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EFFECTS OF GRAVITY ON LAMINAR GAS JET DIFFUSION FLAMES

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16. Abstract

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SUMMARY

An experimental program was conducted to study the burning of laminar gas jet diffusion flames in a zero-gravity environment. The tests were conducted in the Lewis Research Center 2.2-Second Zero-Gravity Facility. The photographic results indicated that a sudden decrease in gravity level from 1 to 0 effected an immediate reduction in the length of the flame. Continued time in zero gravity resulted in the flame expanding away from the burner until extinguishment appeared to occur. Nondimensionalization of the governing flow equation yielded the parameters used to correlate the buoyancy effects.

INTRODUCTION

One of the important considerations in designing manned spacecraft is fire safety. Although nonflammable materials are used wherever possible, some solids and gases remain as potential fuels. The type of combustion process expected, should a fire occur, is termed a diffusion flame. Diffusion flames are characterized by the fact that the rate of the mixing of the fuel and oxidant, a fluid dynamic process, rather than the rate of chemical reaction controls the rate of combustion. The maximum temperature differences in diffusion flames are characteristically high ($\approx 2000^\circ$ C). This raises the possibility that buoyancy, or the lack of it, may affect the fluid dynamics of the hot gases. Therefore, to better cope with the problems of fires aboard spacecraft, an understanding of combustion in low- and zero-gravity environments where buoyancy is small or absent is desirable.

Research that has been done to date in this area has concentrated on gravity effects on the burning of solids and liquids. Kumagai and Isoda (ref. 1) observed liquid droplets burning in reduced gravity and concluded that gravity-induced convection had a definite effect on the combustion process. Hall (ref. 2) experimented with a candle burning in a zero-gravity environment that was attained by flying an airplane through parabolic trajectories. He concluded that, although the geometry of the flame was different in zero-gravity as compared with normal gravity, burning continued for the entire test duration of 28 seconds. Kimzey, et al. (ref. 3) also conducted tests in an airplane with paraffin and other combustibles and found that for some fuels the flames went out in zero gravity. A recent theoretical study (ref. 4) calculated the extinguishment time for paraffin burning in air in zero gravity and obtained satisfactory agreement with the experimental data of reference 3. In further zero-gravity (drop tower) experimentation, Andracchio and Aydelott (ref. 5) burned different solids in an oxygen-rich atmosphere. The primary conclusion of their work was that the flame spread rate in zero gravity was smaller than in normal gravity.

Another combustion process that appears to be affected by gravity is a gas jet diffusion flame. A simple example of this type of flame is fuel flowing from a burner tube into air with which it is reacting. Hottel and Hawthorne have implied the gravity dependence of this kind of burning in reference 6. They developed a general correlation in terms of the Grashof number, $Gr = \rho^2 d^3 \beta g \, \Delta T/\mu^2$ (symbols are defined in the appendix), for the length of laminar flames in normal gravity. Thomas (ref. 7) has suggested for turbulent flames that a reduction in gravity would result in the flames becoming larger. In a recent text, Strehlow (ref. 8) stated that buoyancy should have an effect on the aerodynamics of gas jet diffusion flames. In searching the literature, however, it is apparent that the lack of data on gas jet flames in various gravity environments has made it difficult to validate and extend existing hypotheses.

This report presents the results of research conducted in the NASA Lewis Research Center 2.2-Second Zero-Gravity Facility on the effects of gravity on laminar gas jet diffusion flames. Both color and infrared motion pictures were taken of methane burning in air in normal and zero gravity. Fuel flow rates at the burner ranged from 1.22 to 5.3 cubic centimeters per second for burners 0.186, 0.318, and 0.442 centimeter in radius. The governing flow equation was developed and nondimensionalized to yield the parameters used to correlate the buoyancy effects.

ANALYSIS

Background

The first significant work on jet diffusion flames was done by Burke and Schumann (ref. 9), who investigated the enclosed jet diffusion flame. This configuration was obtained by flowing fuel from a small-diameter burner tube into air flowing at the same velocity in a wider concentric tube. Analytically they solved only the radial diffusion problem. The most important fluid dynamic assumption was that the gas velocity parallel to the tube axis was constant. Comparison of the theory with experimental data indicated satisfactory agreement.

Early work on open jet diffusion flames was done about the same time by Hottel and Hawthorne (ref. 6) and by Wohl, Gazley, and Kapp (ref. 10). The approach of these investigators differed from that of Burke and Schumann in that they included some fluid dynamic effects by using empirical or semiempirical relations in fitting theory to experimental data. The disadvantage of this approach was that no explicit information regarding the nature of the fluid dynamic effects was obtained.

In recent years, workers have attempted more general treatments of the problem. Goldburg and Cheng (ref. 11) found similarity solutions for a horizontal laminar gas jet diffusion flame. Their analysis solved the continuity, momentum, and energy equations, neglecting gravity effects. The primary conclusion of the work was that similarity solutions were only valid far downstream of the burner, away from the reaction zone. Making use of this conclusion, Chervinsky and Timnat (ref. 12) used nonsimilar expressions to solve the same problem; comparison of theory and experimental data is to be made by them in a subsequent publication.

Proposed Gravity Effects

In reviewing the literature, it is apparent that a comprehensive investigation, either experimental or theoretical, of gravity effects on laminar gas jet diffusion flames has not been made. The physics of this problem are complex, and in many parts, undefined, even without considering the gravity effects. For instance, the fluid dynamics of a low-velocity free jet issuing into the same medium are not even adequately understood at this date. Therefore, the objective of the present analysis is not to attempt a complete solution of the problem, but rather to concentrate on the possible effects gravity could have on the fluid dynamics of laminar jet flames.

The nature of a gas jet diffusion flame is determined by the flow in the vicinity of the reaction zone. The terminology laminar or turbulent is descriptive of this flow. These flow criteria are not to be confused with the flow condition in the burner tube. In other words, the Reynolds number of the fuel flow in the burner tube is not necessarily an indication of the character of the flame. In this report, only laminar flames are considered.

A schematic diagram of a laminar flame attached to a tube-type burner in normal gravity is shown in figure 1. Experimental data, such as in reference 13, indicate that the hottest region of the flame is in the reaction zone. Therefore, on the oxidant side of the reaction zone, the temperature gradient is in the opposite direction from the

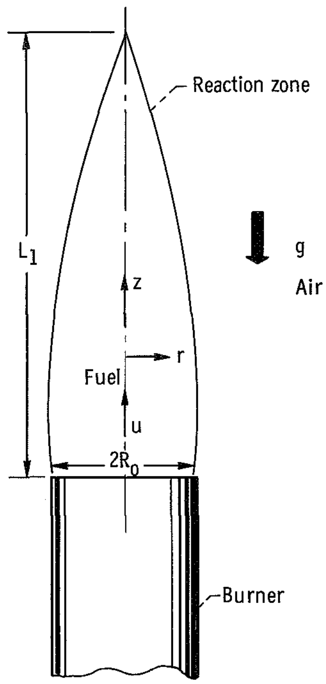


Figure 1. - Normal-gravity laminar gas jet diffusion flame.

acceleration due to gravity, and thus a buoyant effect is created. The axial position in the vicinity of the flame where these buoyant effects should be the strongest is at the flame tip L_1. At this point, buoyancy has increased the momentum of the hot gases over the longest distance.

The equation governing the axial motion of fluid exterior to the reaction zone of a laminar jet diffusion flame is

$$\rho\left(u \frac{\partial u}{\partial z} + v \frac{\partial u}{\partial r}\right) = -\frac{dP}{dz} + \frac{1}{r} \frac{\partial}{\partial r}\left(\mu r \frac{\partial u}{\partial r}\right) + \rho g \tag{1}$$

This boundary layer equation is the same as that used in references 11 and 12, with the addition of pressure and gravitational terms. If it is assumed that pressure differences in the flow field are small and that the continuum is a perfect gas, equation (1) can be reduced to

$$\rho\left(u \frac{\partial u}{\partial z} + v \frac{\partial u}{\partial r}\right) = \rho\ \Delta T g \beta_{AM} + \frac{1}{r} \frac{\partial}{\partial r}\left(\mu r \frac{\partial u}{\partial r}\right) \tag{2}$$

Although this equation is similar in form to the Boussinesq formulation for free convection, it is not as restrictive: it can be applied to problems in which there are large as well as small temperature differences. Nondimensionalization of this equation with respect to characteristic values results in

$$\left(\frac{\rho_M U_\infty R_o}{\mu_M}\right)^2 \bar{\rho}\left(\bar{u}\frac{\partial \bar{u}}{\partial z} + \bar{v}\frac{\partial \bar{u}}{\partial r}\right) = \left(\frac{\rho_M^2 \Delta T_{AF}\beta_M g R_o^3}{\mu_M}\right)\bar{\rho}\,\Delta\bar{T}\,\bar{\beta} + \left(\frac{\rho_M U_\infty R_o}{\mu_M}\right)\frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\bar{\mu}\,\bar{r}\frac{\partial \bar{u}}{\partial \bar{r}}\right) \qquad (3)$$

The characteristic property values have been taken at a mean temperature in the flow field $T_M = \frac{1}{2}(T_{AF} + T_{AM})$, where T_{AF} is the adiabatic flame temperature and T_{AM} is the ambient air temperature. The average free stream velocity at the burner is used to nondimensionalize velocity, while the burner outer radius is assumed to be the characteristic length. The term ΔT_{AF} is the maximum anticipated temperature difference $T_{AF} - T_{AM}$.

The air and products of combustion move in the axial direction under the influence of buoyancy and the inertia of the fluid issuing from the nozzle. A comparison of the relative importance of these two effects in driving the fluid can be made by comparing the order of magnitude of the parameters in equation (3) indicative of these effects. As would be expected, the Grashof number, $Gr = \rho_M^2 \Delta T_{AF}\beta_M g R_o^3/\mu_M^2$, characterizes the buoyancy effects while the Reynolds number squared, $Re^2 = \rho_M^2 U_\infty^2 R_o^2/\mu_M^2$, is representative of the inertia effects. Table I presents these parameters evaluated for conditions typical of the present experimentation. In evaluating the parameters, the fluid properties are assumed to be approximately equal to those for air. It is apparent from this

TABLE I. - GRAVITY AND INERTIA PARAMETERS

FOR TYPICAL TEST RUNS

[Adiabatic flame temperature, 1875° C; ambient air temperature, 21° C; fluid properties obtained from ref. 14.]

Nozzle radius, R_o, cm	Flow rate, cm^3/sec	Grashof number, Gr	Reynolds number squared, Re^2
0.186	1	3.85	1.06
.186	5	3.85	26.62
.318	1	19.15	.37
.318	5	19.15	9.22
.442	1	51.80	.192
.442	5	51.80	4.79

table that buoyancy can play an important role in determining the convective motion of the fluid external to the reaction zone.

The buoyancy influence on the convective motion can affect the flame in at least two ways. The first and most obvious effect is through the diffusive motion of the oxidant. Since the diffusion equation

$$\rho\left(u \frac{\partial c}{\partial z} + v \frac{\partial c}{\partial r}\right) = \frac{1}{r} \frac{\partial}{\partial r}\left(\rho D r \frac{\partial c}{\partial r}\right) \tag{4}$$

contains convection terms, the concentration profile for the oxidant in the flow field will depend on buoyancy. Further, the criterion for the position of the reaction zone is that the rate at which the oxidant and fuel arrive at the zone be in stoichiometric ratio. Therefore, because convection affects the rate of oxidant diffusion, the geometry of flames depends on gravitational effects.

Another factor that affects the oxidant diffusion is the concentration of the products of combustion in the flow field. Since the motion of the products of combustion and, hence, the concentration, is dependent on convection, gravity again affects the diffusive motion of the oxidant and, ultimately, the geometry of the flame.

In summary, it is hypothesized that gravity affects the geometry of laminar gas jet diffusion flames by influencing the diffusion of oxidant. This influence is realized in two ways: the convective motion of the oxidant and the concentration of the medium through which the oxidant is diffusing. Experiments were conducted in the Lewis Research Center 2.2-Second Zero-Gravity Facility to pursue these theories further.

APPARATUS

2.2-Second Zero-Gravity Facility

The zero-gravity experiment results were obtained in the drop tower shown in figure 2. A test time of 2.2 seconds was obtained by allowing the experiment package to undergo an approximate 24-meter unguided free fall. The experiment was prepared on the fifth floor of the tower, hoisted to the eighth floor, and suspended from the ceiling by a highly stressed music wire. Release of the experiment was accomplished by pressurization of an air cylinder that forced a knife edge into the support wire, which rested against an anvil. The experimental package was decelerated by allowing aluminum spikes that were mounted on the drag shield to embed in a container filled with sand.

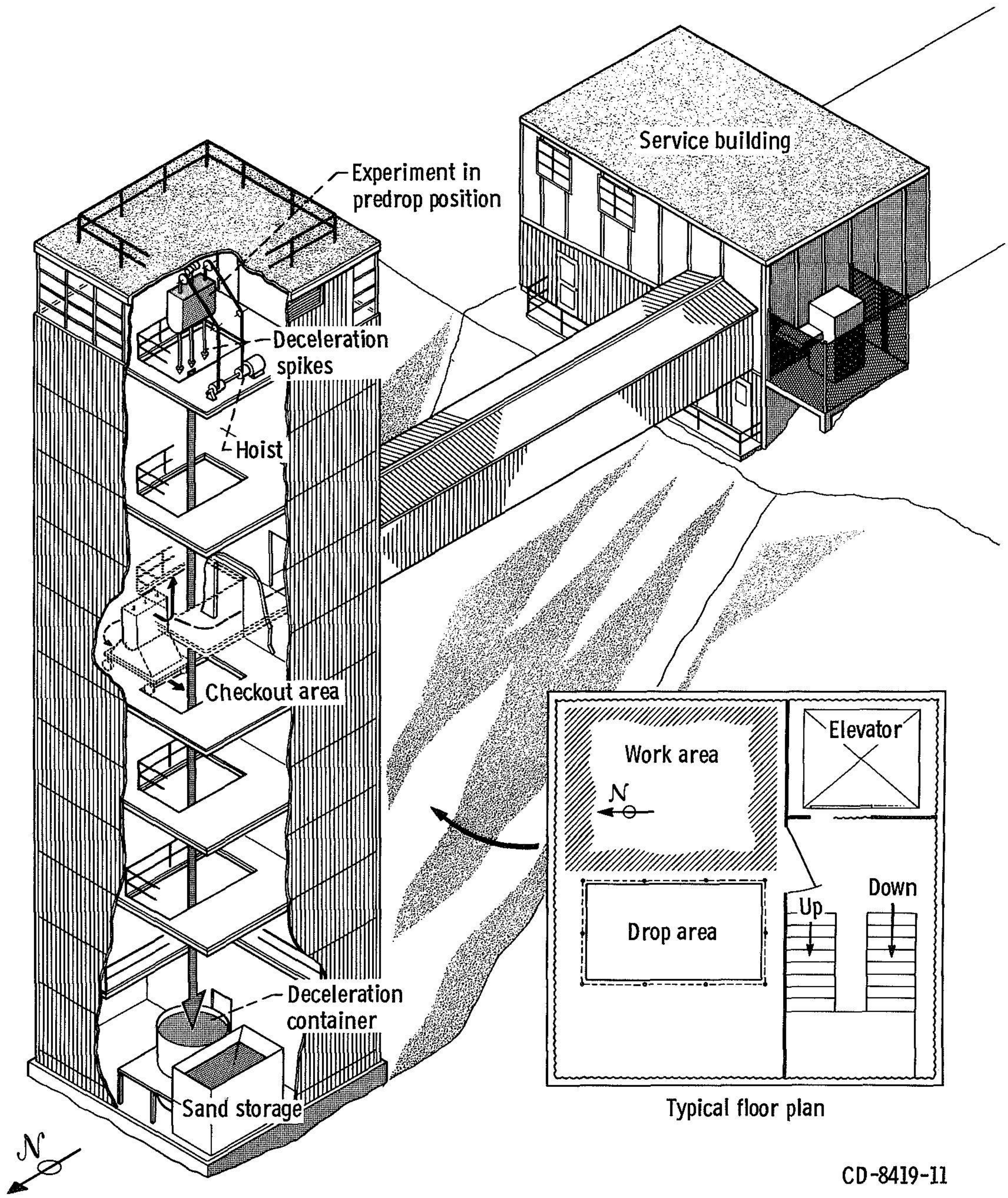


Figure 2. - 2.2-Second Zero-Gravity Facility.

Drag Shield

Air resistance on the experiment package was reduced by allowing it to free fall inside a protective air-drag shield, as shown in figure 3. The drag shield was designed with a high ratio of weight to frontal area and a low drag coefficient so that the deviation from true free fall would be minimized. As a result, the experimental package was subjected to a gravity level of less than 10^{-5} g (essentially zero). Prior to deceleration in the sand box, the package came to rest on the bottom of the drag shield, which resulted in a usable zero-gravity test time of 2.2 seconds.

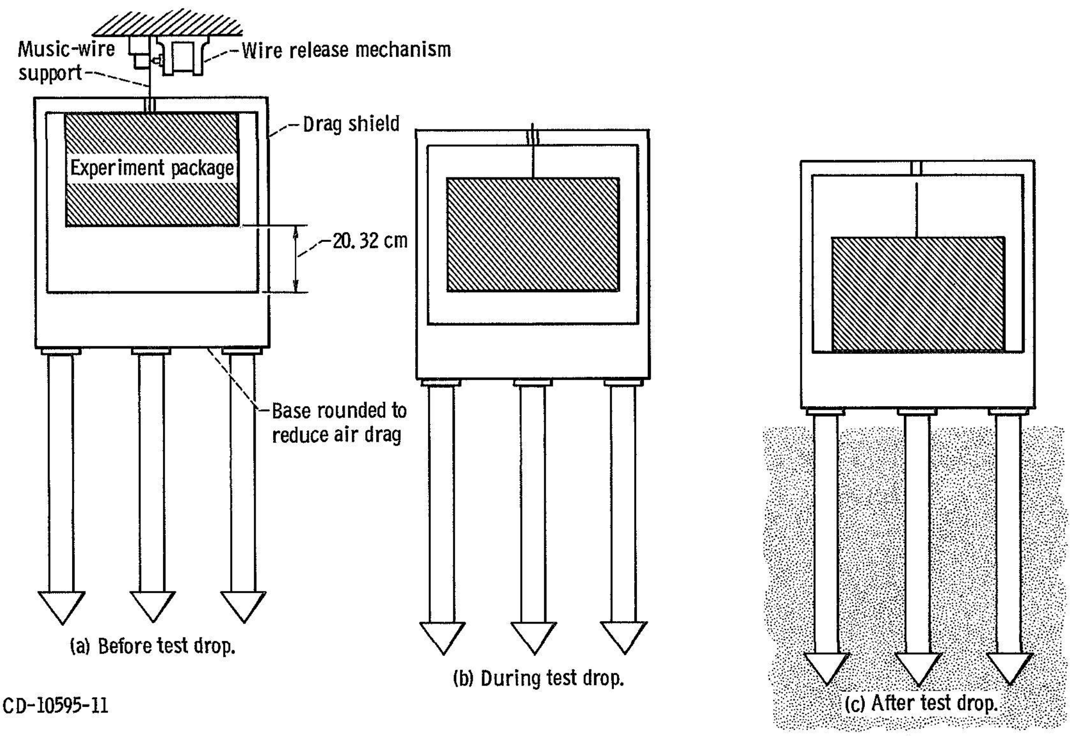
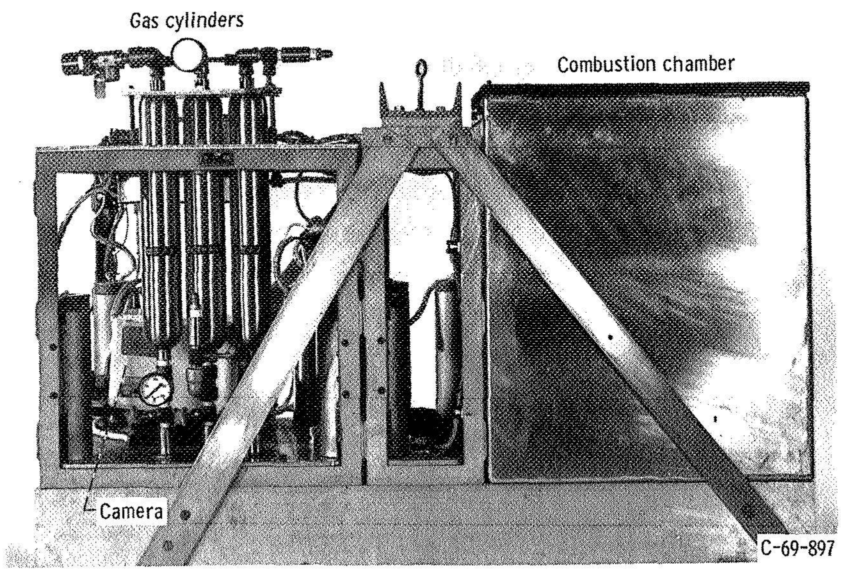


Figure 3. - Position of experiment package and drag shield before, during, and after test drop.

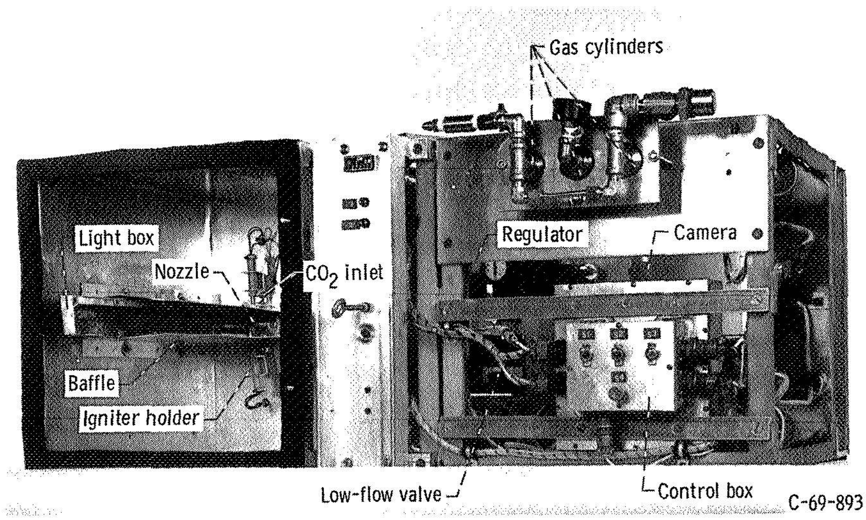
Experiment Package

The experiment package, as shown in figure 4, contained a combustion chamber, camera, clock, methane flow system, carbon dioxide flow system, and associated controls and dc power supplies.

The combustion chamber contained the burner, lighting equipment, baffles, carbon dioxide inlets, and the ignition system. The chamber was approximately 41 centimeters



(a) Side view.



(b) Top view.

Figure 4. - Experiment package.

long by 41 centimeters wiae by 48 centimeters high. The top of the chamber had holes in it to ensure equilization of pressure with the atmosphere during burning. The volume of the chamber was such that there was over 100 times the amount of air necessary to burn the fuel at the highest flow rate for at least 10 seconds. Baffles were used in some tests to reduce flickering of the flames. Their effect on the data, as discussed in the section RESULTS AND DISCUSSION, was concluded to be negligible. The igniter was a 0.33-centimeter-diameter nichrome wire attached at its ends to copper rods. Current to the wire was supplied by a 14.4-volt, 1.75 ampere-hour pack of batteries. One wall of the chamber was cut away and replaced with plastic sheet. Lighting was indirect so that the flames could be photographed against a black background.

The two types of film used were color and infrared. The color was high-speed 16-millimeter Ektachrome EF (tungsten) manufactured by the Eastman Kodak Company. Pictures were taken with this film at an aperture setting of f-1.1 and a speed of 400 frames per second. The color film was processed to an ASA of 250. The infrared film was also a high-speed 16-millimeter film manufactured by the Eastman Kodak Company. The aperture setting was the same as that for the color film; however, the camera speed was much slower at 5 frames per second. These tests were run with no filter on the lens of the camera and the plastic sheet removed so that the film recorded visible radiation as well as infrared radiation up to about 900 millimicrons. A clock radiation accurate to 0.02 second was in the field of view of the camera for the color film tests.

The methane flow system included a 500-milliliter stainless-steel vessel, flow valves, a relief valve, a low-flow needle valve, two explosion-proof solenoids, stainless-steel tubing, and a pressure regulator. In this system, the solenoids were connected in series to ensure that flow stopped upon deactivation.

Carbon dioxide was included to dilute the contents of the combustion chamber below the flammability limit after the test. This system consisted of two 500-milliliter stainless-steel vessels, flow valves, a relief valve, two explosion-proof solenoids, and stainless-steel tubing. Mounting of the solenoids in parallel ensured flow upon activation.

EXPERIMENTAL PROCEDURE AND DATA REDUCTION

Calibrations

Prior to the normal- and zero-gravity experimentation, calibrations to determine flame length as a function of flow rate were conducted. The flow measuring device, a rotameter, was installed in the methane flow system. Motion pictures were then taken of flames at different lengths, and the respective flow rates were recorded. Data were obtained for each of the different burners over the range of flow to be used in the experiments.

Experimentation

The methane cylinder was charged to a pressure of approximately 14×10^5 newtons per square meter ($\approx$200 psi) and the carbon dioxide cylinders to about 34.5×10^5 newtons per square meter (≈500 psi). The experiment package was placed in the drag shield and raised to the top of the tower.

Approximately 5 seconds before the drop, the lights were turned on, and the methane flow, camera, and clock were started. One second later, the ignition system was activated. The remaining 4 seconds before the drop were used to permit the flame to come to steady state. The drag shield and experiment were released, and about 2 seconds of zero-gravity data were obtained. Just before impact in the sand, the methane flow was stopped, the camera, clock, and lights were turned off, and the carbon dioxide system was activated. These steps removed potential ignition sources and diluted a possible combustible mixture.

Data Reduction

The data recorded on film were viewed on a motion analyzer. In addition to generally observing the phenomena, measurements of flame length as a function of time were made. A scale factor for the flame length measurements was obtained from the burner outer diameter.

RESULTS AND DISCUSSION

Normal-Gravity Calibrations

The relation between flame length and flow rate for the different burners was established by conducting a total of 36 normal-gravity tests. The results are presented in figure 5.

It can be seen that, for a particular flow rate, the flame length is insensitive to changes in burner size and, hence, free stream velocity at the burner. This result is in agreement with the findings of previous investigators (refs. 6 and 10). The dependence of flame length on flow rate was approximately linear and is assumed to be represented by the straight line that was faired through the data. These findings are in agreement with those of Wohl, et al. (ref. 10), who measured flame length as a function of flow rate for city gas. Their empirically determined correlation was approximately linear between flow rates of 1 and 6 cubic centimeters per second.

There is relatively little scatter in the data at low flow rates; however, there is some at the higher values. This is attributed to flickering or pulsating of the flame. In all but three tests, the amplitude of the oscillations was less than ±5 percent of the average height. The maximum amplitude was ±7 percent of the average height.

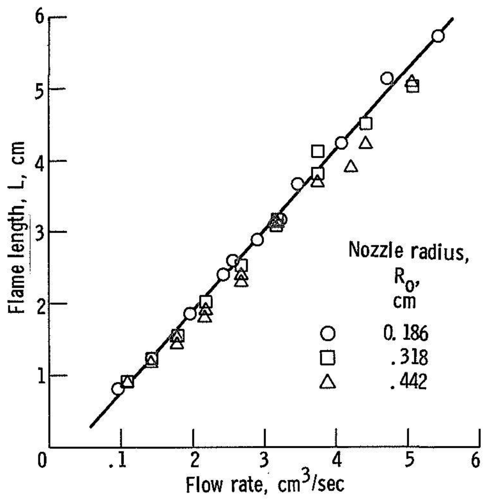
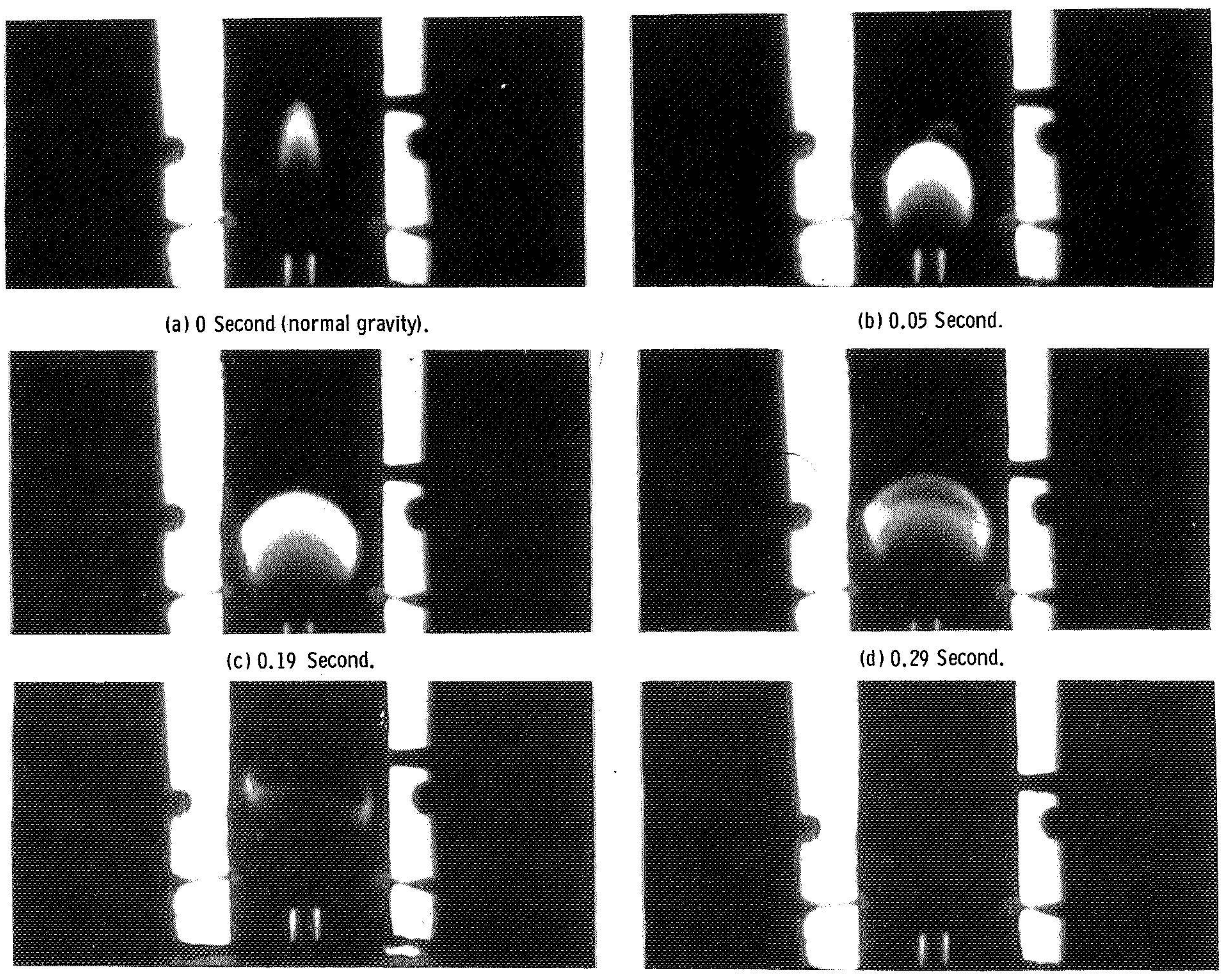


Figure 5. - Flame length in normal gravity.



(a) 0 Second (normal gravity).

(b) 0.05 Second.

(c) 0.19 Second.

(d) 0.29 Second.

(e) 0.55 Second.

(f) 0.71 Second.

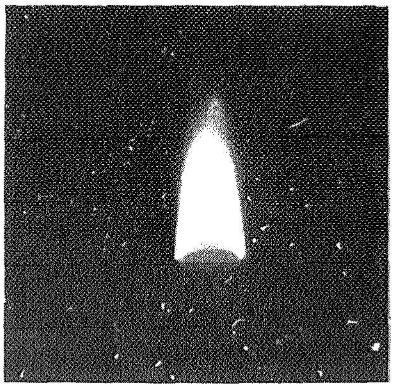
Figure 6. - Effect of gravity on gas jet diffusion flame geometry at various times in zero gravity.

Zero-Gravity Data

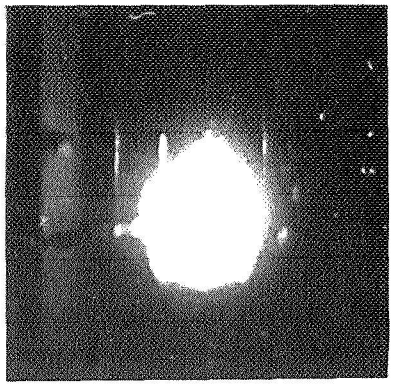
Observations. - The typical effects of zero gravity on a jet diffusion flame are shown in the sequence of pictures in figure 6. The first picture (fig. 6(a)) shows the flame in a stable normal-gravity condition just prior to dropping the experiment. On entering zero gravity, the flame immediately decreased in length and altered its shape to that shown in figure 6(b). The time required for this decrease was about 0.05 second. As time continued, the flame moved away from the burner both axially and radially (figs. 6(c) and (d)). The last two pictures indicate that the flame appeared to extinguish itself. The time required for all visible evidence of the flame to disappear was less than three-fourths of a second for the particular run shown. In general, the time required for a flame to disappear depended on the burner size and flow rate. The color of the flame in normal gravity was basically yellow. A slight blue tinge was also visible, particularly near the burner. In zero gravity the color changed from yellow to orange to dark orange before disappearing. No blue at all was visible in zero gravity.

The infrared films, which were more sensitive to cooler temperatures than the color films, yielded more information regarding the structure of the flames in zero gravity. The results of a typical test are shown in figure 7. The time cited for each picture in figures 7 and 8 is approximate because it was obtained from the framing rate of the camera. Again, figure 7(a) shows the steady-state flame in normal gravity. The zero-gravity pictures show, as before, that the flame experienced a reduction in length after which it expanded away from the burner and faded. However, there is more detail near the burner in these pictures than there is in the color films. For example, in figures 7(b) and (c), it appears that near the burner the hot gases expanded radially (perpendicular to the axial flow). Also, the geometry of the flame appears more spherical in the infrared photographs than in the color ones.

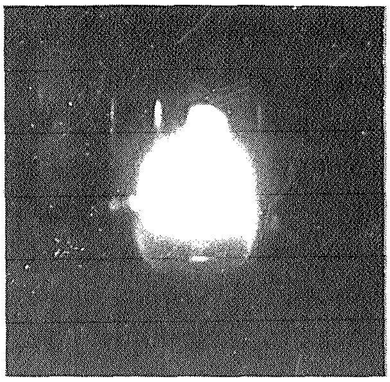
The behavior of the flames in zero gravity can be explained by the two effects discussed previously in the section Proposed Gravity Effects. The initial reduction in length is evidence of the importance of buoyancy on the axial convective motion of the oxidant. On entering zero gravity, this influence dissipates with the result that the axial momentum of the oxidant decreases. Altering the motion of the oxidant changes the rate at which it reaches the reaction zone, which results in the flame geometry changes seen in the films. Subsequent expansion of the flame indicates that the flame is not being cleansed of the products of combustion as efficiently as it was in normal gravity. Without buoyancy, the axial momentum of the products of combustion decreases and their concentration as a function of space changes. This change in concentration also alters the rate at which oxidant diffuses toward the fuel with the result that the flame geometry is changed. Two observations suggest that the flame is extinguished: the color changes from a hotter color to a cooler one (yellow to dark orange); the flame



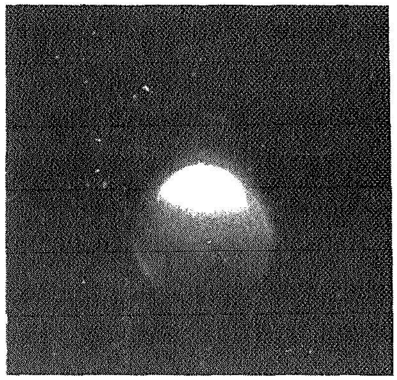
(a) 0 Second (normal gravity).



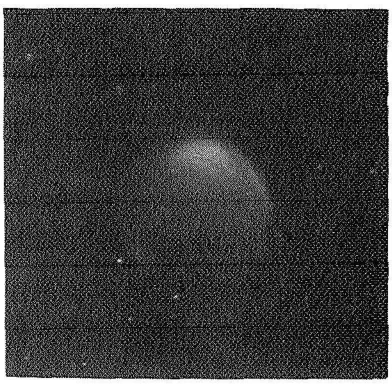
(b) 0.20 Second.



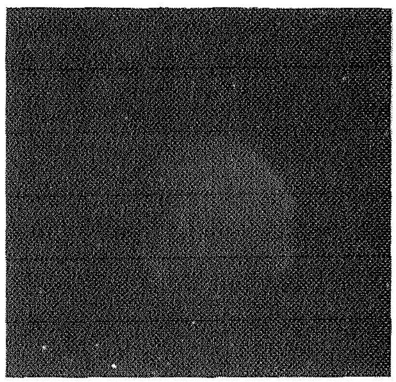
(c) 0.40 Second.



(d) 0.60 Second.

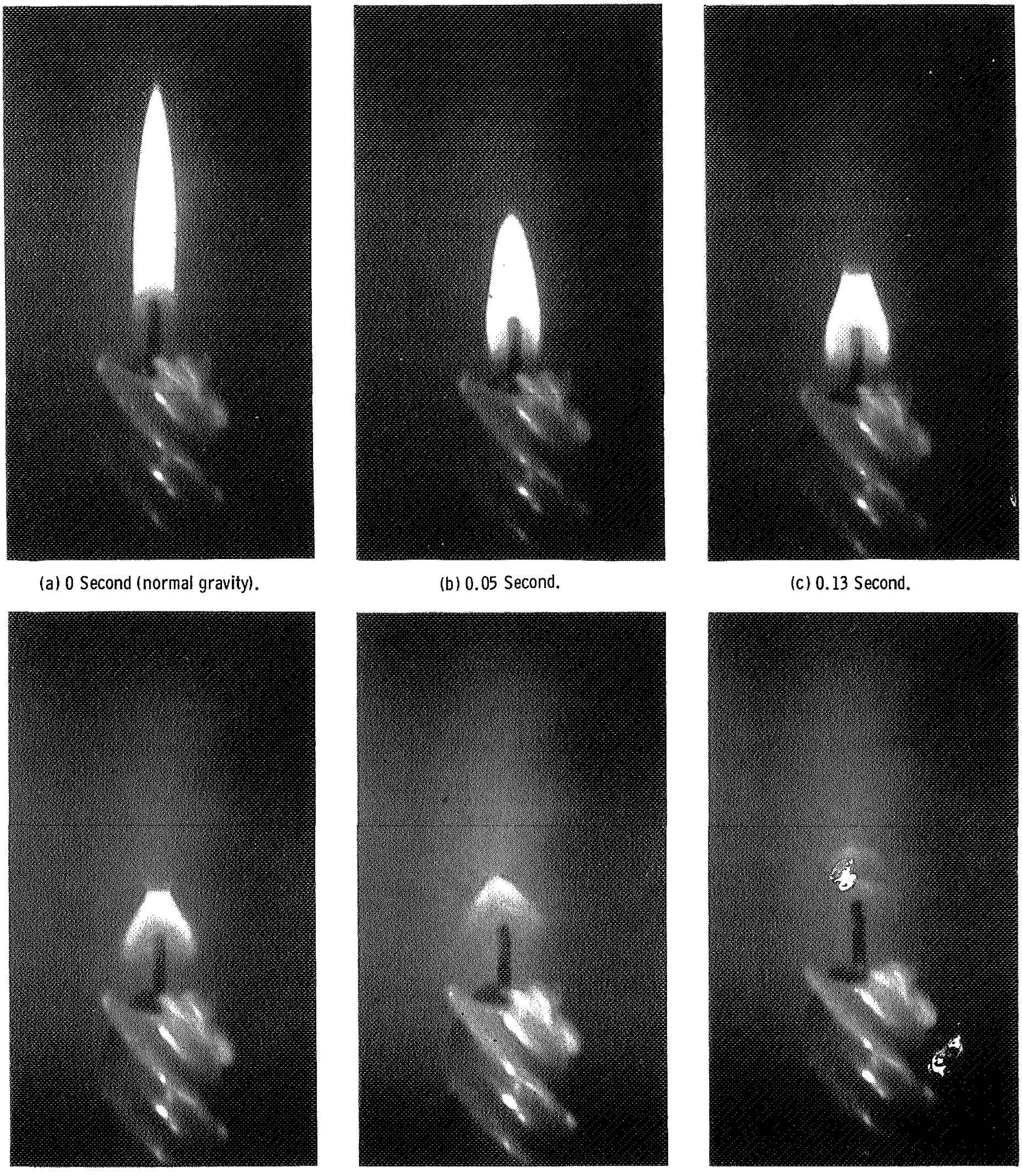


(e) 0.80 Second.



(f) 1.0 Second.

Figure 7. - Infrared photographs of gas jet diffusion flame at various times in zero gravity.



(a) 0 Second (normal gravity).
(b) 0.05 Second.
(c) 0.13 Second.
(d) 0.25 Second.
(e) 0.73 Second.
(f) 2.2 Seconds.

Figure 8. - Effect of gravity on geometry of candle flame at various times in zero gravity.

fades on infrared film, which is sensitive to relatively cool temperatures.

It is of interest to compare the foregoing results with those for a candle. These tests were also conducted in the 2.2-Second Zero-Gravity Facility. The effects of zero gravity on a candle flame are shown in figure 8. Here again, the first picture (fig. 8(a)) shows normal-gravity burning. Similar to the gas jet flame, the candle flame became shorter immediately on entering zero gravity (fig. 8(b)). However, instead of becoming larger again as the gas jet flame did, the candle flame slowly became even smaller (figs. 8(c) to (f)). A possible reason for this difference could be that the fuel flow rate was fixed for the gas jet, while the evaporation rate of the candle paraffin was dependent on heat generated by the flame. In the 2.2 seconds of test time, the flame did not disappear. These results for the candle flame are in agreement with those of reference 2.

Measured data. - Measurements of flame length as a function of time were made for all the color test runs. A typical curve of length as a function of time is shown in figure 9. The flow rate for each run was determined from figure 5 and the measured normal-gravity length. Two characteristics that were specifically noted for each test were the minimum zero-gravity length and the extinguishment length. The latter was defined as that distance from the burner where the top of the flame was last visible.

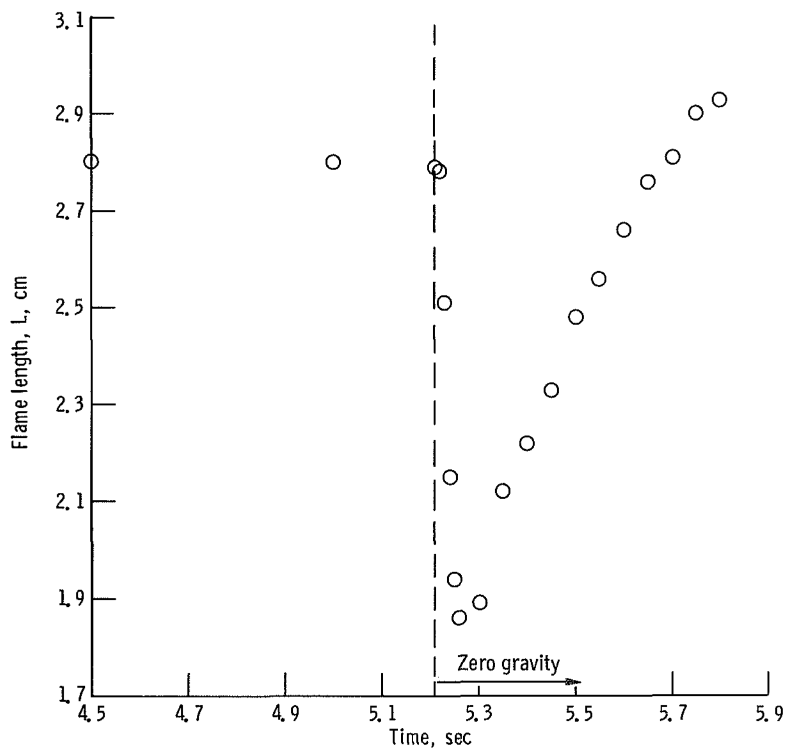


Figure 9. - Flame length as function of time for run 3. Flow rate, 2.8 cubic centimeters per second; nozzle radius, 0.186 centimeter.

TABLE II. - TEST DATA

Run	Normal-gravity length, L_1	Flow rate, cm^3/sec	Nozzle radius, R_0, cm	Velocity, cm/sec	Zero-gravity minimum length, L_0, cm	Extinguishment length, L_e, cm
1	1.46	1.6	0.186	14.73	1.18	1.58
2	4.19	4.04		36.87	2.53	4.59
3	2.78	2.80		25.44	1.86	2.93
4	5.60	5.30		48.31	3.35	6.63
5	4.80	4.56		41.82	2.88	5.20
6	1.02	1.22		11.16	.87	1.07
7	2.02	2.12		19.40	1.48	1.96
8	2.36	2.42	↓	22.14	1.73	2.53
9	2.84	2.84	.318	8.97	1.64	2.50
10	3.96	3.83		12.10	2.04	3.50
11	5.16	4.89		15.48	2.57	4.52
12	1.35	1.51		4.77	1.03	1.32
13	1.53	1.68		5.28	1.12	1.47
14	2.04	2.13		6.76	1.35	1.92
15	2.49	2.53		7.99	1.50	(a)
16	1.89	2.00	↓	6.32	1.29	1.76
17	3.24	3.20	.442	5.22	1.74	2.96
18	1.28	1.45		2.36	.95	1.26
19	2.09	2.18		3.55	1.30	1.96
20	4.24	4.08		6.65	2.08	3.78
21	2.86	2.85		4.64	1.54	2.46
22	3.15	3.13		5.10	1.71	2.69
23	2.68	2.70		4.40	1.56	2.18
24	1.58	1.73	↓	2.82	1.12	1.43

[a]Extinguishment length data were not obtained for run 15 because the flame collapsed on the burner rather than expanding away from it. No reason was found for this misbehavior.

All the measurements were made on the color film. A compilation of all the data is made in table II.

A comparison of the minimum zero-gravity length for the different burners as a function of flow rate is made in figure 10. Also plotted is the normal-gravity curve obtained from figure 5. It is apparent that at low flow rates the minimum zero-gravity length for all the burners approaches the normal-gravity length. As flow rate is increased, the difference between the normal- and zero-gravity data increases and is a function of the burner size. The data indicate a greater reduction for a given flow rate

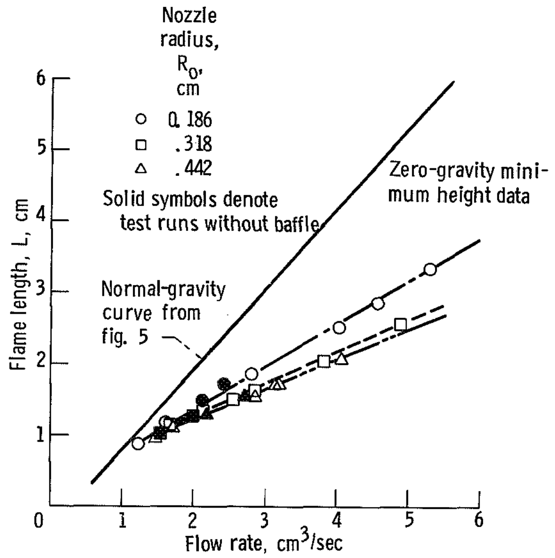


Figure 10. - Flame length as function of flow rate in normal and zero gravity.

as burner size increases. This effect is probably caused by the fact that, as burner size increases for a given flow rate, the average velocity of the exiting gases decreases. This means that the importance of inertia in driving the gases downstream of the burner also decreases.

In figure 10, the solid data points denote tests that were conducted without baffles. This, of course, was done for the smaller flames where oscillation was not a problem. The data indicate that the results from the tests run without baffles are in agreement with those run with baffles. Similar results were obtained for the extinguishment length data. Therefore, it was concluded that the effect of the baffles on the behavior of the smaller flames in zero gravity was negligible. The facts that the trends in the data substantiated by the smaller flames continued for the larger flames and that the flames did not approach the baffles, as seen in the color films, suggest that the effect of the baffles on all the data was small.

Extinguishment length as a function of flow rate for the different burners is shown in figure 11. The separation of the data as a function of burner size there too seems to indicate an inertia effect on the process.

Correlations. - The fractional decrease in the length of a flame when it is suddenly placed in a zero-gravity environment was selected as a measure of the importance gravity plays in the aerodynamics of normal-gravity jet diffusion flames. The fractional decrease is defined as $(L_1 - L_0)/L_1$, where L_1 is the normal-gravity length and L_0 is the minimum zero-gravity length. In seeking a correlation for this parameter, it should be recalled that the data indicated that both buoyancy, or the lack of it, and inertia affected the dynamics of the flames. Accordingly, a correlation in terms of the

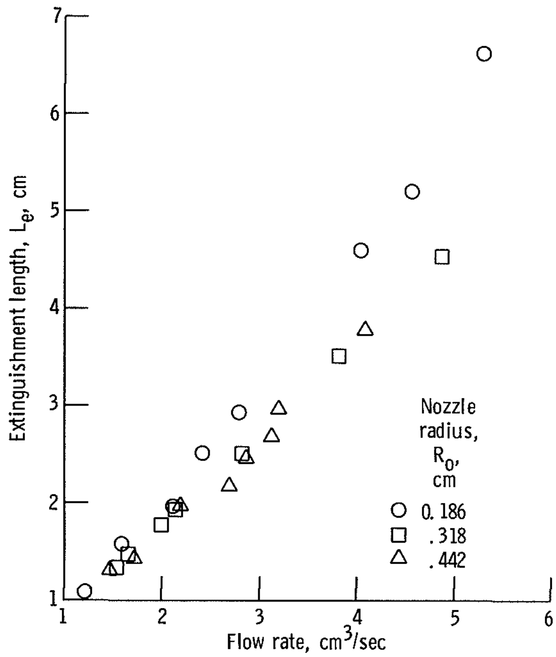


Figure 11. - Extinguishment length as function of flow rate.

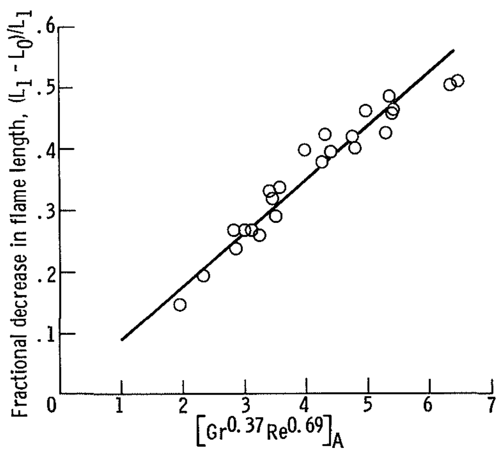


Figure 12. - Effects of gravity-induced momentum on flame length.

Grashof and Reynolds numbers, as defined in the ANALYSIS section, was determined. The results are shown in figure 12. The least-squares line through the data has the equation

$$\frac{L_1 - L_0}{L_1} = 0.09\left(Gr^{0.37}Re^{0.69}\right)_A \tag{5}$$

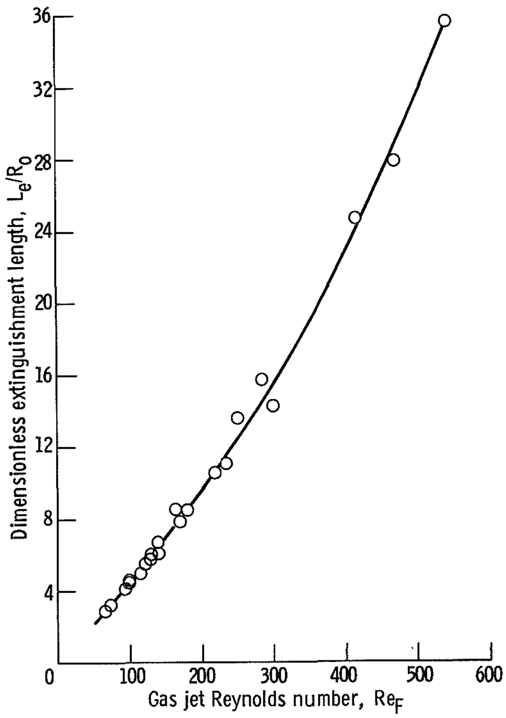


Figure 13. - Dimensionless extinguishment length as function of gas jet Reynolds number.

A correlation for the dimensionless extinguishment length, defined as L_e/R_o was found in terms of the Reynolds number of the fuel, evaluated at the burner. These results are shown in figure 13.

CONCLUDING REMARKS

The subject of this research was an investigation of gravity effects on laminar gas jet diffusion flames. This particular combustion process was chosen because of the apparent lack of a comprehensive analysis to explain existing normal-gravity data and to provide information on gas jet flames in zero gravity. The goals of the work were not only to investigate jet diffusion flames in particular but to provide information concerning the effects of gravity on combustion processes in general.

The governing equation for the fluid flow external to the reaction zone was developed. The following assumptions were made in writing this equation: a boundary layer type of flow existed, the pressure effects were small in the flow field, and the continuum was a perfect gas. Nondimensionalization of this equation yielded the parameters (Grashof and Reynolds numbers) with which to correlate the data.

An experimental program was conducted in which zero-gravity data were obtained in a drop tower. Motion picture photographs were taken of methane burning in quiescent air for various flow rates and burner sizes. The results indicated that a sudden decrease in gravity level from 1 to 0 effected an immediate reduction in the length of a laminar jet diffusion flame. This was attributed to the buoyancy of the oxidant surrounding the reaction zone in normal gravity and the subsequent lack of buoyancy in zero gravity. A correlation for the fractional decrease in the flame length was obtained in terms of the Grashof and Reynolds numbers in the form

$$\text{Fractional decrease} = \frac{L_1 - L_0}{L_1} = \left(0.09\ Gr^{0.37} Re^{0.69}\right)_A$$

Continued exposure of the flame to zero gravity resulted in the flame expanding away from the burner until extinguishment appeared to occur. This was concluded to be caused by the accumulation of the products of combustion about the flame.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 2, 1970,
124-08.

APPENDIX - SYMBOLS

c concentration

D diffusion coefficient, cm^2/sec

d characteristic length, cm

Gr Grashof number, $\rho^2 \Delta T \beta g d^3/\mu^2$

g acceleration due to gravity, cm/sec^2

L flame length, cm

L_e extinguishment length, cm

L_0 zero-gravity minimum flame length, cm

L_1 normal-gravity flame length, cm

P pressure, N/m^2

Re Reynolds number, $\rho U_\infty d/\mu$

R_o burner radius, cm

r radial dimension, cm

T_{AF} adiabatic flame temperature, ^oC

T_{AM} ambient air temperature, ^oC

T_M mean temperature, $1/2(T_{AF} + T_{AM})$, ^oC

ΔT temperature difference, $T - T_{AM}$, ^oC

ΔT_{AF} $T_{AF} - T_{AM}$, ^oC

U_∞ average axial fuel velocity at burner, cm/sec

u axial velocity, cm/sec

v radial velocity, cm/sec

z axial dimension, cm

β coefficient of thermal expansion, $^oC^{-1}$

μ dynamic viscosity, kg/(cm)(sec)

ρ density, kg/cm^3

Subscripts:

A air

AM ambient air conditions

F fuel

M mean temperature condition

$\overline{}$ dimensionless quantity

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