Ignition and Behavior of Laminar Gas-Jet Diffusion Flames in Microgravity

M. Yousef Bahadori* and Raymond B. Edelman†
Science Applications International Corporation, Torrance, California
and
Dennis P. Stocker‡ and Sandra L. Olson‡
NASA Lewis Research Center, Cleveland, Ohio

This paper presents the results of studies on the ignition and behavior of cylindrically symmetric, laminar diffusion flames of methane and propane in quiescent air under microgravity conditions. The experiments were conducted in the 2.2 s NASA-Lewis Research Center Drop Tower. The characteristics of gas-jet diffusion flames ignited in microgravity environments have not been reported in the past. In prior research, similar flames were ignited in normal gravity and then subjected to the microgravity condition once the flame was established. The different ignition methods result in different flame behavior and conclusions in relation to extinction, transient adjustment, and approach toward steady state in microgravity. Specifically, some of the flames of the previous studies, which were in a transient state or reportedly extinguished, reach a near-steady state when ignited in microgravity. In addition, low-flow-rate methane flames in the present study (filmed at 15 frames/s) were entirely blue, whereas blue was not discernible in the microgravity flames of the previous works (filmed at 400 frames/s). Based on these findings, it is concluded that some of the previously reported "extinguished" flames may have been blue (and not visible on the high-speed film). In this paper, comparisons between the two methods of ignition and observations of the flame behavior and distinct nature of flame color and luminosity are presented. Application of a steady-state, parabolic model has shown satisfactory agreement between the predicted and observed flame heights for those flames that reached a near-steady state in the 2.2 s period of microgravity.

Introduction

THE term "diffusion flame" classifies those types of flames in which the fuel and the oxidizer are not premixed, and the combustion process is governed by the diffusion of reactants toward each other. Fires are a complicated type of this class of flames. Regardless of the nature of the fuel involved, (i.e., liquid, solid, or gaseous), the fundamental mechanisms that control the combustion process are the same. These include the coupled processes of mixing, chemical kinetics, flame radiation, diffusion, inertia, soot formation and disposition (in hydrocarbon flames), and, depending upon the Grashof or Froude number, buoyancy-induced convection.

Gas-jet diffusion flames are laminar or turbulent, depending on the relative effects of inertia and viscous forces, which can best be described in terms of the jet Reynolds number based on the fuel properties and nozzle size. Fundamental studies of laminar diffusion should lead to an improved understanding of turbulent diffusion flames, which are of practical interest, and are not fully understood.

The behavior of most fires on Earth is dominated by buoyancy-induced convection which masks the chemical-diffusional interactions that are fundamental to the understanding of combustion phenomena. In low-gravity environments, the buoyant force is suppressed and the remaining mechanisms of kinetics, radiation, diffusion, inertia, soot processes, and mixing become responsible for the very different observed behavior of laminar flames. As a result, aside from the primary goal of understanding the behavior of fires in spacecraft environments, microgravity combustion studies facilitate the study of the physico-chemical phenomena masked by buoyancy under normal-gravity conditions. In addition, numerical modeling of flames can benefit from the removal of one constraint (buoyant force) by focusing on the remaining phenomena, which are not separable and cannot be isolated.

Background

Laminar diffusion flames of hydrogen, methane, ethylene, and propylene have been studied[1-9] in the 2.2 s NASA Lewis Research Center Drop Tower. In these studies, the flames were ignited in normal gravity and allowed to reach steady state. The experiment package was then dropped, subjecting the flame to the microgravity condition. High-speed movies of the flames have shown that during a very short period of adjustment from normal gravity to microgravity, a sudden decrease in the flame height (h) occurred within 0.05 s. After the decrease of the flame height to a minimum with $0.6 < (h_{min}/h_{1-g}) < 1.0$ (depending on the jet Reynolds number), the flame height increased with time. This resulted in either extinction with $1.0 < (h_{ex}/h_{1-g}) < 1.3$, approach toward an apparent steady state with $1.4 < (h_{\mu-g}/h_{1-g}) < 1.7$, or continual increase until the end of the test time. Here, the subscripts min, ex, $\mu-g$, and $1-g$ correspond, respectively, to minimum, extinguished, microgravity, and normal-gravity flame heights. Compared to laminar flames in normal gravity, those observed in microgravity are larger, diffuse, and rather globular. This is due to the absence of the buoyant convection, leaving diffusion a much more important mechanism of

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*Senior Scientist, Thermal Hydraulics Division. Member AIAA. Author to whom correspondence should be sent. On-site at the NASA-Lewis Research Center, MS 500-217, Cleveland, OH 44135.

†Director of the Combustion Science and Advanced Technology Department, Chatsworth, CA. Currently at Rockwell International Corporation, Rocketdyne Division, Canoga Park, CA. Member AIAA.

‡NASA Project Scientist.

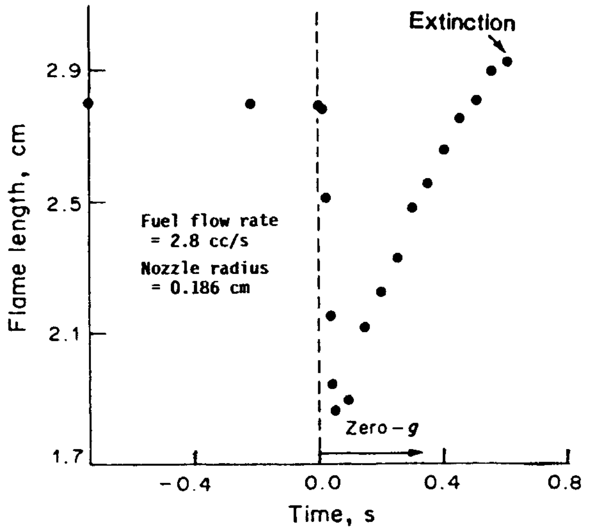

Fig. 1 Length as a function of time in microgravity for an extinguished methane-air diffusion flame.[1]

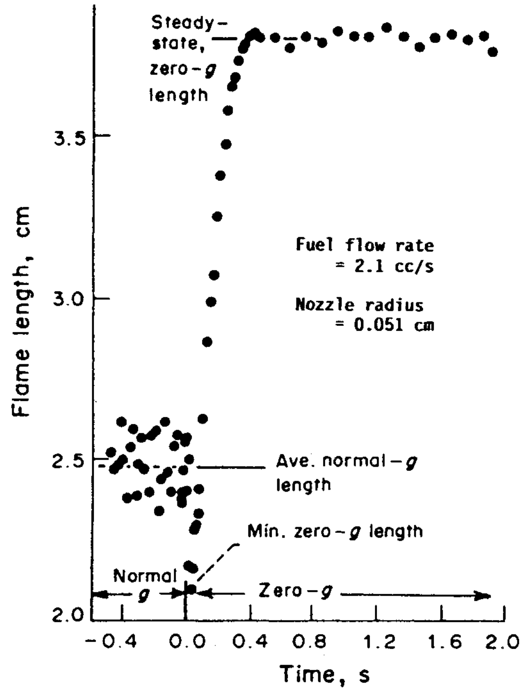

Fig. 2 Length as a function of time in microgravity for a methane-air diffusion flame that reached near-steady state.[4]

transport relative to the jet momentum. However, as will be seen later, jet momentum still affects the flame shape.

The observed flame behavior in microgravity, i.e., steady state, transient, or extinguished, has been attributed to the influence of the jet Reynolds number. Figures 1 and 2 show the behavior of two methane-air flames[1,4] in microgravity: an extinguished flame (Fig. 1) and a flame which apparently reached steady state (Fig. 2) during the drop. The data presented in the previous works[1,4] suggest that for a fixed tube size and variable fuel velocity, a certain range of the jet Reynolds number exists for which the 2.2 s available time is not sufficient to yield either flame extinction or steady state. However, it will be shown (see the Results and Discussion section) that a majority of these "transient" or even "extinguished" flames of the previous studies reached a near-steady state when the flame was ignited in microgravity.

The reported[1,4] microgravity flame behavior may best be described by the following mechanisms, based on the qualitative observations of the films. If the flame is ignited in normal gravity and then dropped, a rapid decrease in flame height occurs (see Figs. 1 and 2). This behavior is due to the sudden accumulation of the hot combustion products in the flame region, resulting from the loss of the buoyancy-driven convective flow. The flame zone then becomes shielded from the oxygen, which promotes pyrolysis of the constantly flowing fresh fuel. A critical reduction in temperature occurs, caused by a reduced heat-release rate probably due to the change in the oxidation kinetics. This enhances soot formation and radiation cooling, resulting in the onset of a chemical-kinetic limitation on the heat release process. The combination of these effects and the jet momentum leads to either extinction or a slow readjustment to a steady-state flame (with convective transport matching diffusive transport).

The sensitivity of the extinguishment process to convective transport in microgravity has been demonstrated.[8] Low forced-air velocities ($\simeq 10$ cm/s) in coaxial jets of methane-air diffusion flames were sufficient to sustain combustion in microgravity, whereas similar microgravity flames in quiescent air reportedly extinguished. This indicates that relatively small forced-convection currents play a major role in combustion under microgravity conditions.

The ignition approach previously used in the drop tower experiments exposes an established normal-gravity flame to a sudden change in the gravity level. It is not clear whether the reported microgravity flame behavior is due to this step change in gravity level or the microgravity environment itself. In addition, it is conceivable that buoyant forces could induce

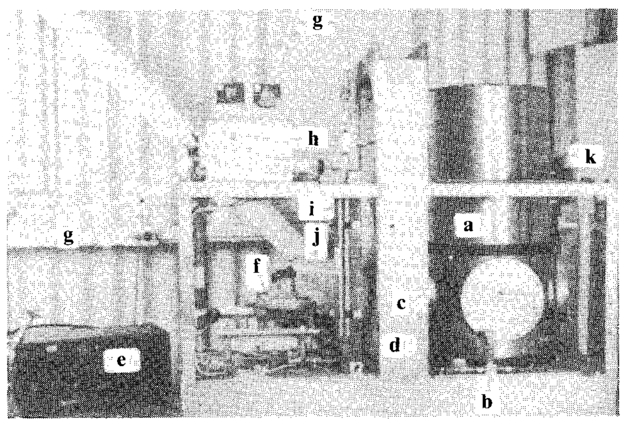

Fig. 3 Experiment package: a) combustion chamber; b) flow meter; c) viewing window partially hidden by strut; d) solenoid valve hidden by strut; e) mixing system; f) pressure regulator; g) fill line; h) control panel; i) fuel bottle; j) camera partially hidden by regulator and fuel bottle; k) to vent.

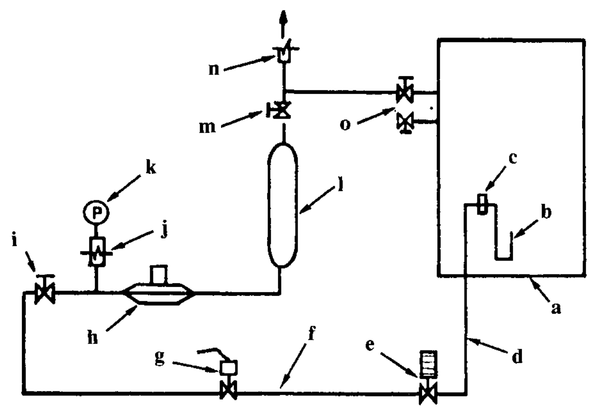

Fig. 4 Schematic diagram of the flow system: a) combustion chamber; b) burner nozzle; c) chamber bulkhead; d) 1/8 in. O.D. tubing; e) metering valve with Vernier markings; f) 1/4 in. O.D. tubing; g) solenoid valve; h) pressure regulator; i) hand valve; j) quick disconnect; k) pressure gauge; l) fuel bottle; m) hand valve; n) quick disconnect; o) vents.

Table 1 Data obtained from microgravity and normal-gravity experiments[a]

Flame number	G	Nozzle radius, cm	Fuel	Fuel volume flow rate, cm^3/s	Steady-state flame height, cm	S.S. maximum flame radius, cm	Approx. time to reach S.S., s	Reynolds number[b]
1	0	0.051	Methane	1.0	1.5[c]	0.67	0.6	38
2				2.0	3.5	0.70	0.8	76
3				3.0	5.1	0.75	1.0	114
4		0.0825		1.0	2.4[c]	1.06	1.0	24
5				2.0	3.7[c]	1.05	0.9	48
6				3.0	5.5	1.11	1.6	72
7		0.051	Propane	0.5	4.0	0.90	1.2	70
8				1.0	7.2	1.02	0.8	140
9				1.5	11.1	1.11	0.8	210
10		0.0825		0.5	3.8	1.32	1.2	44
11				1.0	7.3	1.53	1.8	88
12				1.5	9.9	1.73	1.3	132
13	1	0.051	Methane	1.0	0.9	0.35	0.8	38
14				2.0	2.0	0.43	1.3	76
15				3.0	4.0(?)	0.36	(?)	114
16		0.0825		1.0	0.9	0.38	0.6	24
17				2.0	2.5	0.60	0.4	48
18				3.0	3.6	0.61	0.3	72
19		0.051	Propane	0.5	2.6	0.45	0.4	70
20				1.0	5.6	0.50	0.4	140
21				1.5	8.0	0.50	1.3	210
22		0.0825		0.5	3.0	0.57	0.4	44
23				1.0	7.8(?)	0.50	(?)	88
24				1.5	8.0	0.58	0.4	132

[a]Question marks indicate uncertainties in the measurements due to the flame flicker.
[b]Reynolds number is based on the nozzle radius.
[c]These flames were diffuse, faint, and resembling an underventilated flame; it could not be concluded that they reached steady state.

enough momentum during the pretest normal-gravity period to persist throughout the 2.2 s test time. In order to study the true characteristics of microgravity flames, it seems logical to simplify the initial conditions by igniting the flames in microgravity. The focus of this paper is to study the behavior of flames ignited in microgravity in order to achieve a more fundamental understanding of diffusion flames.

Apparatus

Laminar methane and propane diffusion flames in quiescent air were studied in the 2.2 s NASA-Lewis Research Center Drop Tower (facility described elsewhere[6]). The experiment package and a schematic diagram of the flow system are shown in Figs. 3 and 4, respectively. The combustion chamber contains a burner, the lighting system, a viewing port for the camera, the spark ignitor, and ports for filling the chamber with oxidizer and for venting the burned gases. The other components of the system are shown in Fig. 4. The volume of the combustion chamber is approximately 0.04 m^3. Two fuel nozzles with inside radii of 0.051 cm and 0.0825 cm were used in the studies. The fuel system was calibrated, based on the standard conditions of 0°C and 1 atm. The fuel flow rates were 1.0, 2.0, and 3.0 cm^3/s for methane, and 0.5, 1.0, and 1.5 cm^3/s for propane. The 16 mm movie camera was originally set for a filming rate of 30 frames/s and the film (Tungsten Eastman Ektachrome Video News) was force-processed 2 f-stops. At this filming rate, the dim blue portion of the microgravity flames was not clearly visible in the processed films. Visibility was subsequently improved by reducing the framing rate to 15 frames/s.

A spark electrode was located 4 mm above the nozzle tip and 4 mm away from the nozzle centerline. The electrode was perpendicular to the centerline of the camera. The nozzle, electrically grounded, acted as the second electrode. The spark was pulsed at 4.8 Hz, with approximately 18 mJ/pulse. The flames were ignited during the first 0.2–0.4 s in microgravity. For all of the tests, the spark-ignition system was active for the entire 2.2 s test time and about 0.8 s after impact. The ignitor occasionally did not arc to the burner tip but shorted out elsewhere, however, this did not affect the flame behavior. A frame-by-frame study of the movies showed no disturbance of the flames by the spark during the 3.0 s of burning.

The 500-cm^3 fuel bottle contained either methane or propane filled to 2 atm. The dry air in the combustion chamber was composed of 21% oxygen and 79% nitrogen, and had a pressure of 1.0 atm in the chamber. Due to the short duration of each test, the amount of oxygen consumed was negligible, always less than 0.3% per flame. The air in the experiment chamber was changed after a number of tests were conducted, when $< 5\%$ of oxygen was depleted. Details of the experimental procedure can be found elsewhere.[10]

Results and Discussion

Table 1 shows the experimental conditions and the average steady-state flame lengths, maximum flame radii, and approximate time to reach steady state for both normal-gravity and microgravity flames of methane and propane. The normal-gravity flames flickered (except at low-flow rates), and the steady-state flame heights and maximum radii are averages. Figures 5 and 6 show the flame lengths as a function of time for methane and propane flames in microgravity, respectively. Unlike flames in normal gravity, those under the microgravity conditions are fairly steady and do not flicker. The methane flames at low volume-flow rates were very faint and appeared to have an open tip. They were sufficiently visible to identify the maximum radius, but beyond this height, visible radiation could not be observed and the flame appeared to be underventilated. This is shown by the truncated data given in Fig. 5. The higher flow-rate methane flames reached near-steady state with some fluctuations at the later times. Previous studies of these methane flames with the 0.0825 cm nozzle radius have shown a transient state at the completion of the drop.[4] In general, Table 1 shows the following relationships for flame heights (h) and maximum flame radii (r_m): $1.2 < (h_{\mu-g}/h_{1-g}) < 1.8$ for both nozzle sizes; $1.6 < (r_{m,\mu-g}/r_{m,1-g}) < 2.2$ for the smaller nozzle; $2.3 < (r_{m,\mu-g}/r_{m,1-g}) < 3.1$ for the larger nozzle. Here, the subscripts $\mu - g$ and $1 - g$ correspond to the microgravity and normal-gravity flame dimensions, respectively. An overshoot in the methane flame heights can be seen in Fig. 5, whereas the propane flames in Fig. 6 do not show this behavior. This observation is currently under investigation.

Figure 7 shows a comparison between the two methods of ignition for a methane flame, with a fuel flow rate of 3.0 cm^3/s (2.9 cm^3/s for the normal-gravity ignition case[4]) and a nozzle radius of 0.051 cm. The trends in flame development are similar, and the steady-state flame heights are the same. Typical normal-gravity flame flicker is also shown in Fig. 7. The normal-gravity ignition method suggests that the microgravity flame behavior may be affected by the flickering normal-gravity flame height at the instant the package is subjected to the microgravity condition.

The flame heights observed in the previous[4] and present studies are compared in Fig. 8. The jet Reynolds number is selected as a common parameter because it represents the effects of nozzle size, fuel type, and jet momentum, which are shown to control the behavior of the flame as far as extinction and approach toward steady state are concerned. In Fig. 8, the triangles represent those flames which have reached a (near-) steady state.[4] The flames which are reported extinguished are also shown (circles); the heights correspond to those at extinction during the drop. To distinguish between the different regimes, lines are drawn to connect the different available data points. Thus, the solid lines cover both the steady-state and extinguished regimes for which reported data is available. The broken line for the larger nozzle shows the

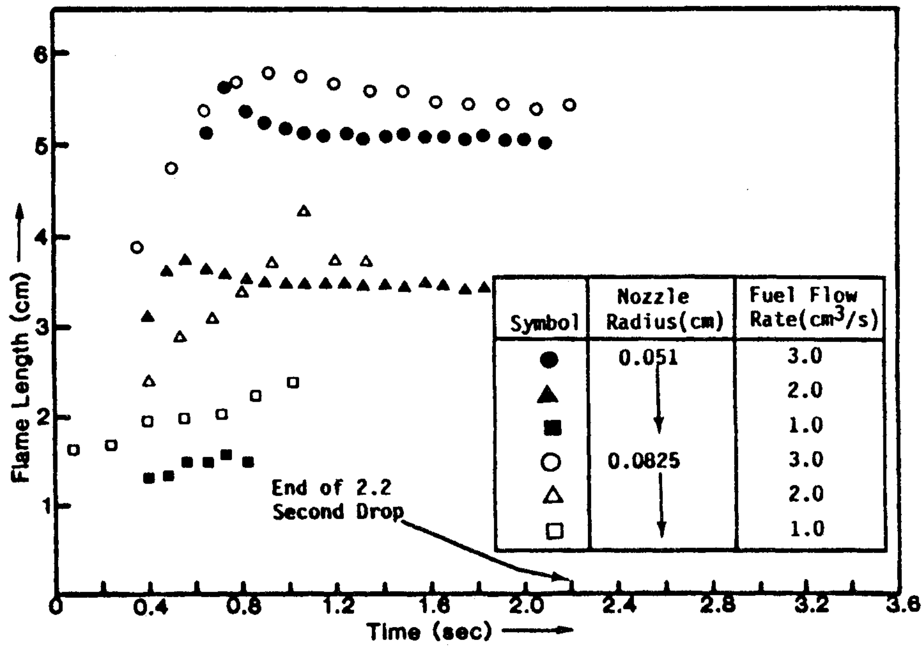

Fig. 5 Microgravity methane flame heights.

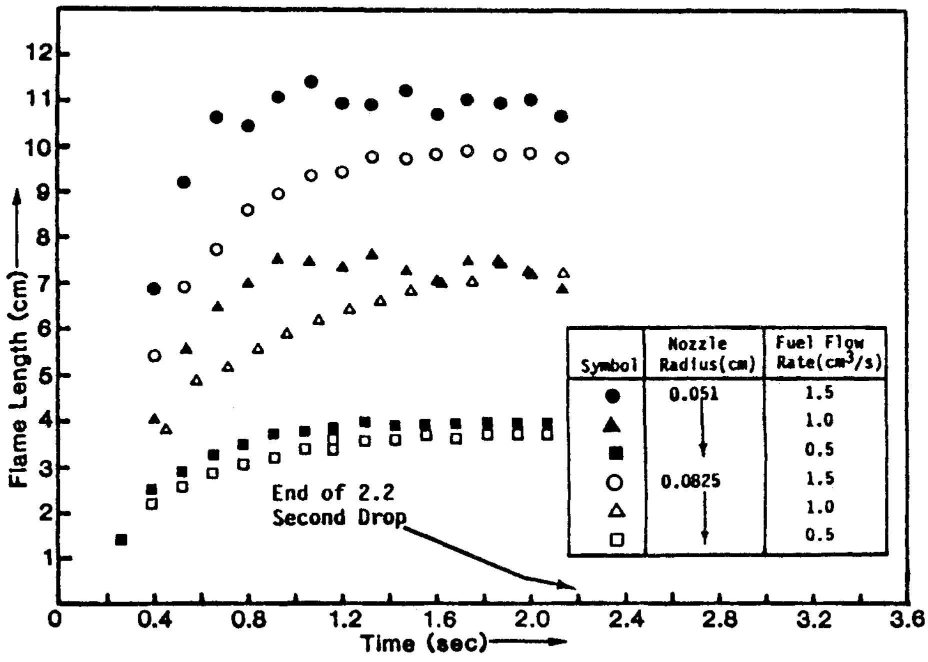

Fig. 6 Microgravity propane flame heights.

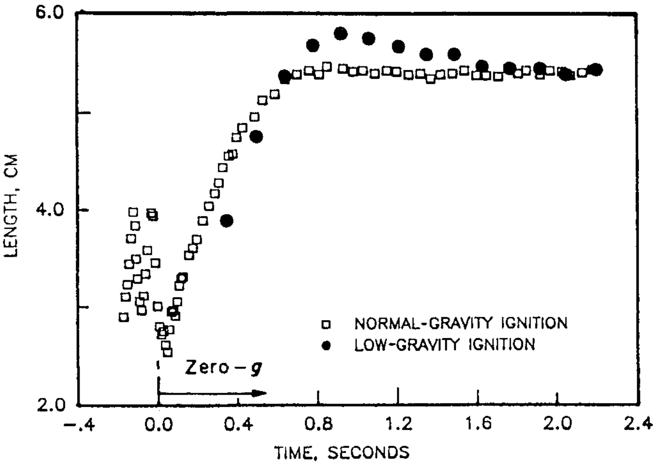

Fig. 7 Comparison between the normal-gravity[4] and microgravity ignition of flame No. 6 of Table 1.

range of Reynolds numbers for which the flames required longer than 2.2 s to establish their final state. This regime comprises the "transient" flames of the previous work,[4] for which no heights are available. In addition the dotted lines correspond to those regions for which no flames were studied. Therefore, the dotted and broken lines are not meant to indicate that flame heights can be deduced at intermediate Reynolds numbers from Fig. 8. Rather, they give the ranges of Reynolds numbers which cover this class of flames. The squares shown in Fig. 8 are the observed (near-) steady-state flame heights of the present study, obtained from Fig. 5. Although the truncated data in Fig. 5 for the lower flow rates may give the impression that the flames extinguished, these flames indeed existed throughout the drop. As mentioned before, they were very faint and appeared to have open tips with indeterminate length, resembling typical underventilated flame behavior.

It can be seen in Fig. 8, that the previously reported extinguished flames (circles) may not extinguish if the flame is ignited in microgravity. However, low-flow rate methane

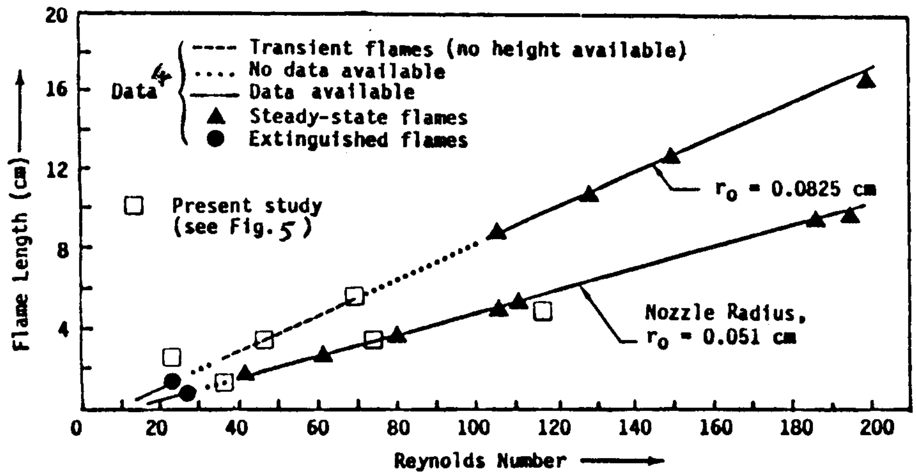

Fig. 8 Microgravity methane-flame heights as a function of jet Reynolds number (see the text for details).

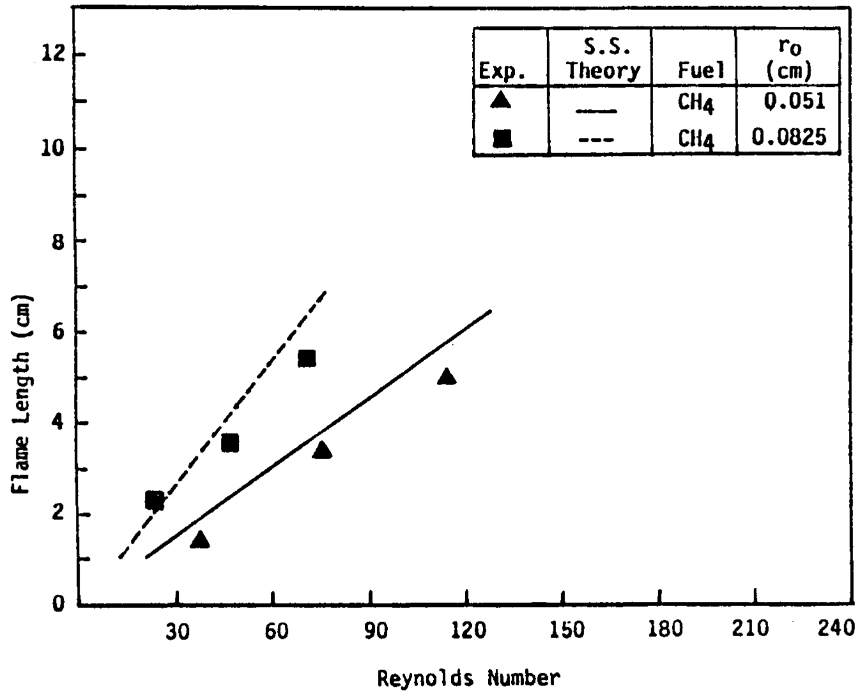

Fig. 9 Predicted and measured microgravity methane-flame heights vs jet Reynolds number.

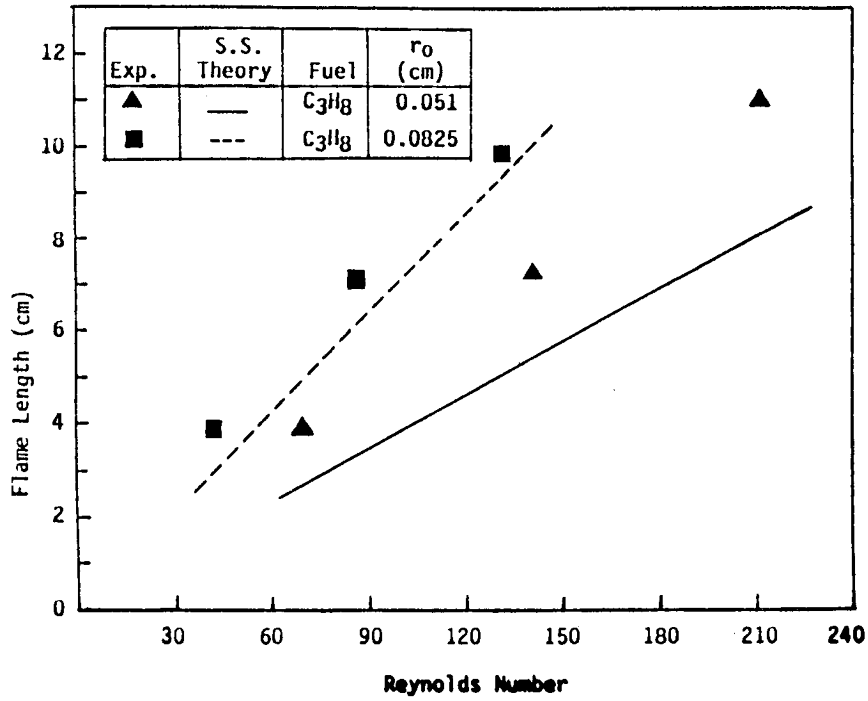

Fig. 10 Predicted and measured microgravity propane-flame heights vs jet Reynolds number.

flames in the present study (filmed at 15 frames/s) were entirely blue, whereas blue was not discernible in the microgravity flames of the previous works (filmed at 400 frames/s). Based on these findings, it is concluded that the previously reported "extinguished" flames may have been blue (and not visible on the high-speed films).

A previously developed computational model[6,7] is used to predict steady-state flame heights for comparison with the experimental data. The parabolic model for studying laminar gas-jet diffusion flames under arbitrary gravitational accelerations consists of the conservation equations for elements, mass, momentum, and energy. It includes the effects of inertia, viscosity, diffusion, and chemical reactions. The chemistry assumed is that of shifting equilibrium, and both Fickian and multicomponent diffusion are considered. The radiation model is a thin-gas approximation using carbon dioxide and water vapor. The differencing scheme is an explicit finite-difference technique. The results have shown a very good agreement with the earlier experimental data for both normal-gravity and microgravity conditions.[6,7] However, it was shown that accurate flame shape predictions require an accurate prediction of the relative rates of molecular transport of species, momentum, and energy. This steady-state, parabolic model has been applied to the microgravity flames of Figs. 5 and 6. The results are shown in Figs. 9 and 10, where a satisfactory trend in the predicted behavior of the flames is demonstrated. However, the propane flames are slightly longer and the methane flames shorter than the predicted flames. One possible explanation is the absence of soot and the associated radiation in the model in contrast to the high concentrations of soot observed in most of the microgravity flames. In addition, the absence of elliptic effects (axial diffusion) and the relatively simple predictions for the molecular transport rates (i.e., species, momentum, and energy) may contribute to the differences between the predicted and measured flame heights.

Figure 11 shows a comparison between different theoretical and experimental results. The data points correspond to the steady-state flame heights of the present study and previous work.[4] The predictions are those presented in Figs. 9 and 10 as well as the results of another theoretical modeling

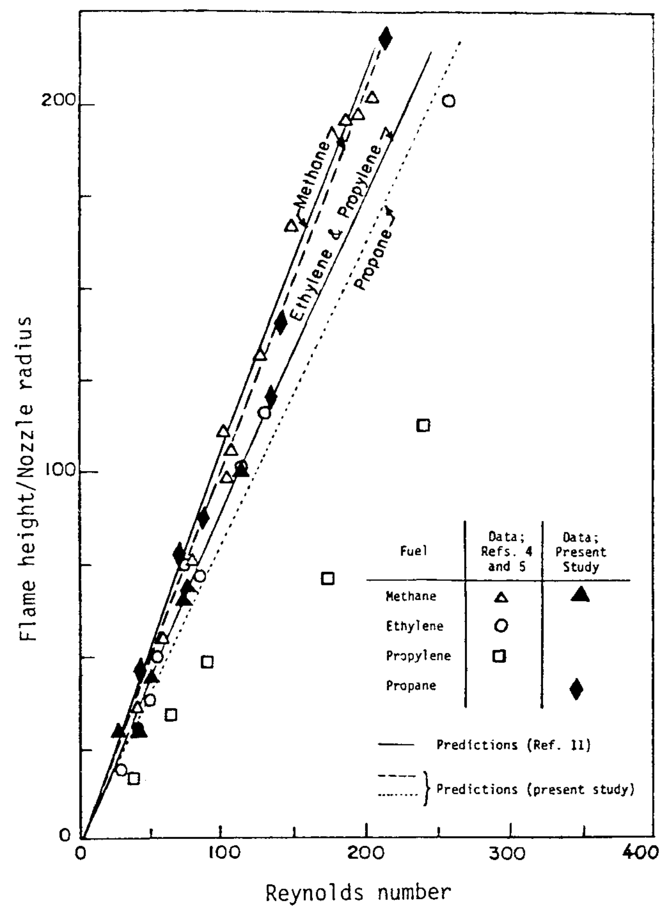

Fig. 11 Measured and predicted microgravity flame heights for different fuels; reproduced,[11] with modifications and additions.

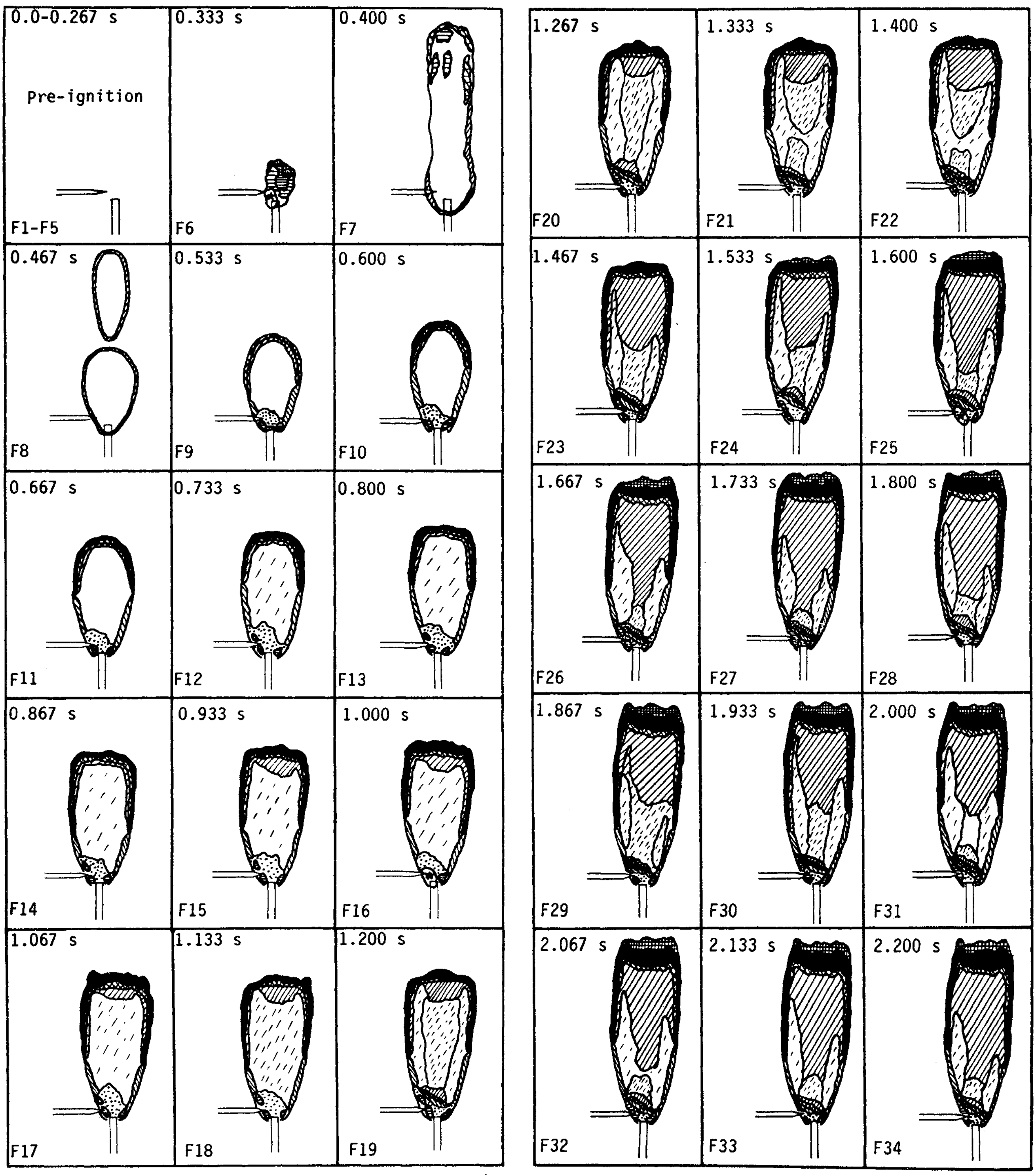

Fig. 12 Frame-by-frame analysis of microgravity propane flame No. 11 of Table 1 with nozzle radius = 0.0825 cm and volume-flow rate = 1.0 cm^3/s. The various observed colors are as follows: bright white; white with little yellow; white with more noticeable yellow; blue; dark blue; violet/pink; mixed blue/violet; yellow; orange; cherry red; dull red, fainting; color at the base, starting with dark at the bottom, becoming dark blue/pink, then pink/blue, then pink/orange, then orange/yellow, and then yellow/white toward the center of the flame; bright white spark with bright blue at its boundary. Scale = 1 cm. Note the asymmetry caused by the electrode.

effort.[11] The two numerical models show a good agreement with each other and with the data. The propylene-flame heights of the previous studies[4] do not agree with the predictions.[11] This is surprising, since propylene and propane are very close in chemical structure and satisfactory agreement is obtained for methane, ethylene, and propane.

In gas-jet diffusion flames, the heat-release mechanism is not uniform throughout the flowfield. Pyrolysis, producing soot and partially oxidized species, dominates in the near-jet region, while the continued heating and increased residence time result in the tendency to burn off these species downstream in the vicinity of the flame tip. However, pyrolysis and soot formation reduce the temperature level in the flame and, with the aid of the increased residence time, sooting is enhanced. This, in turn, results in enhanced radiation, more cooling, and delayed soot burn-off downstream of the flame. This effect is much more pronounced in microgravity flames than those in normal gravity, due to the lack of buoyancy. As

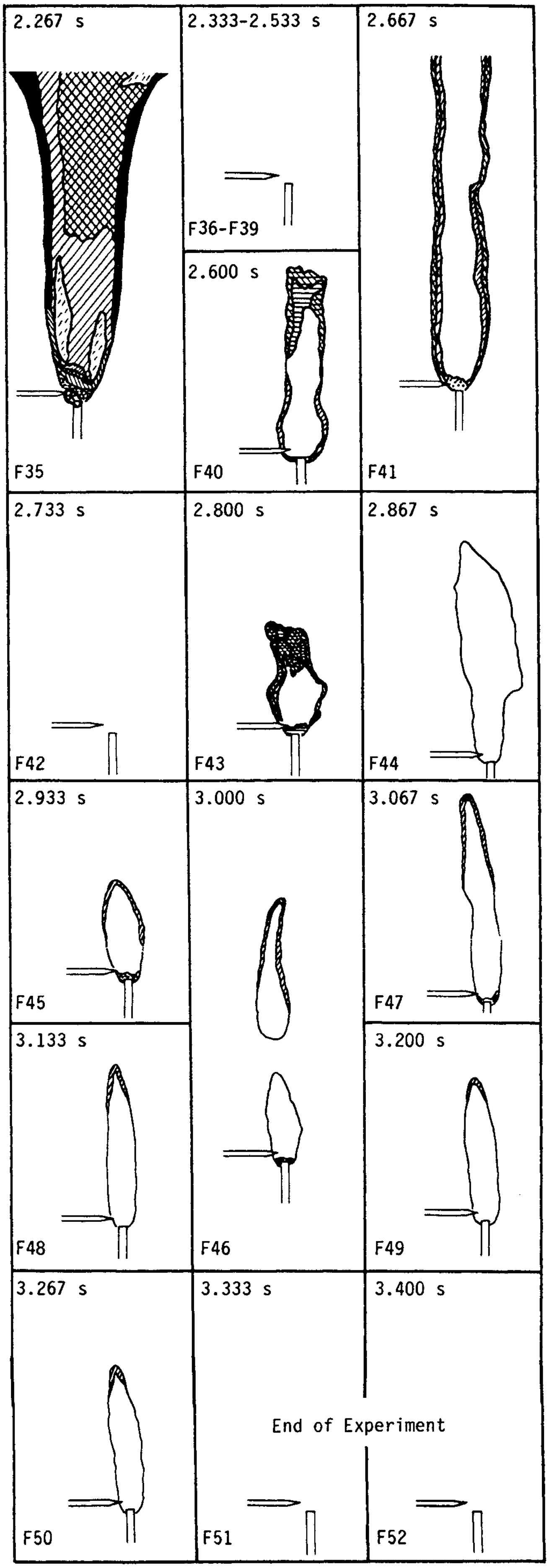

Fig. 12 Continued.

a result, thermophoretic effects may become an important factor in the regions of large temperature gradients with high soot concentrations. The observed open tip of the propane flames and quenching at the tip give the appearance of an underventilated flame (see Fig. 12).

In Fig. 12, a frame-by-frame analysis of flame No. 11 of Table 1 is presented. This propane flame reaches steady state and remains fairly uniform throughout the drop. The colors indicate the presence of particular species in hydrocarbon flames, e.g., blue-violet region (outer region at the base showing the spectrum of burning CO) and bluish-green region (showing C_2 and CH emissions, where C_2 bands appear green shaded toward violet and CH bands appear violet-blue). A highly luminous zone (bright yellow) indicates the thermal emission of burning carbon particles. This luminous zone becomes yellow, then orange, and then red and dark red toward the boundary of the visible region, as the temperature of the unburned soot decreases. The reddish-orange color of the flame is due to the soot at cooler temperatures than would be expected for typical burnoff conditions.

The color of the radiating soot, in conjunction with Wien's law, can be used as an indicator of the approximate local flame temperature. The cloud of burning soot particles is yellow, i.e., ~ 0.58-μm wavelength ($1370\ K < T < 1670\ K$, where 1670 K is the temperature of a white hot body). As the temperature decreases, the soot particles become orange red (~ 1370 K, $\sim 0.6\ \mu$m), then cherry red (~ 1170 K, 0.6–0.65 μm), and finally dull red (~ 970 K, 0.65–0.70 μm). These effects are shown clearly in the results of Fig. 12, which indicate cooling by pyrolysis and enhanced radiation due to increased soot formation.

Frame number 35 of Fig. 12 shows the flame during the rapid deceleration as the experiment package is brought to rest at the end of the drop. The high level of induced convection causes blowoff within <0.1 s. After the impact, reignition can be seen due to the spark pulses, resulting in normal-gravity behavior, i.e., flame flicker. Examination of high-speed movies for the deceleration period reveals the behavior of the flame in the transient state under rapid changes in gravity level, providing byproduct data for further analysis. A study of laminar diffusion flames under elevated gravitational conditions is reported elsewhere.[12]

Conclusions

Ignition of laminar methane and propane diffusion flames in microgravity environments has been demonstrated. The new ignition method combined with the refined photographic technique has shown that flames previously thought to have been extinguished were still burning during the entire 2.2 s of microgravity.

The low-flow rate methane flames are blue and very dim, prompting further studies to determine the extinction limits for laminar diffusion flames in microgravity environments.

Many flames (especially those of propane) have an open tip resembling an underventilated behavior. This is attributed to radiation, soot formation, and possibly thermophoretic effects, which appear to become more important in flames under microgravity conditions. However, a thorough analysis must be made to determine the relative importance of each.

The predicted flame heights, using a steady-state parabolic model, are in good agreement with the measured steady-state flame heights.

Longer test times are planned through the use of the 5.18 s Zero-Gravity Facility and the KC-135 aircraft (free-floating, 10–15 s). Flame visualization, and radiation, temperature, and concentration measurements at these longer test times are going to provide a more complete quantitative description of these flames.

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