

CHARACTERISTICS OF NON-PREMIXED TURBULENT FLAMES IN MICROGRAVITY

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Introduction

The overall objectives of this research are (i) to obtain and analyze experimental data on flame images, and the spatial and temporal distributions of temperature, radiation, velocity and gas-phase species in microgravity turbulent gas-jet diffusion flames and (ii) to utilize these data to validate and refine the existing predictive capabilities. Work on this project commenced in June 1996.

The first investigations on turbulent gas-jet diffusion flames in microgravity were initiated by Bahadori and co-workers in 1991. These studies have shown that significant differences exist in the transition processes in normal-gravity and microgravity flames, and that the turbulent flames in microgravity behave very differently as compared to their buoyancy-dominated normal-gravity counterparts (Hegde 1994, ref. 1). For example, in the transition regime while the visible flame height, for given fuel and nozzle size, in normal gravity decreases, the height of the microgravity flame increases as shown in Fig. 1. In the fully developed turbulent regime, the normal-gravity flame height is independent of injection velocity, whereas the microgravity flame height continues to increase, although at a lower rate than in the laminar and transitional regimes. Other differences between the normal-gravity and microgravity flames arise in the jet shear-layer instability characteristics, extent of the transitional regime and blow-off limit characteristics (Zhou et al 1993, ref. 2, see also Fig. 1).

The parameter useful in assessing buoyant effects on gas-jet diffusion flames is the Froude number, Fr , (Glassman 1996, ref. 3) which denotes the ratio of forced convection and buoyant convection and is given by

$$Fr = u_0^2/gL$$

where u_0 is the jet injection velocity, g is the gravitational acceleration and L is the length of the flame. Note that the Richardson number, $Fr^{-1}\Delta\rho/\rho$, where ρ is a representative flame density and $\Delta\rho$ is the density difference between flame and ambient, may also be considered for estimating the influence of buoyancy. For a diffusion flame, however, $\Delta\rho/\rho$ is of unit order so that the Richardson number is essentially the inverse of the Froude number. Previous results have shown that significant differences exist between the normal-gravity and microgravity flames even when the normal-gravity flames have Froude numbers in excess of 10^3 . This indicates that to obtain momentum-dominated flames under normal-gravity conditions requires extremely high jet velocities of the order of tens of meters/second. This leads to extremely large Reynolds number for typical nozzle sizes used in the laboratory which leads to problems in resolving the turbulent flow field both experimentally and computationally.

In microgravity, momentum-dominated turbulent flames are obtained at much smaller velocities than in normal gravity. Thus, significantly larger length and time microscales of the turbulent flow field under momentum-dominated conditions are obtained. Hence, studying and making measurements in turbulent gas-jet diffusion flames in microgravity offers the potential to capture the details of the turbulent flow field under momentum-dominated conditions. This understanding has a wide range

of practical applications such as diffusion flames in industrial combustors and engines where, because of high velocities, buoyancy effects are small and in the turbulence decay process in large-scale fires.

Experimental Apparatus and Approach

The experimental phase of the program has commenced and testing is planned at NASA Lewis in the 2.2-Second Drop Tower, the 5.18-Second Zero-Gravity Facility and the DC-9 aircraft. The tests are designed to take advantage of the different individual nature of these facilities.

The 2.2-Second Drop Tower provides a high-quality microgravity environment and quick turnaround times. While 2.2 seconds is not sufficient time to make statistically stationary flow field measurements, previous experience suggests that it is sufficient to provide good estimates for overall flame dimensions. Hence, tests in this facility will be conducted primarily to select the candidate flames for the detailed measurements. This is important since typical microgravity flame heights for the injection Reynolds numbers of interest (3000-10,000) for hydrocarbon fuels such as propane and methane are of the order of 50 cm for nozzle diameters to be utilized (around 1mm). It is desirable to reduce both the flame height and the heat release rate to conduct flow field measurements. One way to do this is to dilute the fuel with an inert gas, for example, nitrogen and these tests will quantify the effect of fuel dilution. The drop rig has been designed and is currently under construction.

The 5.18-Second Zero-Gravity Facility provides a high-quality microgravity environment and significantly greater time for quantitative measurements than the Drop Tower. These tests will utilize the Gas Jet Diffusion Flame hardware (Fig. 2) with selected candidate flames with the objective of making detailed measurements of temperature and flame radiation. Fine-wire thermocouples will be utilized to obtain temperatures at different axial and radial locations. Time constants of the utilized thermocouples will also be measured in order to correct the fluctuating components of the measured signals. Flame radiation will be measured using thermopile detectors both from the entire flame (i.e., global radiation) and from narrow wedge-shaped regions of the flame. At this time, a thermocouple rake with eight thermocouples has been constructed and installed in the rig. Also, the radiometer assemblies have been constructed.

The DC-9 aircraft provides more reduced-gravity time than the Drop Tower and the Zero-Gravity Facility; however, the g-levels are not as low and there can also be g-jitter effects. Tests are planned in the Gas Jet Diffusion Flame rig for aircraft experiments with selected candidate flames with the objective of visualizing the turbulent structures and for making LDV measurements. An IR camera, if available, will be used to obtain the infrared signatures of specific species by incorporating optical filters. A 16-bit data acquisition system with high sampling rate capability will be incorporated into the aircraft rig for the LDV measurements. The rig upgrade will commence this year.

Modeling

The obtained experimental data will be useful for assessing both direct numerical simulations as well as standard turbulent flame models. The primary modeling objective in this project is to assess the validity of turbulent flame models since the obtained data will provide a benchmark case for momentum-dominated gas-jet flames.

The numerical model is under development and utilizes standard turbulent models in conjunction with state relationships for chemistry for predicting the time-averaged flow field and correlations. Thus, the set of governing equations utilized are of the form

$$\text{div}(\rho u \phi - \Gamma_{\phi} \text{grad} \phi) = S_{\phi}$$

where

$$\begin{array}{lll} \phi = u, v, w & : & \text{Momentum} \\ \Gamma_{\phi} = \rho (v_t + v_l) & & \\ S_{\phi} = -\text{grad}(p) + \text{gravity} + \text{viscous} & & \end{array}$$

$\phi = h$	:	Enthalpy	$\Gamma_\phi = \rho (v_t + v_l) / a_h$ $S_\phi = -Dp/Dt + \text{heat sources}$
$\phi = 1$	:	Continuity	$\Gamma_\phi = 0$ $S_\phi = 0 + \text{boundary sources}$

In the above equations, u , v , and w are the three components of the velocity, ρ is density, p is pressure, h is enthalpy, and v_t and v_l are the turbulent and laminar kinematic viscosities, respectively. These equations are supplemented by equations for the turbulent kinetic energy, k , and the dissipation rate, ϵ . The model solves for pressure, velocity, temperature, species concentrations, and turbulent kinetic energy and dissipation rate. Radiative transport, utilizing models such as the six-flux model, for major gas species (e.g., CO₂ and H₂O) will be included in the code.

Results and Discussion

In general, gas-jet diffusion flames may be classified as momentum-dominated, buoyancy-dominated or flames that are influenced by both momentum and buoyancy. Similitude and scaling arguments have been presented in the literature (e.g., Blake and McDonald 1995, ref. 4) to distinguish these regimes based upon weighted Froude and Richardson numbers. However, for the purpose of retaining clarity in the discussion herein, attention is focused only on momentum-dominated and buoyancy-dominated flames.

The fundamental difference between momentum-dominated and buoyancy-dominated gas-jet flames is illustrated in Fig.3 which plots the flame centerline velocity (normalized by injection velocity) as a function of axial distance (normalized by flame length) downstream of the nozzle for three different cases: (i) laminar 1-g (ii) laminar 0-g and (iii) turbulent flame. The laminar flame calculations are from a laminar flame model (Edelman and Bahadori 1986, ref. 5) and the turbulent flame calculations utilized a preliminary fast-chemistry version of the model described above using a k - ϵ formalism which does not include the gravitational acceleration term. Some success for the mean flow quantities has been reported in the literature using similar models for a high-velocity hydrogen jet flame with air co-flow where buoyant effects were reported to be small (e.g., Kent and Bilger 1976, ref. 6).

Considering the laminar case it is clear that for the buoyancy-dominated flame the axial velocity increases with distance downstream of the nozzle whereas for the momentum-dominated (0-g) case it decreases. The difference is due to buoyant acceleration in the 1-g case which yields an axial velocity dependence on the square root of the axial distance (Bahadori et al 1996, ref. 7). For the turbulent case, which represents a momentum-dominated flame because of the neglect of the gravitational acceleration term, the axial velocity exhibits a decay over the flame length although the predicted decay is not as dramatic as for the laminar 0-g case. While computations of a buoyancy-dominated turbulent flame are not presented here, there is evidence in the literature that the axial velocity increases with downstream distance in this case (e.g., Durao and Whitelaw 1974, ref. 8).

This difference in the velocity field for momentum-dominated and buoyancy-dominated flames leads to striking differences in their behavior. For example, for the laminar and transitional flames, the instability characteristics of the flame and associated shear layers are completely different. Application of parallel shear-layer instability theory showed that for the axisymmetric mode, the microgravity, momentum-dominated flame has a single critical layer which originates at the nozzle rim and crosses the flame near the tip. The normal-gravity buoyancy-influenced flame, however, has three critical layers associated with the axisymmetric mode. The innermost layer originates at the nozzle rim and is associated with the instability of the fuel jet issuing into the atmosphere. A pair of critical layers is formed on the oxidizer side of the flame sheet and, being buoyancy driven, are believed to be responsible for flame flicker which is absent in the microgravity case.

In the turbulent regime, the significance of the difference in the velocity fields may be understood in terms of the variation of the local Reynolds number based upon the local centerline velocity and local flame width. The magnitude of the local Reynolds number increases with axial distance for the normal gravity buoyancy-dominated flame and decreases with axial distance for the microgravity flame. If it is assumed that the local turbulent velocity magnitude scales with the local centerline velocity, and that the local integral length scale is proportional to the local flame width (which is relatively invariant over the flame length) then it is clear that the local turbulent Reynolds number, Re_T , follows the same trend as the local mean flow Reynolds number.

The smallest scale of turbulence, that is the Kolmogorov length scale, varies as $Re_T^{-0.75}$ indicating that for the buoyancy-dominated flame, the size of the smallest scales decreases with increasing distance along the flame (since Re_T increases) whereas for the microgravity flame, the opposite occurs (since Re_T decreases). This is consistent with turbulence dissipation behavior. The turbulence dissipation is of order u'/l where u' is the turbulent velocity fluctuation magnitude and l is the integral length scale. This is a measure of the highest frequencies (i.e., the smallest scales) in the turbulent spectrum. The integral length scale is expected to be relatively invariant over the flame length whereas u' will scale with the mean velocity. Thus, u'/l is expected to decrease downstream for the microgravity case indicating a decrease in the highest frequencies and an increase in the size of the smallest scales.

Experimental evidence supporting the above discussion is provided by Fig. 1 which shows that the microgravity turbulent flame heights are larger than the normal gravity buoyancy-dominated flame heights. Following Glassman (ref. 3), it may be argued that flame height, L , is proportional to the fuel volume flow rate, Q , and is inversely proportional to the effective diffusivity, D_{eff} ; that is

$$L \propto Q/D_{eff}$$

In the laminar regime D_{eff} represents the molecular diffusivity whereas in the turbulent regime it represents an eddy diffusivity. From Fig. 1, it may be inferred that D_{eff} for the normal gravity turbulent flame is between two to three times the value of D_{eff} for the corresponding microgravity flame. D_{eff} in the turbulent regime scales as the product of a turbulent velocity scale (u') and an integral length scale. Since the integral length scale is the same for both cases, it is expected that u' is smaller for the microgravity flame as was suggested earlier.

Pending the completion of the 2.2 Second Drop Tower rig, preliminary work in the Zero-G Facility has commenced with the Gas Jet Diffusion Flame apparatus. The objectives of this initial testing are to establish the feasibility of reducing flame height in microgravity by adding a diluent to the fuel and also to assess changes in the flame behavior because of the added diluent. The initial testing has been with moderate Reynolds number flames ($Re = 1000$) with a propane (60%) - nitrogen (40%) injection mixture utilizing a 1.6 mm diameter nozzle. At this Reynolds number, the flame is in the laminar regime (ref. 1) which facilitates comparison with laminar flames of undiluted propane in microgravity for which a substantial data base exists. For the undiluted propane case the (luminous) flame height for the corresponding flow rate as extrapolated from available data would be approximately 40 cm. The addition of the nitrogen reduces the visible flame height to approximately 25 cm. The flame luminosity appears to be considerably reduced however compared to the undiluted case consistent with decreased amount of soot in the flame compared to the undiluted propane flame during the corresponding period of its development. This behavior is similar to the normal gravity behavior (Axelbaum and Law 1990, ref. 8) where it is attributed to a combination of reduction in fuel concentration (which is expected to be the primary effect at the investigated dilution) and flame temperature.

Temperature measurements on the centerline of the nitrogen-diluted flame are compared with corresponding measurements in the undiluted propane case in Fig. 4. The undiluted case is at a lower Reynolds number ($Re = 400$) but this is compensated by normalizing the axial distance by the flame length. This figure shows that the temperature distribution is similar in the two cases. It must be cautioned that the temperatures do not reach a steady state at the end of the microgravity period for the laminar flames. This is shown in Fig. 5 which plots a representative temperature development for the nitrogen-diluted flame ($Re = 1000$). It is unclear at present whether the temperatures will reach steady state during the available time for the moderately turbulent flames that are to be studied. The ratio of the times to reach steady state for the laminar and turbulent cases is inversely related to their effective diffusivities. From Fig. 1 and earlier discussion, the effective diffusivity for the moderately turbulent flames is approximately 30% more than for the laminar flames which indicates that the turbulent flames will reach steady state only 30% faster than the laminar flames.

Acknowledgments

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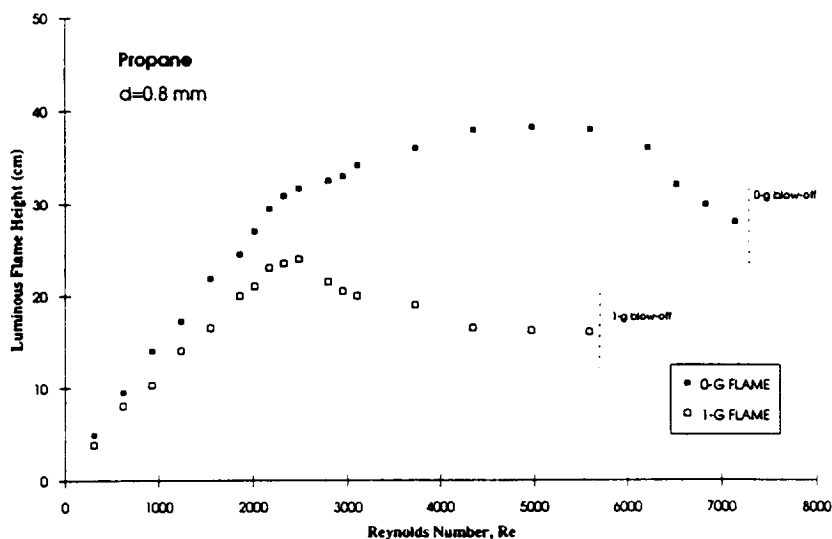
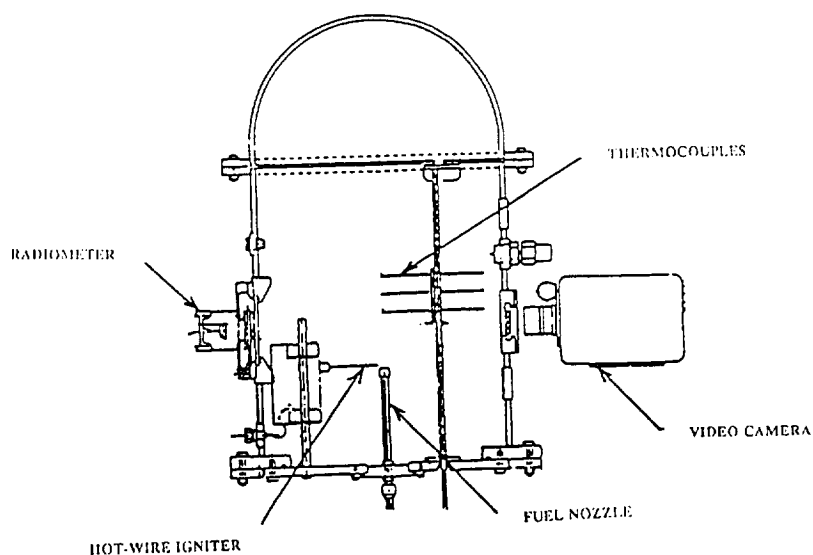


Fig. 1 Measured height of the luminous flame zone as a function of Reynolds number for propane-air flames in microgravity and normal gravity (nozzle diameter = 0.8 mm).

Fig. 2 Gas-Jet Diffusion Flame hardware for the Zero-Gravity Facility.



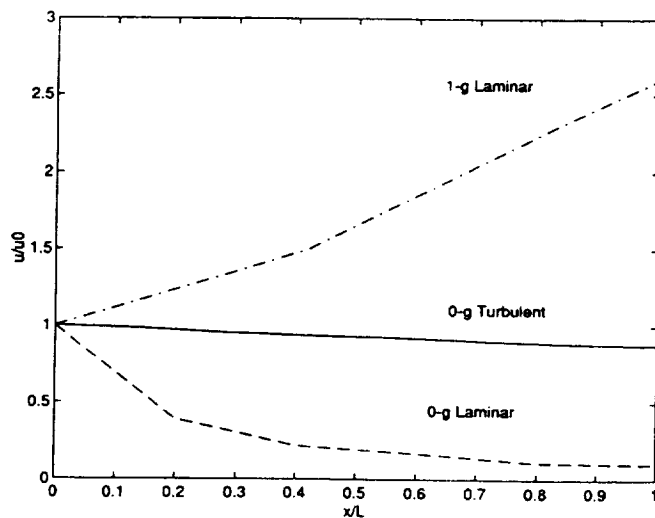


Fig. 3 Predicted normalized centerline velocity as a function of normalized axial distance. The Reynolds number for the laminar flame computations is 400 and for the turbulent flame computations is 5000.

Fig. 4 Centerline temperature measurements for propane and nitrogen-diluted propane flames in microgravity.

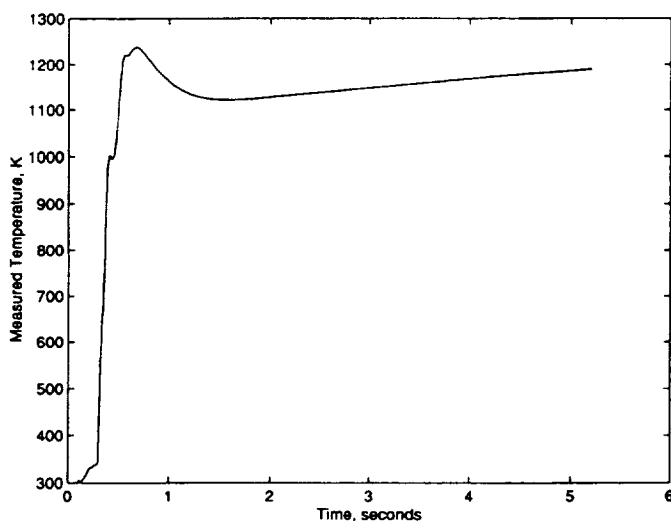
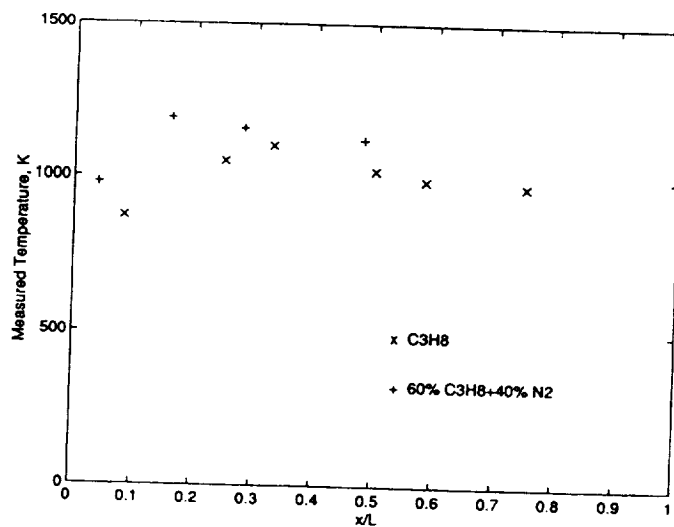


Fig. 5 Temperature development of the nitrogen-diluted propane flame on the centerline at a height of 4 cm above the nozzle. The drop commenced at time = 0 seconds. ($Re = 1000$).