COMBUSTION OF GASEOUS FUELS UNDER REDUCED-GRAVITY CONDITIONS

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The need for an improved understanding of fires is becoming critically important with increased space travel and utilization. While the control of fires in low-gravity environments is not well understood, it is known that buoyancy significantly affects flame behavior and characteristics. The objective of this research is to gain a more fundamental understanding of fires, and to quantify flame behavior under reduced-gravity levels. Non-premixed flames of gaseous fuels are considered in this study because they are relatively simple and easy to control, yet embody mechanisms found in all types of combustion processes ranging from uncontrolled fires to practical combustion systems. This paper presents some recent results from microgravity studies of these flames. In addition, the potential usefulness of lunar- and martian-based laboratories is discussed in order to understand the characteristics and behavior of fires in reduced-gravity environments.

INTRODUCTION

The problem of fire safety has been of equal concern both on Earth and in space. The twenty-first century will begin a period of regular space travel, manned space stations, lunar and martian bases, and deep-space exploration. All these activities raise the question of fire prevention in space, and the use of low-gravity environments to further our knowledge of combustion on Earth.

Microgravity combustion research has been vigorously pursued in the last decade in relation to fire safety issues as well as the fundamental understanding of combustion phenomena. Combustion studies of solid, liquid, and gaseous fuels have been conducted in Earthbound facilities that provide short durations of microgravity. Promising results have so far been obtained to warrant the continuation of this branch of combustion science.

The objective of this research is to gain a more fundamental understanding of fires, and to quantify flame behavior under reduced-gravity levels. Non-premixed flames of gaseous fuels are being investigated because they are relatively simple and easy to control, yet embody mechanisms found in all types of combustion processes.

In the following sections we discuss (1) the general characteristics of laminar and turbulent diffusion (i.e., non-premixed) flames, (2) the available Earthbound facilities for conducting reduced-gravity combustion studies, (3) some new results obtained from laminar diffusion-flame studies in microgravity, and (4) the critical need for understanding low-gravity turbulent flames, all directed toward the goal of understanding the behavior of flames not only in space but on Earth as well.

LAMINAR AND TURBULENT DIFFUSION FLAMES

The term "diffusion flame" classifies those types of flames in which the fuel and oxidizer are not premixed, whether the reactants are in solid (e.g., coal combustion), liquid (e.g., droplet combustion), or gaseous form (e.g., cigarette lighter flame). Unlike "premixed" flames, as in internal combustion engines, the burning process in diffusion flames is governed by diffusion of the fuel gas and oxygen toward each other to form a thin flame sheet that separates the two reactants. The schematic diagram of a normal-gravity gas-jet diffusion flame burning in a quiescent oxidizing environment is shown in Fig. 1, where the different physicochemical phenomena governing the combustion process

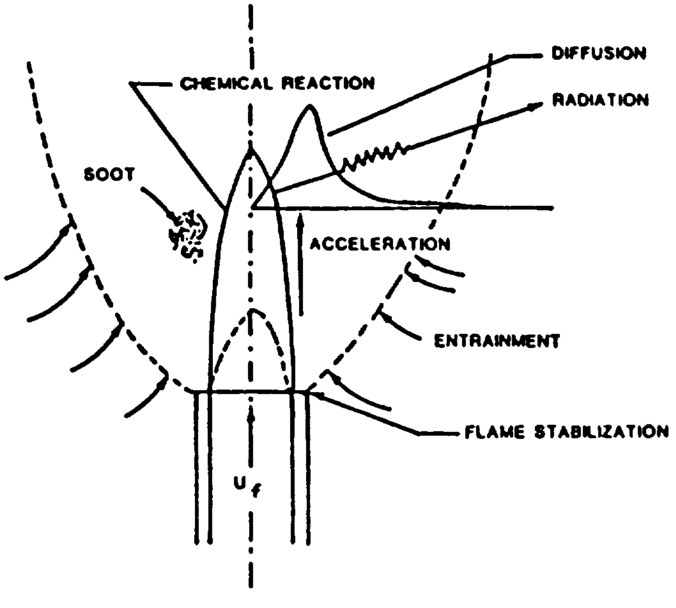

Fig. 1. Physical and chemical processes occurring in laminar gas-jet diffusion flames of hydrocarbons in normal-gravity environments.

are indicated. The gaseous fuel (e.g., methane) is injected through a nozzle, the tip of which acts as a flame holder.

In combustion processes, coupling exists between chemical kinetics, fluid dynamics, diffusion of species, inertia, radiation, and soot formation and disposition. In addition, under non-zero-gravity, buoyancy is imposed on these processes (due to the density difference between the hot combustion products and the cold environment). The buoyant force causes the hot products to be removed from the flame in the direction opposite to the direction of the gravitational force. This complicates the understanding of the coupled processes involved in combustion.

In zero-gravity environments, the buoyant force is eliminated, and the remaining processes become more tractable. Isolation, or even reduction of buoyancy, makes it easier to understand the interplay between these chemical and physical processes, which are not separable regardless of the gravity level. These phenomena are responsible for the very different behavior of flames observed in microgravity compared to those in normal gravity (*Edelman and Bahadori,* 1986).

Gas-jet diffusion flames are selected in this study because they are representative of a wide variety of combustion processes from the fundamental standpoint. These flames are laminar or turbulent, depending on the combination of jet momentum, nozzle diameter, and fuel properties. The classical behavior of a gas-jet diffusion flame in normal gravity (*Hottel and Hawthorne,* 1949) is shown in Fig. 2, which plots the dependence of length and structure of the flame on fuel velocity for a tube of given size. As the jet velocity increases, the flame transists from laminar (where mixing is governed by molecular diffusion) to fully developed turbulent behavior (where mixing is largely due to eddy diffusion or convection, with the final homogeneity being attained by molecular diffusion). It is this type of behavior that is anticipated to be strongly affected by the reduction in gravity level, as discussed later.

LOW-GRAVITY EARTHBOUND AND ORBITER FACILITIES

Several Earthbound and space shuttle facilities provide low-gravity environments for combustion research (see *Lekan,* 1989). To date, most of the reduced-gravity combustion studies (including premixed flames, solid-surface combustion, laminar gas-jet diffusion flames, particle-cloud combustion, pool fires, and droplet combustion) have been conducted in the 2.2-sec drop tower (10^{-5} g), 5.18-sec zero-gravity facility (10^{-5} g), and model 25 Learjet (10^{-2} g for approximately 15 sec, attached payloads) of NASA Lewis Research Center. In addition, studies are being conducted in the KC-135 aircraft of NASA Johnson Space Center (10^{-2} g, approximately 20 sec for attached payloads; 10^{-3} g for free-floating payloads). For an overview of combustion studies in low-gravity environments, see *Sacksteder* (1991) and *NASA* (1989). The middeck and spacelab of the space shuttle (10^{-5} g) provide much longer test times and lower gravity levels, and also allow more detailed diagnostic measurements of flames.

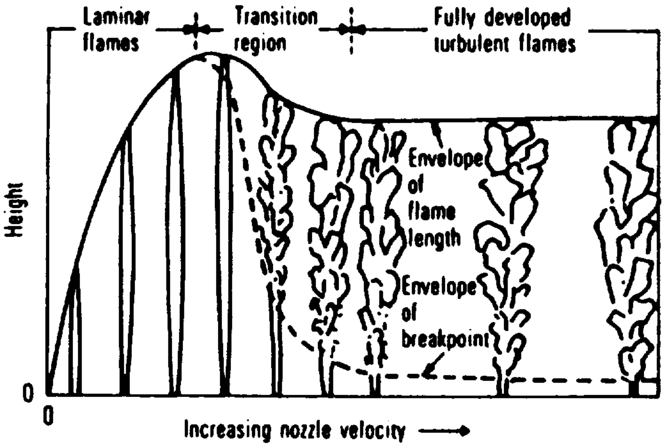

Fig. 2. Change in the flame height and behavior with increase in nozzle velocity for a typical gas-jet diffusion flame. From *Hottel and Hawthorne* (1949).

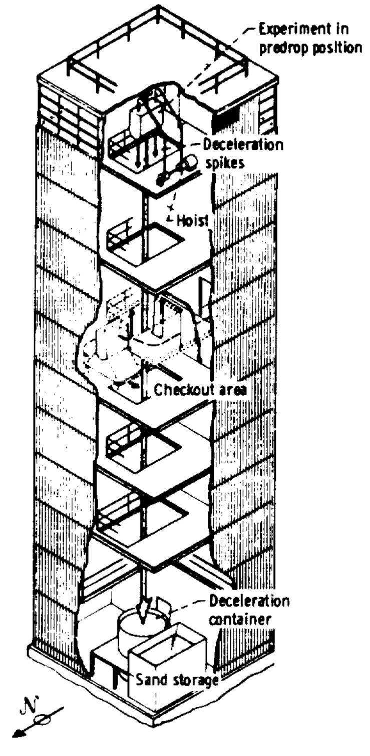

Fig. 3. 2.2-sec drop tower.

In the 2.2-sec drop tower (Fig. 3), the experiment package is enclosed in a drag shield that has a low drag coefficient. As the drag shield falls in this 27-m tower, the experiment package is released inside the shield. The air drag associated with the relative motion of the package within the shield is the only external force acting on the package. The shield comes to rest in a sand box at the bottom of the tower. The 5.18-sec zero-gravity facility, which provides a 132-m free-fall distance, is a 6.1-m-diameter, 145-m-deep steel-walled vacuum chamber at 0.01 torr. The sealed package is decelerated in a 6.1-m-deep container of polystyrene pellets. Aircraft flying parabolic (Keplerian) trajectories provide longer low-gravity test times, but at the cost of higher gravity levels. In the Learjet, the experiment is attached to the body of the aircraft. The KC-135 provides the same gravity level as in the Learjet for bolted-down experiments, but because of its size, also permits free-float packages. Intermediate acceleration levels, especially lunar (1/6 *g*) and martian (1/3 *g*) gravities can also be achieved in the aircraft, providing opportunities to study combustion and fluid-physics phenomena under these specific reduced-gravity conditions.

MICROGRAVITY LAMINAR DIFFUSION FLAMES

Laminar diffusion flames of hydrogen and various hydrocarbons have been studied in the 2.2-sec drop tower (*Cochran and Masica,* 1970; *Cochran,* 1972; *Haggard and Cochran,* 1973; *Edelman et al.,* 1973; *Haggard,* 1981; *Babadori and Stocker,* 1989; *Babadori et al.,* 1990a,b; for a review of earlier work, see *Edelman and Babadori,* 1986) and the 5.18-sec zero-gravity facility of NASA Lewis Research Center (*Babadori et al.,* 1990c, 1991).

The normal-gravity flames of these fuels, when burned in quiescent oxidizing environments, generally flicker (due to hydrodynamic instabilities), are yellow (due to soot emission and burn-off), and are pencil-like in shape (due to the presence of buoyant force). In addition, the color of these flames is not strongly affected by changes in either pressure or oxygen concentration. This is a consequence of strong entrainment of oxidizer, again due to the effect of buoyancy (see Fig. 1).

Figure 4 shows a normal-gravity and the corresponding microgravity flame of propane. Compared to laminar flames in normal gravity, those observed in microgravity are flicker free, larger, diffuse, and rather globular. This is due to the absence of buoyant convection, leaving diffusion a much more dominant mechanism of transport. In addition, these flames are generally orange-reddish in color, which is a result of prolific sooting. Significant soot formation is caused by increased residence time, since the hot products of combustion accumulate in the vicinity of the flame due to the absence of buoyancy. As a result, continued combustion depends mainly on the diffusion of oxygen toward the flame front, causing major pyrolysis of the hot fuel-rich portion of the flame. As can be seen in Fig. 4, the microgravity flame appears to have a completely open tip. This suggests that extensive soot formation, radiative loss, cooler overall flame temperature, and a reduced oxygen supply contribute to extinction at the flame tip. It is quite possible that unburned and pyrolyzed hydrocarbons may escape through the flame tip in microgravity environments.

Pressure and oxygen concentration have a significant effect on flame characteristics, color, luminosity, and sooting behavior in microgravity compared to normal gravity (*Babadori and Stocker,* 1989; *Babadori et al.,* 1990b). Sooting was not visible in microgravity hydrocarbon flames at 18% oxygen in nitrogen, 0.5-atm environments, and the flames were entirely blue, whereas their normal-gravity counterparts were yellow, luminous, and very similar to flames under atmospheric conditions, or even high-pressure/high-oxygen-concentration flames. This has a very important implication; namely, there is reduced radiative heating and reduced hazard of flame spread to surrounding combustible materials in low-pressure/low-oxygen (compared to high-pressure and/or high-oxygen) microgravity flames. Figure 5 shows the effects of oxygen concentration on normal-gravity and microgravity flames.

High-pressure and high-oxygen-concentration environments also affect the intensity of burning in microgravity. Massive sooting, flame-tip opening, and extinction and soot breakthrough at the tip were observed even in 50%-oxygen environments. The tip-opening and soot-escape phenomena are unique characteristics of microgravity flames. Figure 6 shows the effects of pressure.

Recent tests (*Babadori et al.,* 1991) have shown that flame radiation is an order of magnitude higher in microgravity compared to normal gravity for laminar gas jet diffusion flames. Enhanced soot formation, larger flame size, and slow transport of the hot combustion products are the contributing factors. Figure 7 shows the flame radiance as a function of fuel volume flow rate

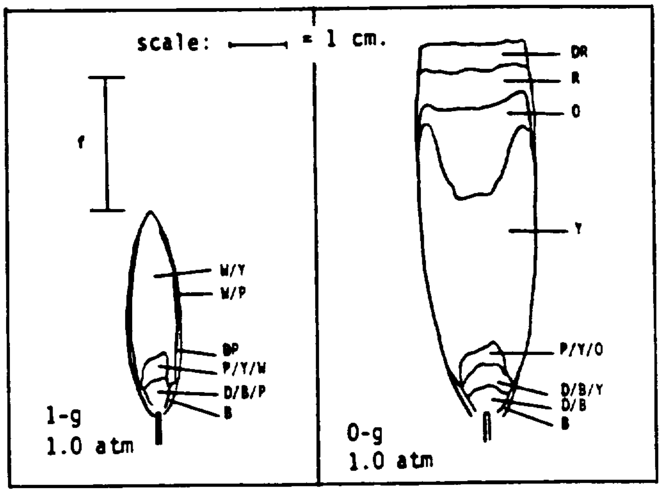

Fig. 4. Normal-gravity and microgravity flames of propane burning in quiescent air at 1 atm; nozzle radius = 0.0825 cm and fuel-flow rate = 1.0 cc/sec. The various colors observed are as follows: B (blue), BB (bright blue), D (dark), DB (dark blue), DP (dark pink), DR (dull red), O (orange), P (pink), R (red), W (white), and Y (yellow). The range of flicker (f) is also shown for the normal-gravity flames. From *Babadori et al.* (1990b).

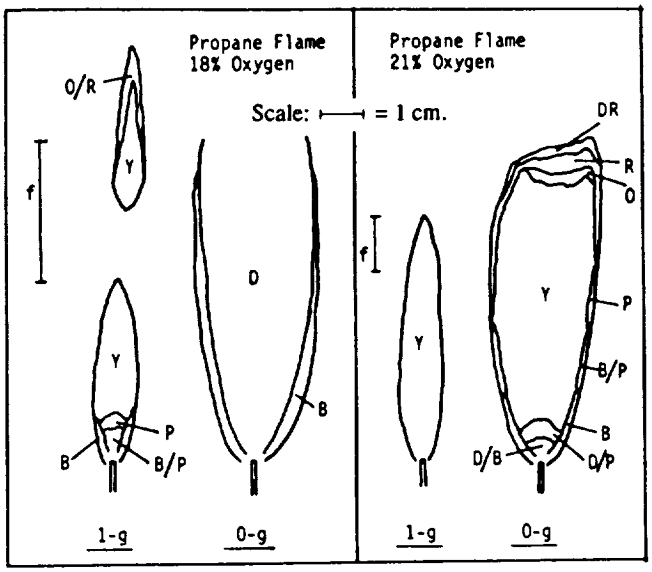

Fig. 5. Effects of oxygen concentration on normal-gravity and microgravity flames of propane at 1 atm; nozzle radius = 0.074 cm and fuel-flow rate = 0.96 cc/sec. The various colors indicated in the diagram are as follows: B (blue), D (dark), DR (dull red), O (orange), P (pink), R (red), W (white), and Y (yellow). The bars show the range of normal-gravity flame flicker (f). From *Babadori and Stocker* (1989).

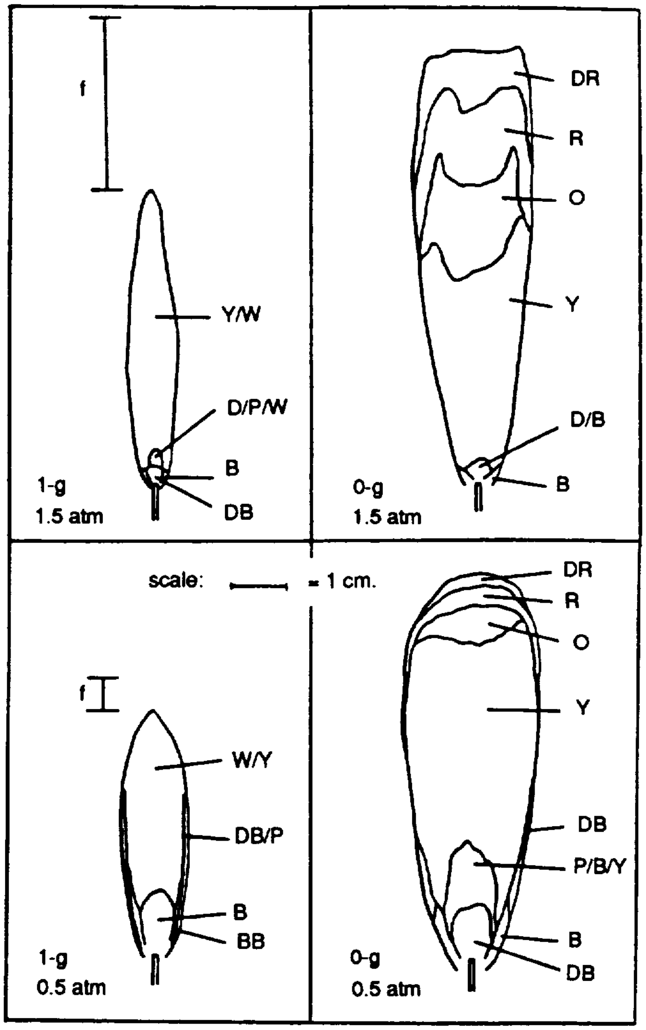

Fig. 6. Effects of pressure on normal-gravity and microgravity flames of propane burning in quiescent air (21% oxygen in nitrogen). For details, see Fig. 4. From *Babadori et al.* (1990b).

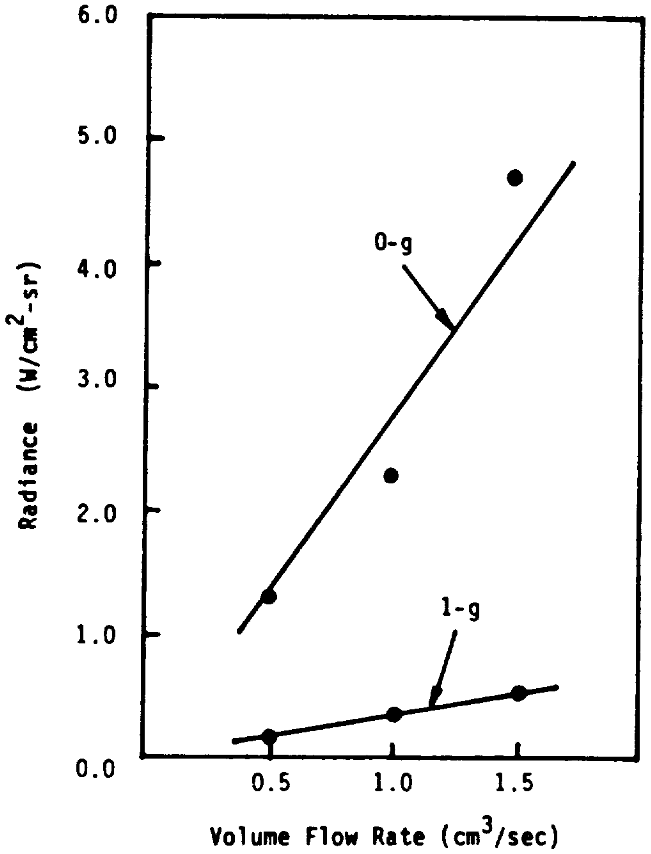

Fig. 7. Radiance as a function of fuel volume-flow rate for propane flames burning in air at 1.0 atm; nozzle radius = 0.0825 cm. From *Babadori et al.* (1991).

under both normal gravity and microgravity. The data suggest that compared to normal gravity conditions, radiative ignition of nearby materials may be promoted in low-gravity environments due to the increased radiative transfer.

A mathematical model has been developed (*Edelman et al.,* 1973) for the study of laminar diffusion flames under arbitrary gravitational accelerations based on the parabolic form of the equations of motion, which includes the effects of inertia, viscosity, multicomponent diffusion, and chemical reactions. Figure 8 shows the excellent agreement between the predicted and measured flame heights under both normal gravity and zero gravity. We have recently applied this model to a family of methane flames under different gravitational levels. Figure 9 shows the nondimensional centerline velocity vs. axial distance. Clearly, convective effects play a major and different role for different gravitational environments.

The full spectrum of observations on shape, color, luminosity, sooting, radiation, combustion products, and other characteristics of the flame are not understood. Experiments are required, along with appropriate diagnostics, under the gravity level of interest. Then, when combined with theoretical analyses, these results would provide a better understanding of fires on Earth and under reduced-gravity conditions such as those on the Moon, Mars, and in spacecraft environments.

TURBULENT DIFFUSION FLAMES

Turbulent gas-jet diffusion flames under normal gravity have been the subject of extensive theoretical and experimental studies for a number of decades. Figure 2 shows the classical behavior of a turbulent jet diffusion flame. As the jet velocity increases, the flame transists from laminar to fully developed turbulent behavior. For the tube size used in the flame study of Fig. 2, a velocity is reached where further increases in the jet velocity result in no change in flame height. This is a characteristic of momentum-dominated turbulent flames, i.e., flames in which buoyancy is not important.

Much progress has been made toward the characterization of momentum-dominated turbulent flames. However, this is not the case for low-momentum turbulent flames characteristic of unconfined fires. In this case, the fire research community depends primarily on empirical results that, having been obtained under normal gravity, have the buoyancy effect inherently embedded within these correlations. When buoyancy is important (i.e., low-momentum flames, unlike Fig. 2), a constant height as a function of velocity is not reached in the turbulent region (see Fig. 10; *Wohl et al.,* 1949). The mechanisms responsible for this behavior are far from fully understood. Thus, the need for more fundamental data and analysis is apparent because of the requirement to define the hazard and control of fires not only on Earth but in space as well.

For low-momentum flames, strong interactions between buoyancy and turbulent-flame structure exist that affect the flame behavior and chemistry through two gravity-induced mechanisms. The first arises directly from the buoyant force acting on the time-averaged or mean flow field, and appears as a gravity term in the mean momentum equation. The second mechanism arises out of the interaction between density and velocity fluctuations, which appears as a source of turbulent kinetic energy. Under normal gravity, it is not possible to separate these two effects in terms of their impact on mixing rate, and hence, flame structure. Clearly, the advantage of operating in a low-gravity environment would be to provide a significant base of new information by isolating the combined effects of buoyancy.

CLOSURE

Although the effects of buoyancy on low-momentum flames have been qualitatively observed, it is only recently that quantitative descriptions of the phenomena affected by gravity have been attempted. Understanding this phenomena is not only of fundamental interest, but it is of critical importance to fire safety in space as well as on Earth. Furthermore, for processing and manufacturing in space, controlled flames are likely to be employed.

This paper has presented results that indicate significant effects of gravity on the flame structure. Moreover, it has been shown that to develop a more fundamental understanding of this phenomenon along with a reliable prediction capability, quantitative data obtained under reduced-gravity conditions uninhibited by test time and size limitations are needed. The potential to obtain data from experiments conducted on the Moon and Mars offers this opportunity, one that cannot be equaled in Earthbound facilities.

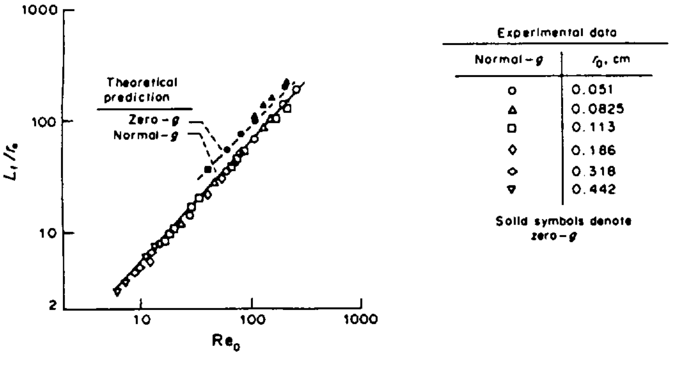

Fig. 8. Comparisons between the theoretical predictions (*Edelman et al.,* 1973) and experimental results (*Cochran and Masica,* 1970; *Cochran,* 1972) for nondimensional flame height (height/nozzle radius) vs. jet Reynolds number (jet velocity × nozzle radius/fuel kinematic viscosity); methane-air flames at 1.0 atm. From *Edelman et al.* (1973).

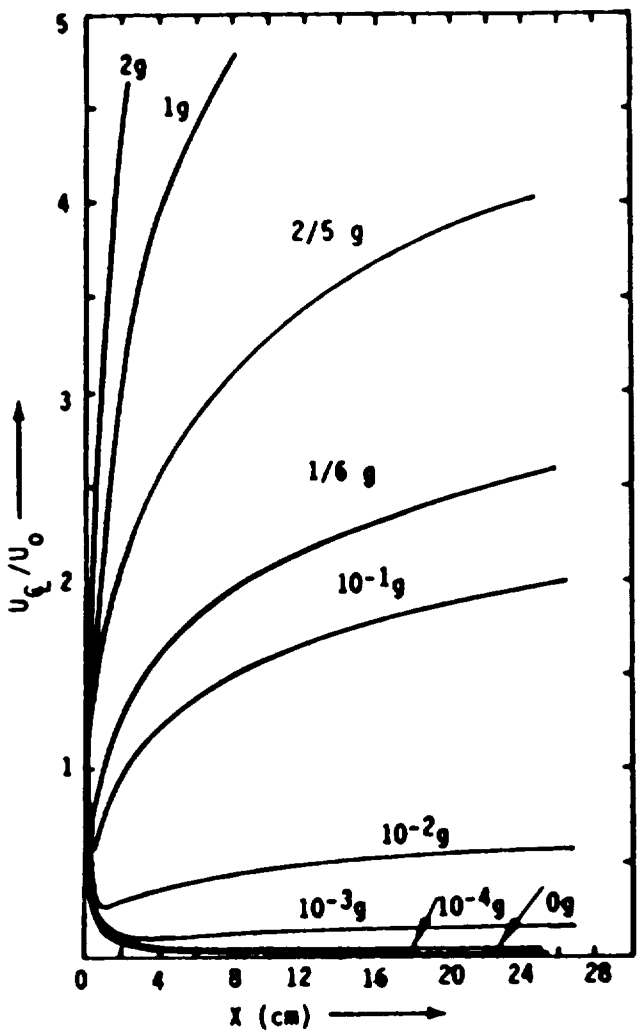

Fig. 9. Predicted nondimensional centerline velocity (with respect to jet exit velocity) vs. axial distance along the jet as a function of gravitational level; methane-air flames, nozzle radius = 0.0825 cm, fuel-flow rate = 1.0 cc/sec, pressure = 1.0 atm, and jet exit velocity = 46.8 cm/sec. From *Edelman and Babadori* (1986).

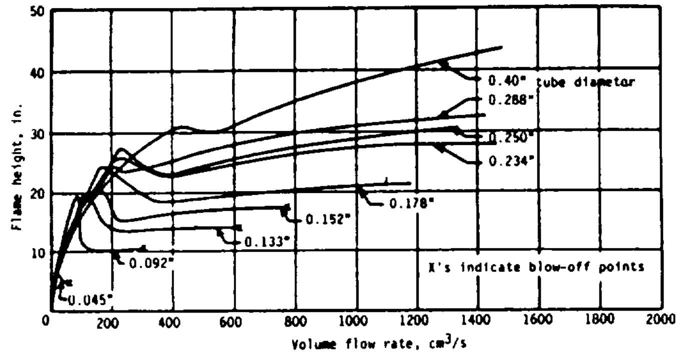

Fig. 10. Effects of fuel-volume flow rate and tube diameter on flame height for city gas diffusion flames. From *Wohl et al.* (1949).

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