

STRUCTURE OF MICROGRAVITY TRANSITIONAL AND PULSED JET DIFFUSION FLAMES*

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Introduction

This paper describes results obtained in a study of pulsed gas jet diffusion flames to better characterize the recently observed vortex/flame interactions in microgravity transitional and turbulent diffusion flames (refs. 1 and 2), and to improve the understanding of large-scale structures in corresponding normal-gravity flames. In preparation for a space experiment, tests were conducted in the 5.18-Second Zero-Gravity Facility of the NASA Lewis Research Center. Both unpulsed and pulsed laminar flames were studied and numerical modeling of these flames was carried out for data comparison and model validation. In addition, complimentary tests for a series of unpulsed flames were conducted on-board the NASA KC-135 research aircraft.

The microgravity transitional and turbulent gas-jet diffusion flames have been observed to be dominated by large-scale disturbances, or structures. These structures first appear intermittently in the flame at Reynolds numbers (based on the cold jet injection properties) of about 2100 (ref. 1). With increase in injection Reynolds number, the rate of intermittent disturbances increases until the generation becomes continuous at Reynolds numbers of 3000 and higher. The behavior of these structures depends upon the velocity and temperature characteristics of the jet/flame shear layer. These characteristics are different in normal gravity and microgravity (ref. 2).

Large-scale structures are an integral part of turbulent flames in normal gravity as well, but these evolve and interact with the flame in a different manner compared to the microgravity case. In normal gravity, the two primary mechanisms for large-scale vortex generation are the instability of the central fuel jet and the instability of the buoyancy induced natural convection layer on the outside of the flame. Vortices generated by these mechanisms then evolve by interaction with the flame and each other. One of the results of this interaction is flame flicker (e.g., ref. 3). In microgravity, the buoyancy induced convection layer does not occur, and interactions between buoyancy-generated structures and other vortices are absent. Consequently, flame flicker is also absent. Previous normal-gravity investigations (e.g., ref. 4) have studied the interaction of well-defined and controlled vortices with the flame. It is found that enhanced entrainment may occur, and that vortex/flame coupling has an important influence on time-dependent flame behavior. These studies also show that coupling between buoyancy-generated and jet-instability generated vortices may dominate the behavior of the flame, particularly in the downstream regions. It is then of fundamental interest to investigate the behavior of pulsed diffusion flames in microgravity where buoyancy-induced structures are absent.

In the present study, large-scale, controlled disturbances are imposed on a well-defined microgravity laminar diffusion flame to better understand the effects of the structure parameters (e.g., frequency) responsible for the observed characteristics of transitional and turbulent gas jet diffusion flames. A novel technique, utilizing a sinusoidally driven iris is used to provide harmonic axisymmetric disturbances for interaction with the flame. In the following sections, the experimental method, the modeling approach, and comparisons between data and predictions are presented.

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Experimental

The microgravity experiments were conducted at the 5.18-Second Zero-Gravity Facility of the NASA Lewis Research Center. The cylindrical experiment chamber was approximately 87 liters in volume with a length of about 50 cm. Propane was injected into quiescent air at atmospheric pressure through a 1.65-mm diameter nozzle made of stainless steel tubing. The nozzle tip was located 5 cm above a base plate which held the nozzle and igniter assembly. The volume flow rate of fuel was 2 scc/sec, corresponding to a cold jet Reynolds number of approximately 400. Ignition occurred shortly after the drop commenced, and was initiated by a hot wire mounted on a rotary actuator which retracted the igniter out of the flow field after ignition. Both unpulsed and pulsed flames were studied, and imposed pulsations commenced approximately two seconds after start of the drop and continued until the end of the drop.

The disturbance mechanism utilized an iris mounted approximately 5 mm above the exit plane of the nozzle. The iris opening was changed by a rotary movement of the iris leaves about pivot points, actuated by a stepper motor. The open diameter varied in a sinusoidal fashion at the selected frequency. The amount of angular movement of each leaf was limited to less than 10 degrees, so that points on the leaf moved predominantly in a radial direction giving rise to an axisymmetric excitation of the flame. The open diameter of the iris was varied sinusoidally between 1.5 cm and 2.5 cm. This range was selected based upon considerations of flame diameter and forcing disturbance strength, and ensured that the iris leaves would not physically cut into the flame and act as a heat sink. Also, this variation in iris diameter provided a disturbance of sufficient strength that could be measured by the thermocouples and radiometers. The pulsation frequencies were in the range of 0-10 Hz. There were two main reasons for selecting this range. First, this range is consistent with the frequencies of occurrence of large-scale structures that have previously been observed in microgravity transitional flames. Second, this range yields structures that have been found to interact with the buoyancy-generated structures in normal-gravity flames. It is of fundamental interest to ascertain the behavior of the structures in microgravity where such interactions are absent.

Orthogonal side views of the flame were imaged by video cameras at 30 frames per second. Type K thermocouples with bead sizes in the range of 150-200 microns were used at various axial and radial locations above the nozzle exit plane. Thermopile radiometers were mounted at a radial distance of 10 cm from the flame centerline. Both global radiation and radiation from a wedge-shaped slice of the flame (using a lens assembly mounted to the face of the radiometer) were measured. The height and width of the wedge at the flame centerline were approximately 6 mm and 18 mm, respectively. The slice radiometer was equipped with a bandpass filter centered at 1865 nm with a halfwidth of 105 nm. This wavelength corresponds to water vapor radiation. The slice radiometer enabled obtaining local oscillations of flame radiation, and was located at 4 cm above the nozzle tip. The thermocouple and radiometer data were sampled in excess of 500 Hz. Since the oscillatory response of the flame was of interest, the measured signals from the thermocouples and the radiometer have to be compensated for their time response. Measured time constants of thermocouples were in the range of 120-250 milliseconds depending upon thermocouple location, with the lower thermocouple registering the smaller time constants. The obtained time constant for the radiometer was of the order of 30 milliseconds.

In addition to tests conducted for pulsed flames in the Zero-Gravity Facility, flames were studied on-board the KC-135 research aircraft to better understand the behavior of jet diffusion flames under reduced-gravity conditions. These tests provided data such as flame radiation and flicker frequency as a function of gravitational level. Flame visualization (using video cameras at 30 frames per second) and radiation measurements (using a thermopile detector) were obtained. These tests provided better insight into the characteristics of flames under partial-gravity level, and helped in the model validation, as discussed later.

Theoretical

Two numerical models, a steady state model and a transient model, are being developed in this study. The steady, two-dimensional model which is constructed for studying axisymmetric laminar diffusion flames, incorporates the effects of inertia, viscosity, diffusion, gravity, and combustion in the boundary layer form of the partial differential equations for mass, momentum, energy, and species (ref. 5). These governing equations and their associated boundary conditions are transformed into the von Mises plane, and then solved numerically using an explicit finite-difference scheme. Radiation from water vapor and carbon dioxide is accounted for through the assumption of optically thin medium. Soot is not accounted for in this model, although it contributes to radiation. However, previous measurements suggest that most of the radiative loss in the investigated microgravity flames is from carbon dioxide and water vapor (ref. 1). The combustion model is that of a shifting equilibrium. Details of the flow field such as velocity, temperature, radiative loss, and flame shape have been predicted, and some of the results are presented later.

The numerical model of the pulsed laminar flame provides the capability of calculating transient-flame behavior under imposed disturbances. This comprehensive transient, Navier-Stokes model is utilized to predict the characteristics of the flame under the influence of imposed oscillations. The model can be one-, two-, or three-dimensional, and Cartesian, cylindrical, or curvilinear systems with non-orthogonal coordinates can be selected. The model provides velocity, pressure, temperature, and species fields in the presence of convective, conductive, and radiative heat transfer. Both diffusion-controlled and kinetic-controlled combustion models can be used. Radiation models, e.g., flux model, are structured in the code. Predictions such as oscillatory flame shapes, oscillatory temperature field, and oscillatory velocity field in the flame can be obtained, as discussed in the next section.

Results and Discussion

The measured and predicted centerline temperatures for a laminar, unpulsed microgravity propane flame are shown in Fig. 1. Predictions indicate that the temperature increases initially, and then (unlike temperature in normal-gravity flame) decays monotonically, except in a small region around $x = 12$ cm. This location corresponds to the theoretical flame tip. Beyond the flame tip, the temperature is predicted to drop again. The measurements are in good agreement with predictions considering the insufficient microgravity time available in the drop test. Estimates based upon radial diffusion suggest a quasi-steady state after about 15 seconds of burning. It must be noted that, on the other hand, the corresponding normal-gravity flame establishes in a fraction of a second following ignition, due to the presence of buoyant force and associated entrainment. The predicted and measured radial distribution of temperature at the axial location of 5 cm are shown in Fig. 2 for the microgravity flame. The trend of the data is in good agreement with the predicted radial distributions.

Different investigations (e.g., ref. 3) have shown that the frequency of oscillation of a normal-gravity laminar diffusion flame burning in quiescent oxidizing environments is in the 10-18 Hz range. These flames flicker due to hydrodynamic instability. Data on flame oscillation as a function of gravity (except for the normal-gravity case) are difficult to obtain. To date, no data on flame flicker has been available for partial gravity. The aircraft tests of a methane flame (2.5 scc/sec flow rate) provided the required data. Figure 3 shows the relationship between flicker frequency and gravitational level (see ref. 6). This relationship is in satisfactory agreement with that obtained in a separate study for high gravity levels (ref. 7).

Gravitational level was also shown to have a significant effect on global radiation from the flame. Figure 4 shows the radiation level for the range microgravity to 1.5g. The tests were conducted in the KC-135 aircraft for methane flames. With the aid of the steady state numerical model, it is shown that the predicted radiation level agrees with the data. Note that radiation from a microgravity flame can be up to an order of magnitude higher than that of a normal-gravity (or higher-g) flame due to the strong influence of buoyant effects and the resulting differences in the temperature, velocity, and species (especially the radiating water vapor and carbon dioxide) fields of the flames under buoyant and non-buoyant conditions.

Although the velocity field in the microgravity flames has not been measured to date, convection velocities of the imposed disturbances have been obtained from flame images as well as by cross correlation of the temperature oscillations. Instability theory shows that the convection velocity is usually some fraction of the local centerline velocity and can be used to infer the trend of the axial velocity. Figure 5 shows that indeed the convection velocity of the imposed disturbance decays with downstream distance. The convection velocity of large-scale structures observed in transitional and turbulent microgravity flames (ref. 2) has also been observed to decay axially suggesting that in the microgravity turbulent case both the amplitude and frequency range of the turbulent fluctuations will also decay with downstream distance.

The phases of the temperature and radiation oscillations with respect to the iris phase provide significant insight into the behavior of pulsed flames in microgravity. Figure 6 shows the time-constant corrected thermocouple signals at the flame centerline for $x = 1$ cm and $x = 4$ cm for the 3-Hz pulse case. Note that the amplitude of the temperature oscillation at $x = 4$ cm is smaller than that further upstream at $x = 1$ cm. The oscillations in the temperature signals are better depicted in Fig. 7, which shows an overlay of two (normalized) temperature signals and the time corresponding to maximum iris opening. The temperature oscillations are shown for approximately one second toward the end of the drop. Based on the phase difference between the two signals, the convection velocity for the temperature oscillations between the two axial locations is approximately 30 cm/sec. This is very close to the average centerline velocity between these locations as computed from the steady-state numerical model described earlier. The maximum centerline temperature at $x = 1$ cm coincides approximately with the minimum iris open position (i.e., maximum inward displacement of the iris).

The phase relationship between the radiation and iris opening for a pulse frequency of 3 Hz is shown in Fig. 8. The radiation at $x = 4$ cm peaks when the iris is near the minimum open position. Assuming that the convection speed of the local radiation is the same as that of the centerline temperature, the phase of the radiation at $x = 1$ cm can be obtained. It is estimated that the local radiation at $x = 1$ cm will be a maximum approximately a quarter cycle after the phase of maximum iris opening. This corresponds to the phase of maximum inward velocity of the iris.

The measured radiation, Q , is proportional to YT^4 , where Y is the concentration of water vapor and T is the temperature. The maximum contribution to the radiation is therefore expected from the flame surface where both the temperature and the water vapor concentration peak. Thus, the oscillatory components of the radiation, concentration, and temperature (Q' , Y' , and T' , respectively) are related as $(Q'/Q) \propto (Y'/Y) + 4(T'/T)$, where both Y and T are measured at the flame surface. At the low frequencies of interest in this paper, both Y' and T' at the flame are expected to be in phase with the reaction rate, and therefore, with each other. Thus, the increase in radiation level during a cycle is expected to be caused by an increase in both the temperature and water vapor concentration at the flame.

The increase in reaction rate as the iris moves in is believed to be related to enhanced air entrainment. Physically, from the no-slip condition at the iris surface, the air next to the iris must follow the motion of the iris. This behavior is also consistent with the smoke trace visualization tests conducted in this study, which indicated entrainment of the vortex during the inward movement of the iris. Numerical computations also confirm this behavior. Figure 9 shows the flow field generated by the iris movement in the presence of a cold jet, where the instantaneous field at 1/2 cycle (iris fully open) and 3/4 cycle (iris closing) are shown. It is seen that as the iris moves toward the jet (closing), air is pushed inward and more entrainment occurs.

The transient model has also been successful in predicting the oscillatory nature of the temperature and velocity in the presence of iris pulsing. Examples of predicted oscillatory temperature and centerline velocity (T' and U') are shown in Figs. 10 and 11, respectively. The predicted amplitude of temperature oscillations (Fig. 10) is of similar order as the experiment (see Fig. 6). Also, Fig. 11 shows that the mean velocity at $x/L = 0.3$ (where L is the predicted flame length) is approximately 20% of the injection velocity, which is in agreement with prediction from the steady-state model (see Fig. 5).

Conclusions

The tests conducted for unpulsed laminar diffusion flames show the significant effects of low gravity on these flames. Temperature distribution, flame radiation, and flame flicker data are obtained. Predictions from a steady state numerical model developed in this program are in satisfactory agreement with the data. New data on pulsed microgravity laminar diffusion flames have provided insight into the characteristics of vortex/flame interactions. These data are generated in preparation for a space experiment on pulsed flames in microgravity. With the aid of a transient numerical model of jet diffusion flames, the effects of imposed disturbances on flame structure are investigated. These results help to develop a better understanding of the behavior of transitional and turbulent jet diffusion flames in microgravity as well as in normal gravity.

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References

1. Bahadori M.Y., Stocker D.P., Vaughan D.F., Zhou L., and Edelman R.B. (1993), *Modern Developments in Energy, Combustion, and Spectroscopy*, pp. 49-66, (F.A. Williams, A.K. Oppenheim, D.B. Olfe, and M. Lapp, Eds.), Pergamon Press, New York.
2. Hegde U., Zhou L., and Bahadori M.Y. (1994), *Combustion Science and Technology*, vol. 102, pp. 95-113.
3. Buckmaster J. and Peters N. (1986), *21st Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, p. 1829.
4. Lovett J.A. and Turns S.R. (1993), *Combustion Science and Technology*, vol. 94, pp. 193-217.
5. Edelman R.B. and Bahadori M.Y. (1986), *Acta Astronautica*, vol. 13, pp. 681-688.
6. Bahadori M.Y., Zhou L., Stocker D.P., and Hegde U. (1996), "Measurement of Flame Flicker Under Different Gravitational Levels," Fall Eastern States Meeting of The Combustion Institute, Hilton Head, SC.
7. Katta V.R., Goss L.P., and Roquemore W.M. (1992), Paper AIAA-92-0335, AIAA 30th Aerospace Sciences Meeting, Reno, NV.

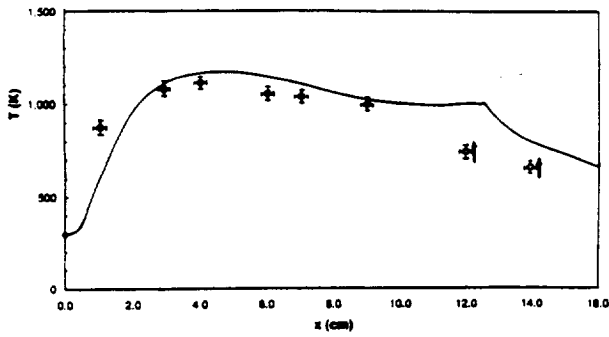


Fig. 1. Predicted and measured flame centerline temperature vs. axial distance. The temperature data at 12 and 14 cm have not reached steady state in the available microgravity period; 2 scc/sec propane flame.

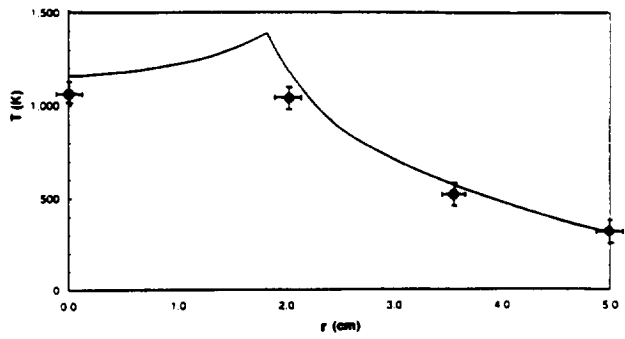


Fig. 2. Measured and predicted radial distribution of temperature for an axial location of 5 cm. The data are averages over a number of tests; 2 scc/sec propane flame.

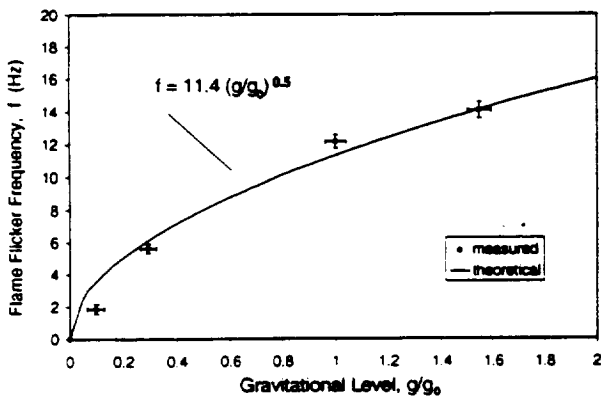


Fig. 3. Flame flicker frequency as a function of relative gravitational level; 2.5 scc/sec methane flame.

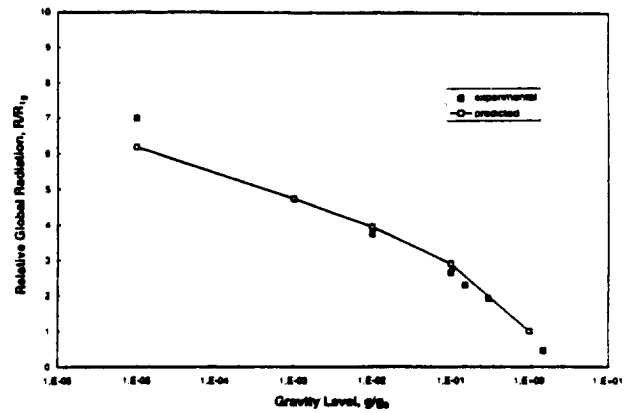


Fig. 4. Predicted and measured radiation as a function of gravitational level; 2.5 scc/sec methane flame.

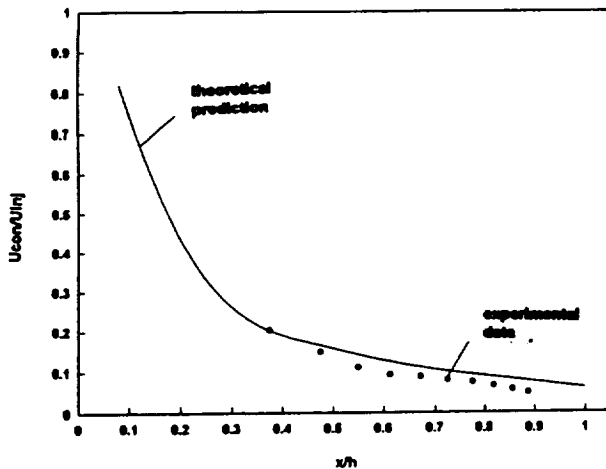


Fig. 5. Normalized predicted (solid line) and measured convection velocity for a microgravity propane flame.

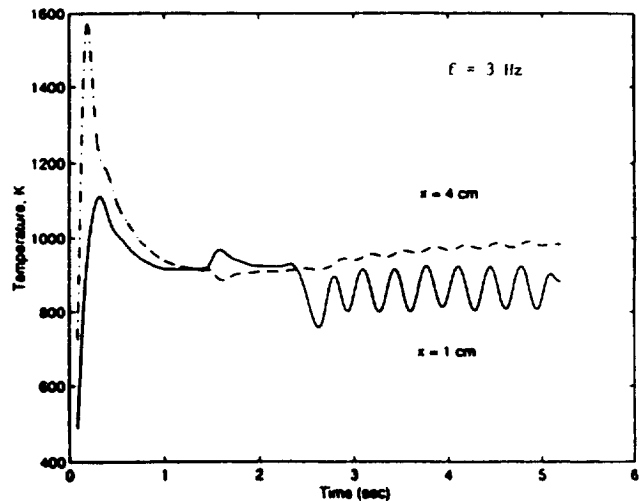


Fig. 6. Temporal evolution of the centerline temperature at $x = 1$ cm and $x = 4$ cm during a microgravity test of a 2 scc/sec propane flame; pulse frequency = 3 Hz.

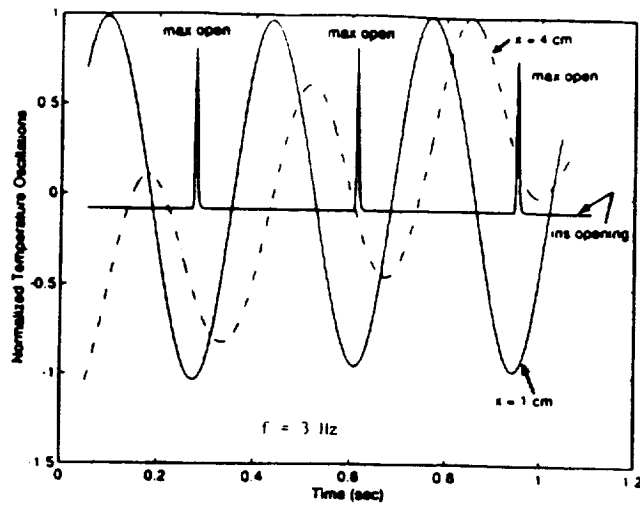


Fig. 7. Behavior of normalized temperature oscillations and iris opening; pulse frequency = 3 Hz.

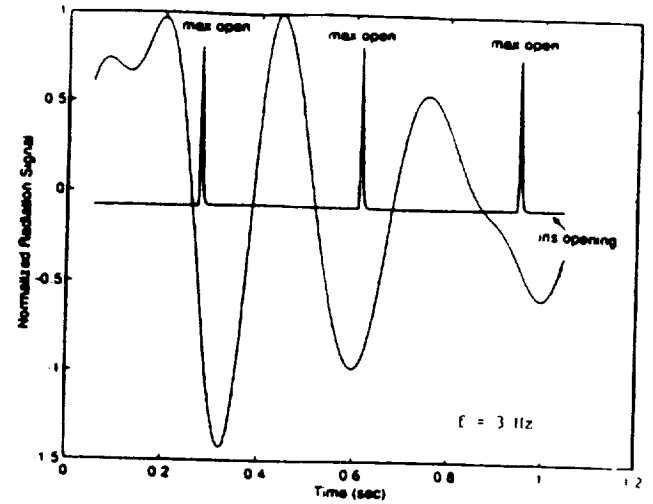


Fig. 8. Behavior of normalized radiation oscillations and iris opening; pulse frequency = 3 Hz.

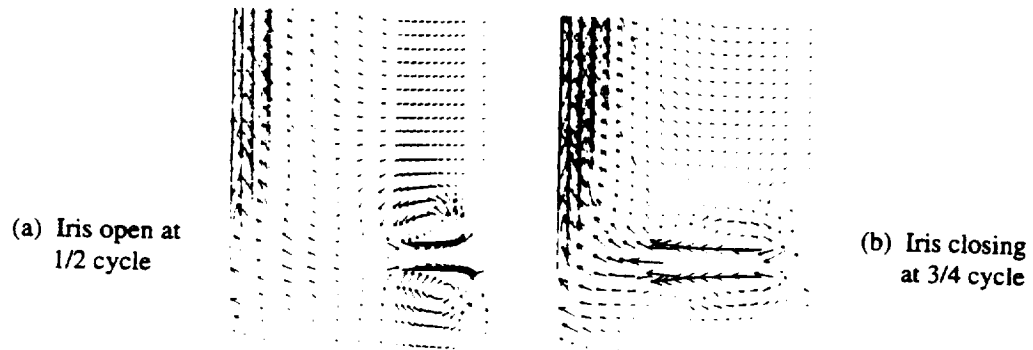


Fig. 9. Predicted instantaneous map of the velocity field of a jet under the influence of iris pulsations at 5 Hz; (a) iris open at 1/2 cycle, and (b) iris closing at 3/4 cycle.

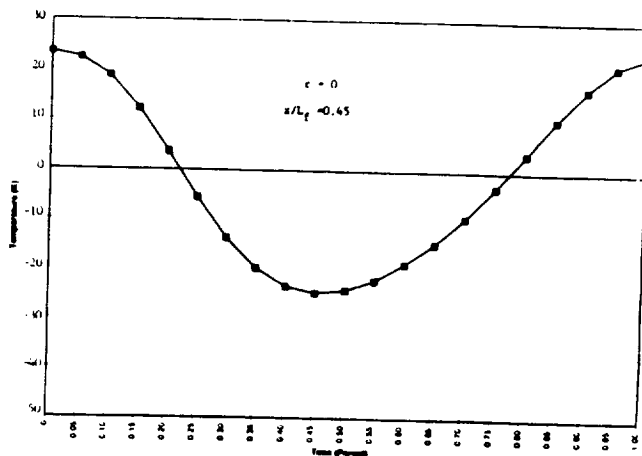


Fig. 10. Predicted oscillatory centerline temperature of a microgravity propane flame at a nondimensional height (w.r.t. flame height) of 0.45 during one cycle; pulse frequency of 5 Hz.

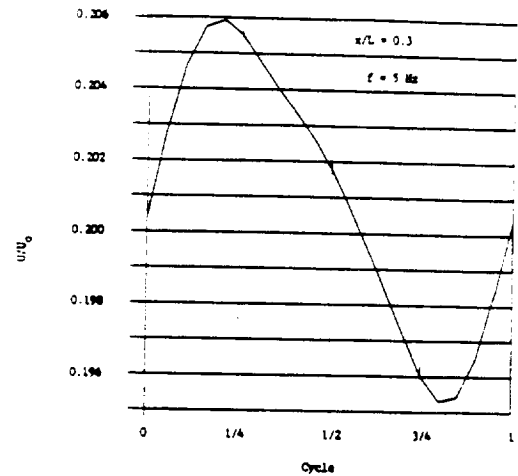


Fig. 11. Predicted nondimensional centerline velocity (w.r.t. jet exit velocity) of the microgravity flame during one cycle at an axial location of 0.3 (nondimensionalized w.r.t. flame height); iris frequency = 5 Hz.