

STRUCTURE AND STABILITY OF BURKE-SCHUMANN DIFFUSION FLAMES*

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Introduction

The general goal of this NASA Grant, NAG3-1592, is twofold: to improve our understanding of (1) the influence of buoyancy on the stability and structure of Burke-Schumann type diffusion flames, and (2) the effects of buoyancy on vortex-flame interactions in co-flow diffusion flames. A numerical code with a higher order accuracy for spatial discretization is developed in this project for simulation of time-dependent diffusion flames by Sheu (ref. 1) and Sheu and Chen (ref. 2), and an extended reduced mechanism is incorporated for prediction of methane oxidation and NO_x (NO, NO₂, and N₂O) formation and emission from methane Burke-Schumann diffusion flame (BSDF) as reported in Sheu (ref. 1), and Sheu and Chen (ref. 3). Initial investigation of vortex and flame interaction within the context of fast chemistry is reported in (ref. 2). Experiments are conducted in reduced pressure to study the lift-off and stabilization of methane-fueled BSDF in reduced buoyancy environments due to reduced pressure (ref. 4). Measurements of temperature and species concentrations are made in normal and reduced pressure environments to study the effects of buoyancy on the structure of BSDF, and will be reported in this paper. To study the buoyancy effects on the lift-off and stabilization of methane-fueled jet diffusion flames in coflowing air, a glovebox investigation, Enclosed Laminar Flames (ELF), has been proposed and approved for space-based testing on the fourth United States Microgravity Payload (USMP-4) mission, scheduled for October 1997. A brief description of the ELF investigation is also presented.

Reduced Pressure Experiments

The reduced-pressure experiments are conducted in a vacuum chamber (Vacuum Atmospheres Model HE-133-5) as illustrated by Fig. 1. This vacuum chamber has an interior volume of 0.43 m³ (inside diameter of 0.76 m and horizontal length 0.91 m) and an antechamber of 0.044 m³. The chamber is rated to hold pressure down to 1.3×10^{-3} Pa, and has been used in an earlier experiment of Li and SF₆ wick combustion by Hsu and Chen (ref. 5). The vacuum chamber is fitted with (three) optical windows. A rectangular window of 0.46 x 0.23 m is used for photographic and video recording of the flame. The chamber is also fitted with sixteen service ports, including four electrical terminals. The service ports provide access for fuel and air supply, exhaust, gas sampling, and electrical channels for device control and data acquisition. A two-stage chemical vacuum pump (Alcatel model 2020CP) with a capacity of 7.6×10^{-3} m³/s is used for evacuation of the test chamber. A ballast chamber attached to the main vacuum chamber is used to help to keep the pressure constant during the experiments. The chamber pressure (the main, as well as, the ante-chambers) is monitored by a differential pressure transducer (Pennwalt Model 66-100), and two pressure gages (Wika, gauge pressure range of -100 to 200 kPa).

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A concentric burner similar to that used by Stocker (e.g., ref. 6) is placed vertically upward inside the vacuum chamber for measurements in reduced pressure environments. The technical grade methane (purity better than 97 %) is used as the fuel and room air as the oxidizer. The burner consists of two concentric tubes, a fuel tube and a surrounding Pyrex chimney shown by the expanded view of the burner in Fig. 1. The fuel tube is made of stainless steel tubing with an inside diameter of 2.4 or 4.8 mm, and length of 140 mm. The length-to-diameter ratio is 58 for the 2.4 mm tubing and 29 for the 4.8 mm, designed to provide a fully developed flow at the tube exit. The Pyrex chimney has an inside diameter of 44.5 mm and length of 203 mm, providing a ducted, co-flowing air surrounding the fuel jet. Air enters the burner from four radially positioned inlets near the base of the burner assembly, and passes through layers of fine glass beads (nominal diameter of 3 mm) and steel wool for flow conditioning. The fuel and air flow rates are regulated by pressure regulators and needle valves. In-line particle filters (Matheson, specified valve coefficient of 0.15) are installed immediately downstream of the pressure regulators. The fuel and air flowrates are measured by two mass flowmeters (Aalborg, Models AFM2600 and AFM4600). The mass flowmeters are calibrated using N_2 over the flow range 0 to 1.7×10^{-6} m³/s (0-100 ml/min) and 0 to 8.3×10^{-6} m³/s (0-500 ml/min). The specified accuracy is ± 2 percent of the full scale reading for temperature in the range 278 to 323 K and pressure 35 to 1030 kPa. A constant-temperature hot wire anemometer is used to cross check the velocities at the burner inlet.

Uncoated S-type (Pt-Pt/10%Rh) fine-wire thermocouples (wire diameter of 76 μ m) are used for temperature measurements. The thermocouple probe is mounted on a (stepping motor and computer controlled) micro-translational device with a specified resolution 320 μ m. The automated micro-translational device and data acquisition facilitate the usage of a scanning thermocouple probe in this study. Species concentrations are determined using a microprobe. The microprobe has a tapered sampling tip of 12 ± 5 mm in length, and an orifice diameter of 210 ± 20 μ m. This in-house made microprobe (by YGL) is carefully verified for choked flow condition before its usage in the flame measurements. The choked flow condition (probe pressure set in the range of 0.08 to 0.09 bar) is necessary for aerodynamic quenching to occur in the probe. The microprobe is mounted on the same micro-translational device for temperature measurements. Several gas analyzers are used to determine the species concentrations, for example, gas chromatography (Varian Model 3400 with TCD) for CH_4 , CO_2 , CO , N_2 , O_2 , Ar and H_2 , chemiluminescence (Thermo Electron Model 10) for NO , NO_2 and NO_x , and infrared (ir) (Infrared Industries, Inc.) for H_2O . The gas-sampling line (continuous flow) upstream of the ir analyzer is heated to prevent condensation of water vapor. An in-line water trap is used to prevent water vapor to enter the chemiluminescence NO_x analyzer.

Detailed measurements of temperature and concentrations are made of a methane-fueled BSDF with equal fuel-jet and co-flowing air velocities set at 0.14 m/s. Two pressure conditions are considered, normal pressure (1 bar) and reduced pressure (0.3 bar). The reduced pressure condition has an equivalent buoyancy effect of that at 0.1 g, where g denotes the standard gravitational acceleration; recall that the buoyant effects are inversely proportional to pressure squared when the fuel-jet Reynolds number, or the mass flowrate, is kept constant in the experiments (ref. 7). The fuel and air mass flowrates in reduced pressure testing are kept unchanged from the normal pressure. The flame remains laminar and stabilizes at the burner exit for both normal and reduced pressure conditions.

ELF Glovebox Investigation

The lift-off, reattachment, and blow-out of enclosed jet diffusion flames will be investigated in the Enclosed Laminar Flames (ELF) investigation that will be conducted in the glovebox facility on the USMP-4 mission, scheduled in October 1997. A 50/50 mixture (volume basis) of methane and nitrogen will be used for the fuel. A co-flow of air will be produced in a miniature fan-driven wind tunnel. This investigation will be manually performed by an astronaut, and the operational parameters include the both the fuel flow and air velocity (i.e., fan speed). Astronaut training is in progress.

The hardware consists of an experiment module, a control box, 3 electrical cables, and sets of exchangeable fuel bottles and ignitors. A 1.5-mm diameter nozzle is located on the duct's flow axis. The air velocity is measured by a hot-element anemometer, and the fuel flow is set with a mass flow controller. The nozzle is instrumented with a surface thermocouple, and another thermocouple at the outlet is used to indicate extinction of the flame. The duct is also equipped with an astronaut-positionable temperature rake, instrumented with 5 thermocouples and 26 silicon carbide fibers. When exposed to the flame, the fibers will thermally radiate giving a qualitative indication of the near-flame temperature profile. The rake can be positioned at 6 discrete radial positions. The digital data will be displayed on the module for astronaut viewing and recorded with the glovebox video system. The flame will be imaged with 2 color video cameras. The flight hardware is currently being assembled.

Results And Discussion

The flame appearance in reduced pressure is qualitatively similar to that report by Yuan et al. (ref. 8). The flame luminosity greatly decreases in reduced pressure environments; a faint-blue contour is seen, consistent with μg experiments. The fine spatial resolution of thermocouple measurements allows for construction of the isotherms shown in Fig. 2. The isotherms show that the maximum temperature contour in reduced is wider, consistent with the visible flame appearance. The flame length defined by the maximum temperature in reduced pressure is also longer (by around 3 mm), although the visible flame length is shorter. This observation is different from that observed in microgravity (μg) environments by Stocker (e.g., ref. 6). The μg flame shows a longer visible length than the corresponding normal gravity flame. The temperature data show a maximum in the shoulder region for the methane fueled BSDF, cf. Fig. 2, consistent with earlier observations in the literature. The maximum temperature is higher in reduced pressure than that in normal pressure, for example, by 40 K at $z = 6$ mm, where z denotes the axial height above the burner exit. This observation is interesting because one expects a lower maximum temperature in reduced pressure environments due to the effects of (a) higher coefficients of species diffusion and (b) higher decomposition (e.g., based on the La Chatelier principles) of CO_2 to CO and O_2 , and H_2O to H_2 and O_2 . The measured species concentrations, indeed, indicate higher mole fractions of CO and H_2 in reduced pressure flames, cf. Fig. 3. This level of difference in measured maximum temperatures appears to be beyond the uncertainty of temperature measurements. Sources of uncertainty in data acquisition of temperature measurements include (a) catalytic effects resulting from the presence of Pt-Pt/10%Rh thermocouple wires, and (b) soot build-up on the thermocouple junction. We have found that the soot build-up on the thermocouple can substantially reduce the temperature. As an example, we observed a temperature decrease of 200 K at $z = 18$ mm (near the tip of the visible flame in normal pressure) and slightly off the centerline (by mm) within 3 s from setting the probe to this location. The temperature difference of 40 K reported at $z = 6$ mm is near the maximum width of the visible flame, and no obvious soot build-up is detected for measurements in both normal and reduced pressure environments. To ascertain the catalytic effects, a silica coated thermocouple is being used to determine the temperature-time history at locations near the flame-tip.

Measured mole fractions of eight major species, CH_4 , O_2 , N_2 , CO_2 , H_2O , H_2 , CO and Ar , at $z = 6$ mm are summarized in Fig. 3. where r denotes the radial distance from the centerline. Similar to that exhibited by the isotherms, the flame in reduced pressure shows a slightly wider width. The main reaction zone of methane oxidation appears to be located in the region $5 < r$ (mm) < 6 for pressure of 0.3 bar, and $4 < r$ (mm) < 5 for pressure of 1 bar. The species concentration measured by using the micro-probe, in conjunction with the micro-translational device, has fine spatial resolutions, providing physical insight into the reaction zone structure. The N_2 concentration shows a drastic decrease entering the high temperature zone from the fuel-lean side. The O_2 concentration first decreases entering the high temperature zone, and increases to reach a local maximum, for example, around $r = 5.3$ mm, and continues to decrease and 'leak' into the fuel-rich region. This increase of O_2 in the high temperature zone coincides with the sharp decrease of CO_2 concentration and sharp increase of CO measured for the reduced-pressure flame. The leakage of O_2 into the fuel-rich region is consistent with that predicted by the rate-ratio asymptotics of Linan and Williams (ref. 9) and numerical simulation, for example, by Sheu (ref. 1) and Sheu and Chen (ref. 1-3) using a four-step reduced mechanism. We have obtained preliminary data of NO and N_2 (i.e., NO_x) in the flame, and are working on data reduction to quantify the emission index from the measurements.

Conclusions

The flame in reduced pressure becomes less luminous, and shows a faint-blue visible spontaneous emission. The temperature measurements show that the methane fueled Burke-Schumann diffusion flame (BSDF) has a wider flame width and slightly longer flame length in reduced pressure (0.3 bar in this study). The maximum temperatures in the BSDF studied show a maximum temperature in the shoulder region of the flame. A by-product of this research is the illustration of the microprobe usage for species measurements can provide physical insight into the reaction zone structure of a laminar diffusion flame.

Acknowledgment

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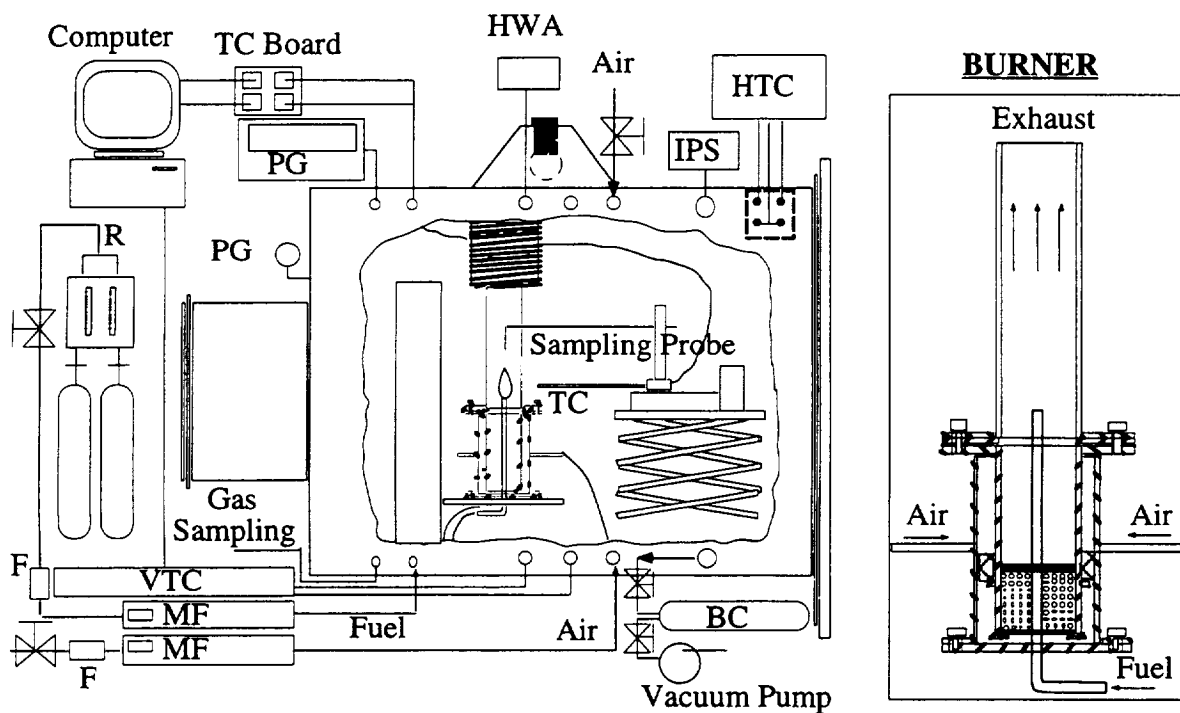


Figure 1. Experimental setup; BC denotes the ballast chamber, F the filter, HWA the hot wire anemometer, IPS the ignitor power supply, MF the mass flowmeter, PG the pressure gage, R the rotameter, TC the thermocouple, HTC the horizontal translation controller and VTC the vertical translation controller.

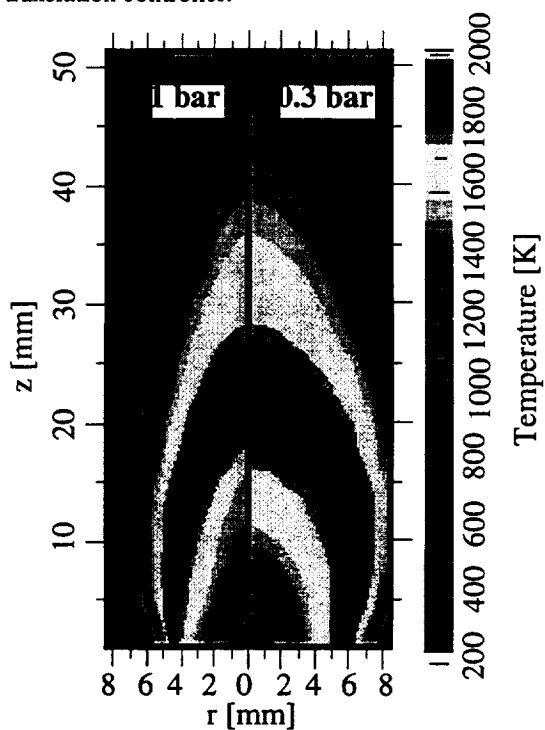


Figure 2. Comparison of measured isotherms of methane-fueled BSDF (at 0.14 m/s in normal condition) in normal pressure and reduced pressure (0.3 bar, or 0.1-g equivalent).

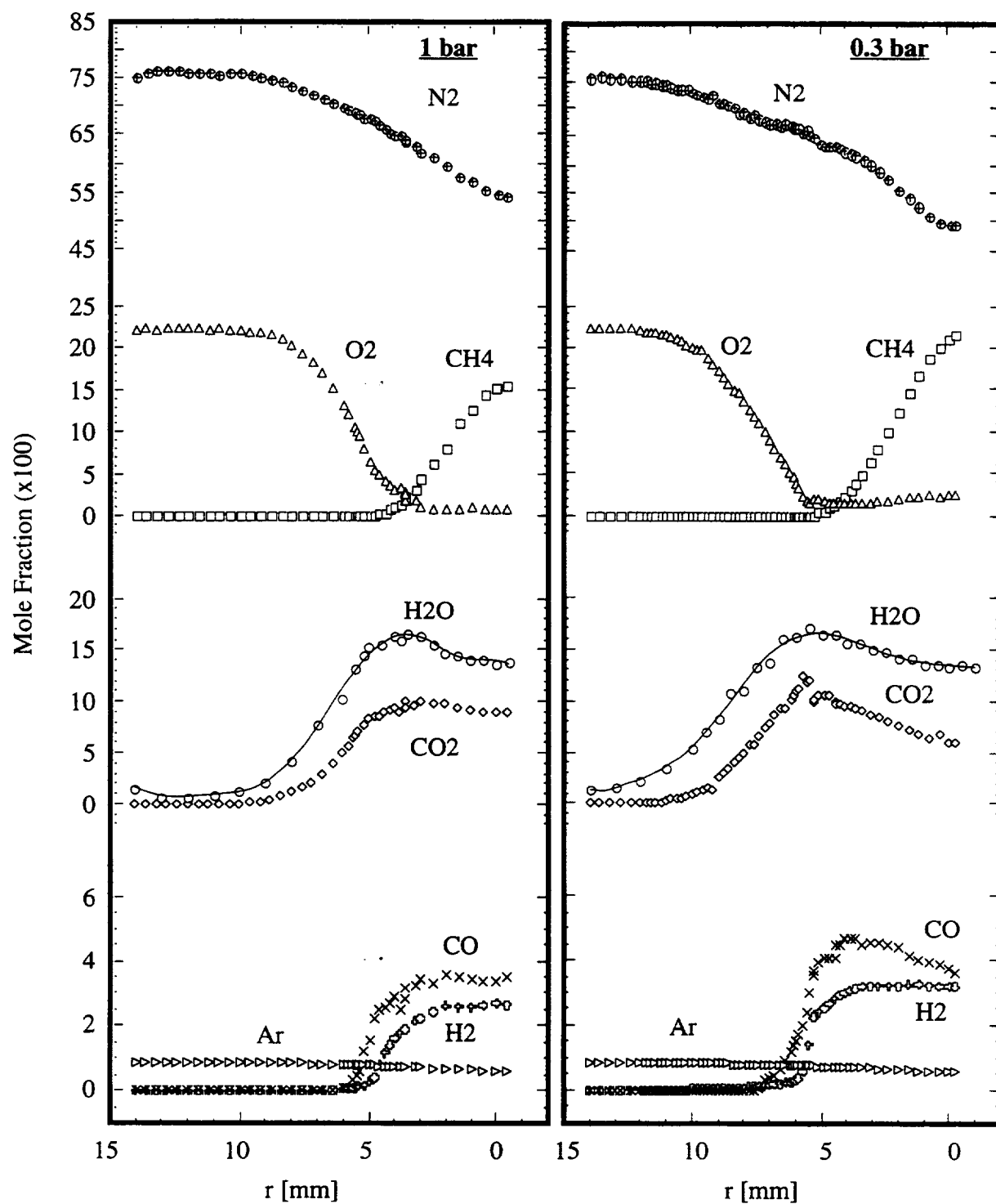


Figure 3. Comparison of measured species concentration of methane-fueled BSDF (at 0.14 m/s in normal condition) in normal pressure and reduced pressure (0.3 bar, or 0.1-g equivalent).