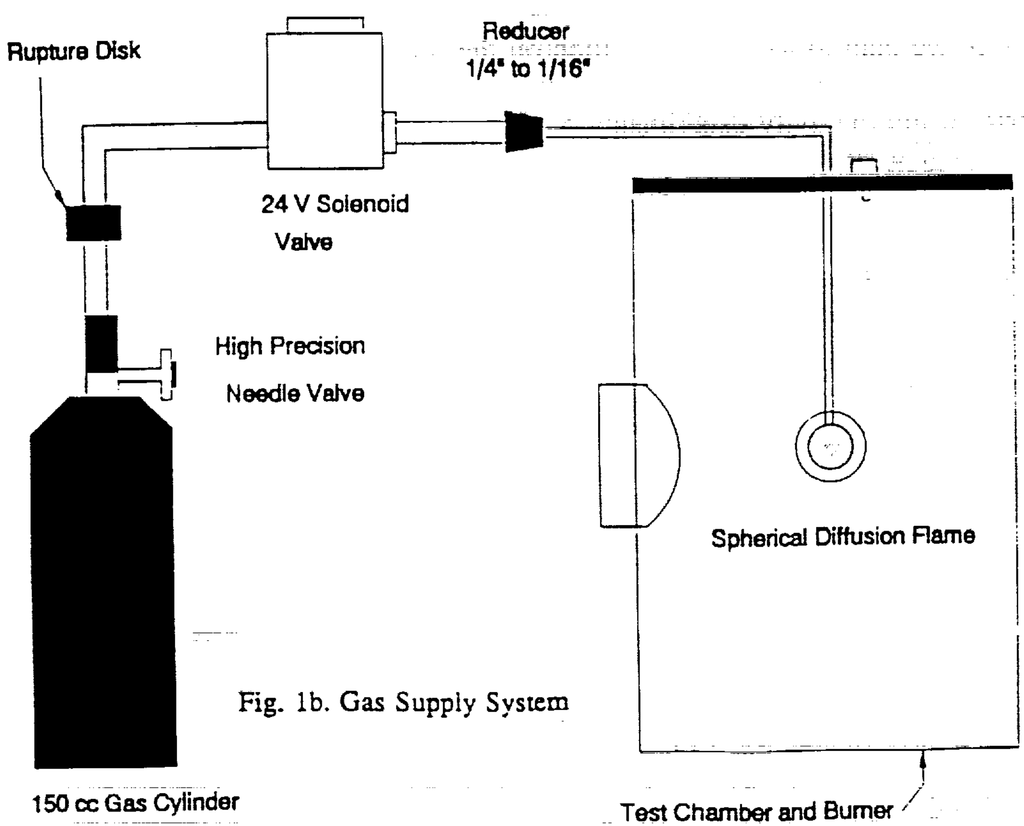

Fig. 1b. Gas Supply System

Fig. 1a. and 1b. Microgravity spherical diffusion flame apparatus for 2.2 second drop tower.

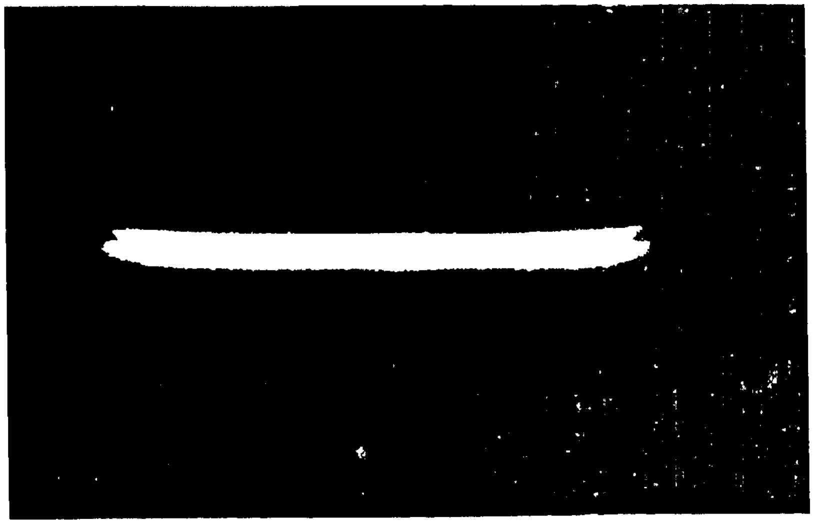

Fig. 2a. Low strain rate, sooty counterflow diffusion flame on the oxidizer side of the stagnation plane

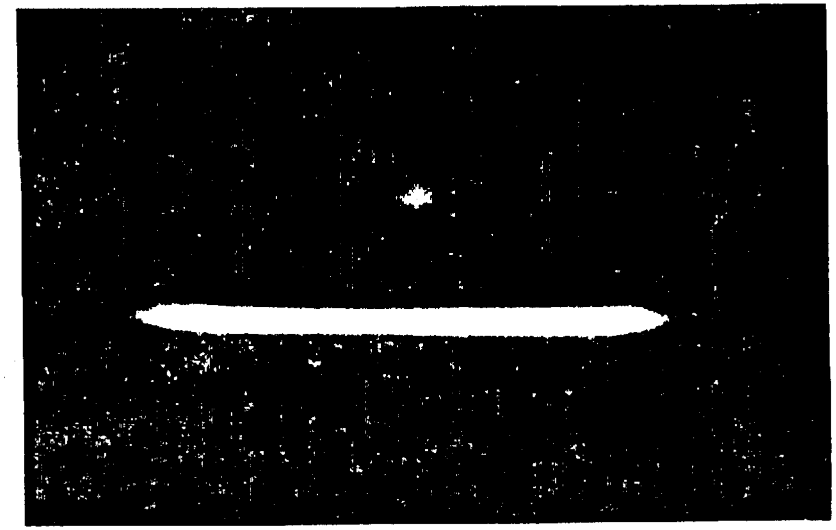

Fig. 2b. Same as Fig. 2a. The $TiCl_4$ streak shows the location of the stagnation plane

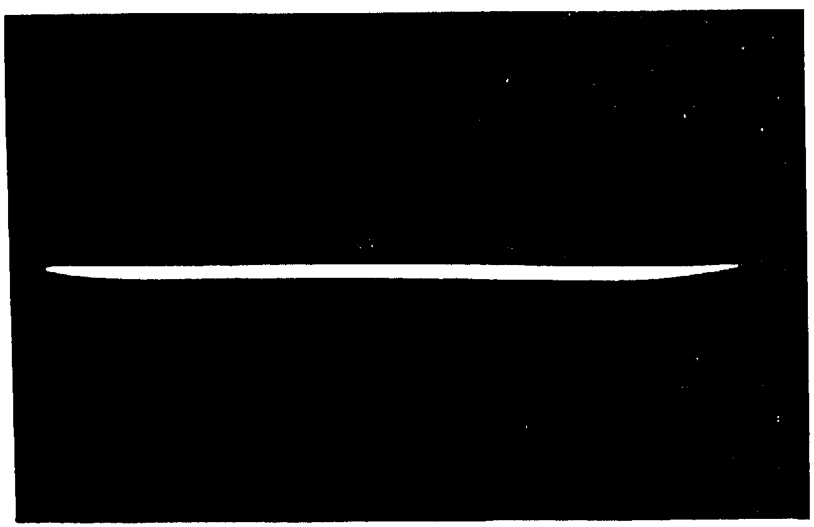

Fig. 3a. Low strain rate, sooty counterflow diffusion flame on the fuel side of the stagnation plane

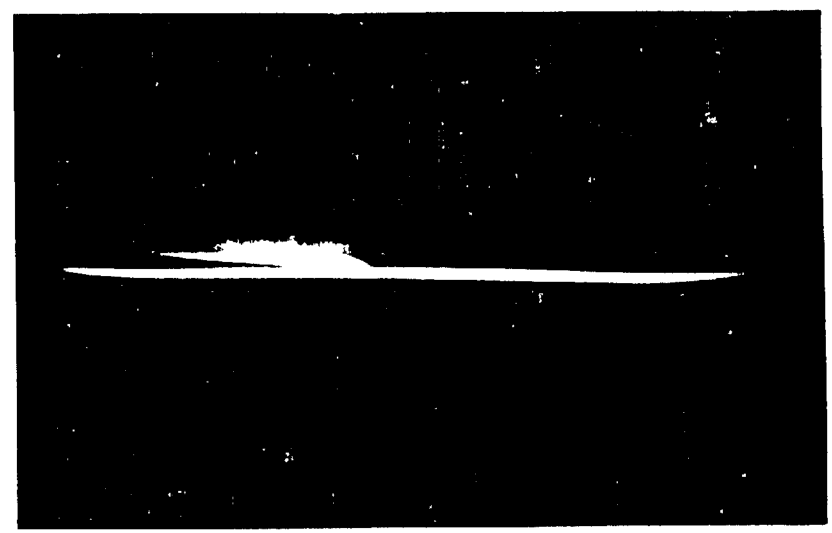

Fig. 3b. Same as Fig. 3a. The $TiCl_4$ streak shows the location of the stagnation plane

See Color Plate C3

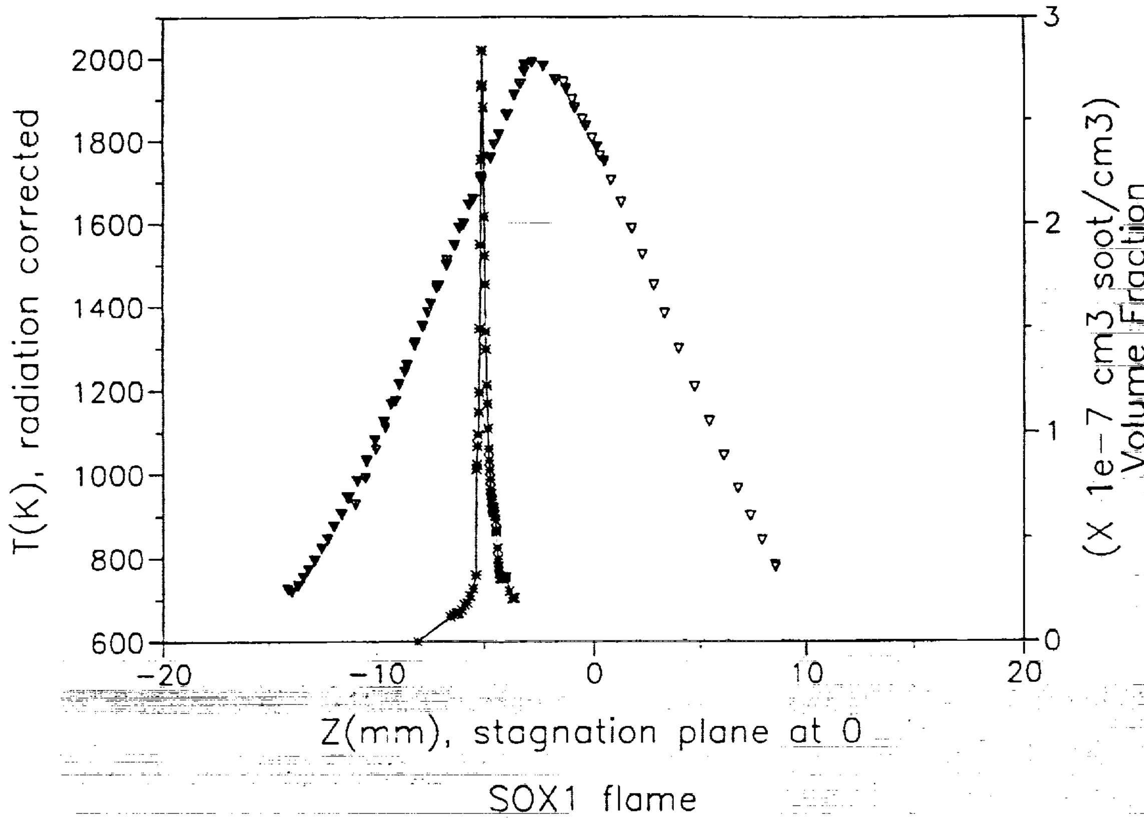

Fig. 4. Soot Particle Volume Fraction and Temperature Profile

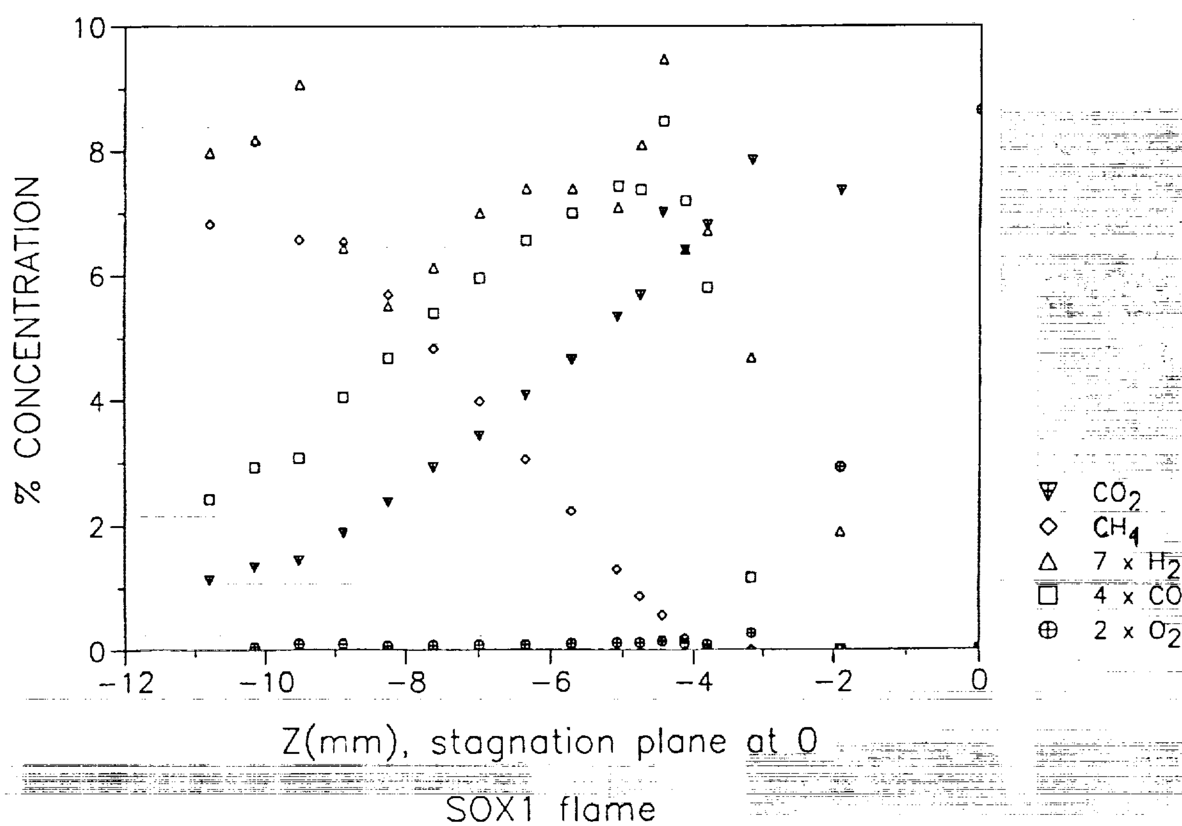

Fig. 5. Concentration Profiles of Stable Gases