

GRAVITATIONAL INFLUENCES ON FLAME PROPAGATION THROUGH NON-UNIFORM PREMIXED GAS SYSTEMS[‡]

FLETCHER J. MILLER
&
Ed White
Case Western Reserve University

Howard D. Ross
NASA Lewis Research Center

55-25
02 7372

Introduction

Flame spread through *uniformly* premixed gas systems, while not completely understood, is nevertheless a well-studied problem in combustion science. In contrast, flame propagation through *non-uniform* premixed gas systems (also called "layered systems") has been the subject of relatively few previous studies. In a recent theoretical paper Talley [1] lists sprays, flame spread over liquids, and the leading edge of lifted turbulent diffusion flames as applications where flame behavior in layers is important, and goes on to note that, "Compared with the two better known limiting cases [pure diffusion and pure premixed flames] these intermediate mixtures have so far received relatively little attention." Layered mixtures, however, are ubiquitous in terrestrial fire hazards such as chemical spills, underground mining operations, and automobile and aircraft crashes. The flames in such systems have been shown to carry over fences, and to propagate past the ends of the fuel spill, thus representing a hazardous area beyond that associated with the original fuel location. They also represent a likely fire hazard aboard long-duration spacecraft such as the International Space Station -- perhaps second in probability only to electrical wire /insulation breakdowns -- because flammable gases may accumulate near waste storage, laboratory fluids, fuel cells, lasers, etc.

In addition, it is known that gravitational effects, while only of minor importance for stoichiometric mixtures, are strong for lean-limit, *homogeneous* gas mixtures [2]. While not specifically mentioning layered systems, Law and Faeth in their review on microgravity combustion call for more research on near-limit phenomena [3]. Flammability limits have been found by some investigators to be not only different in μg , but also outside (lower than) the normal range of upward vs. downward spread limits at 1-g [4]. This, coupled with the finding cited below by Liebman et al [5] that in layered systems the flame can propagate in regions *outside the accepted lean flammability limit even at normal gravity*, makes it especially difficult to assess fire hazards in μg based on 1-g data. Indeed, Law and Faeth state that "... any notion that flammability limits for [homogeneous, premixed] gases at normal gravity are applicable to conditions at μg is erroneous." Since gaseous fire hazards aboard spacecraft would likely involve propagation through a mixture spanning a range of concentrations and fuel layers, experiments in such systems are critical to understand the phenomena.

A review of the existing literature, as described below, suggests gravity may influence the flame propagation rate of layered premixed systems by up to 50% in a wide range of circumstances. Thus, observations of flame propagation rates in normal gravity and in microgravity should readily establish this effect; such experiments would validate at a global level existing models which include gravitational influence. In this paper we present the beginning of a project to experimentally determine flame spread rates in layered systems in normal and microgravity. In particular, we focus on the case where there is nowhere a stoichiometric concentration of fuel vapor (i.e., the system is always fuel lean). Research on layered systems in which the mixture is everywhere below stoichiometric proportions has been scarcely reported for normal gravity, and not at all for microgravity conditions. See Fig. 1 for a schematic of the layered system under consideration in this work.

Gravity can influence the rate of flame propagation in a layered system in at least three ways: through a hydrostatic pressure gradient, through buoyantly induced flows during spread, or by affecting the initial distribution of fuel vapor. The first effect has been professed as important for all equivalence ratios since agreement between predicted and observed flame spread rates in normal gravity tests is improved by the inclusion of the hydrostatic pressure term in models (see below) [6]. Without this term, underpredictions by 50% compared to experiments were observed. This improvement, however, only proves correlation, not cause, and needs to be experimentally verified.

[‡] This research is supported by NASA Grant NCC3-500

The second way in which gravity may influence the flame propagation in a stratified layer is in how it affects the flows responsible for the redistribution of the fuel vapor, oxygen, and combustion products once a propagating flame is established. Previous research indicates that convective or aerodynamic effects can induce flows ahead of the flame that alter the fuel vapor concentration distribution and assist the flame spread. The high propagation speeds in layers that maintain at some height in the layer a stoichiometric concentration suggest buoyant flow might not develop rapidly enough to affect spread; however, in the sub-stoichiometric regime this may not be the case. These flows and their causes have not been measured in either normal gravity or microgravity.

Effects of gravity on the initial distribution of fuel from a point source and how that affects flame spread are essentially unexplored in the literature. In normal gravity a leaking buoyant fuel (e.g., hydrogen) will rise from its source dispersing somewhat as it goes until it encounters a ceiling where it may collect and form a flammable layer. In microgravity the fuel would not be buoyant and instead will collect around its source or be redistributed by the slow (5-10 cm/s) flows due to ventilation systems and crew movements. Just the opposite may occur with point sources of heavier-than-air fuels. These differences in fuel vapor distribution can lead to very different flame propagation behavior and thus different fire hazards.

Previous Experimental Research with Liquids

For flames spreading over a liquid above its flash point, the main parameters governing the flame spread rate are the height of the flammable layer, the fuel-air mixture concentration, and the mixture's concentration gradient within the layer. Behavior of the flame also depends on whether T_o is high enough to create a stoichiometric concentration of fuel vapor and air. For $T_o < T_{st}$ the presence of the pool affects the flame spread rate even though a flammable gas-phase mixture exists prior to ignition (T_{st} is the temperature at which a stoichiometric mixture exists). Ishida [7] showed this convincingly in experiments with glass beads in a pool of n-octane; without the beads the flame spread almost an order of magnitude faster than with the beads for the same temperature above the flash point. Further experiments showed that for $T_o < T_{st}$ the fuel bed orientation relative to the gravity vector also affected V_f , [7].

If $T_o > T_{st}$, the flame appearance and V_f are similar to a system comprised of layered gases without a liquid surface, indicating that the liquid phase is uninvolved in propagation. In this range V_f is two to five times greater than the laminar burning velocity, S_L , for a stoichiometric, homogeneous mixture. In order to exceed S_L to this degree, the flame front must be curved which causes a significant pressure gradient across the front; flame spread is then enhanced by gas-phase motion ahead of and in the same direction as spread [8]. From aerodynamic and mass continuity considerations, the motion can be driven by the expansion of the low-density products which displaces and redistributes the unburned gas layers ahead of the flame into a broader, curved area [8]. The reported upstream distance covered by this disturbance ranges from a few centimeters [9] to 10-15 cm [6].

The redistribution of flammable layers preceding the flame has significant safety implications. Flames may jump over fences or barriers or propagate past the end of the fuel spill. A redistribution of flammable gases preceding a spreading flame can enable a flame to jump over an endwall and continue propagating for some axial distance. As long as the height of the endwall is less than about 10 times the height of the flammable layers experiments show that the flame will make this jump [10]. A similar experiment was conducted with a fence spanning the width and extending above a pool of flammable liquid [11]. In this way flammable gases were available to promote the flame spread if the initial flame could jump over the fence, which it did for some the initial conditions.

Previous Experimental Research on Gas-Phase Systems

Phillips conducted foundational experiments in a gallery by diffusing methane through a porous surface that formed the top of a gallery [12]. He employed a color schlieren technique to measure the concentration profiles perpendicular to the diffusing surface before ignition, but apparently did not record schlieren data during the flame propagation [13]. For the conditions he tested, Phillips found a constant flame speed regardless of the quantity of methane or the concentration gradient. However, except for a few experiments with coal gas which were not quantified, all of the tests were conducted with methane layers that were above unity equivalence ratio.

Feng et al employed a separator plate in a gallery so a two-layer system could be formed, the flammable layer of methane (or methane/air) being on top [8]. In particular they explored the effect of gallery height and found that the flame spread steadily for tall galleries, but was unsteady and accelerating for shorter ones. They employed a multiple exposure camera to get the spread rate, but had no way to visualize the flow or concentration distribution. These tests again always included a layer at

stoichiometric concentration.

Researchers at the Bureau of Mines also have investigated this problem both for heavy gases sitting on floors [5] and for lighter gases trapped under ceilings [9]. As with their predecessors, all the mixtures tested had concentrations above the stoichiometric level. They reported that the flame speed was dependent on the flammable zone thickness and the concentration gradients (in contrast to Phillips [12]), and interestingly, that the flame propagated through regions that were *below* the lean flammability limit for homogeneous mixtures. They attribute this to a stabilizing influence of combustion in nearby richer zones, but this finding further suggests that fire hazards of this type may extend outside their initial boundaries.

Previous Modeling Efforts

In their data analysis Liebman et al [9] found that inclusion of gravitational effects through the Richardson number (which they defined as the ratio of buoyant forces tending to stabilize a layer to shear forces tending to mix it) was useful for the closed gallery case. However, extension of their correlation to 0-g predicts infinitely fast spread, which is obviously wrong.

Feng et al [8] treated both the open and bounded gallery configurations through a streamtube approach. In its simplest form, the infinite flow field is divided into three regions: a layer of combustible gas of *uniform concentration*, a burned gas layer, and a pure air layer. For the infinite open gallery, V_f/S_f is predicted to be equal to the square root of the ratio of the unburned to the burned gas density [8]. When the gallery is also a finite length with open ends, they showed that V_f is never steady, but increases along the gallery length. The model of Feng et al, however, overpredicted by about 50% the V_f observed in Kaptein and Hermance's experiments [6]. The latter authors demonstrated that agreement with their experimental results was improved by modifying the Feng model to include a *gravitational* potential energy term accounting for the different heights of the combustible and burned gas layers.

Objectives of This Work

The following are objectives of our 4-year study: (a) to determine experimentally if there is a gravitational influence on the flame spread rate in layered fuel mixtures, (b) to determine what factors influence the gravitational dependence; (c) to measure the flame spread rates, the fuel vapor concentration levels, and the hypothesized redistribution of flammable gases ahead of the spreading flame in both normal gravity and in microgravity; and (d) to extend an existing numerical model for sub-flash flame spread over liquid pools to the case of layered mixtures and use it to explore gravitational effects as well as to compare to experimental findings.

Experimental Apparatus and Procedure

A schematic of our experimental apparatus is shown in Fig. 2. It consists of an aluminum fuel tray 76 cm long by 10 cm wide by 3.2 mm deep with a wall thickness of 4 mm. The tray is inlaid flush to the tops of the side walls with porous bronze with an average pore size of 110 μm and a porosity of 40%. An aluminum panel, through which water from a temperature bath flows, is bolted to the bottom of the tray and is used to control the tray temperature. The tray is surrounded on one long side as well as on the top by Lexan panels, and on the other long side by an aluminum panel, forming a duct around the tray with dimensions 108 mm wide by 112 mm high. The end walls of the duct have openings 80 mm by 90 mm (to allow gas expansion out each end) which are covered with perforated plates to reduce the chance of room air currents entering the duct. A hot wire at one end of the duct ignites the mixture.

Two color CCD cameras are used to record the flame spread process. A top view of the entire tray length is used to determine the flame spread velocity by recording the flame on S-VHS video and using previously developed software [14] to track its progress. The shape of the flame front is also noted in the top view. The side view camera has a horizontal field of view of 70 mm and is centered on a point about 25 cm from the ignitor. It is operated with a shutter speed of 1/250 sec per video field to better capture the flame as it passes. The signals from the cameras are mixed and recorded on one tape.

A sheathed, type T thermocouple is glued into a small slot flush with the top of the porous bronze at the end of the tray opposite the ignitor and recorded manually. Prior to conducting any experiments (and with the duct lid removed) the fuel tray surface temperature was recorded with an infrared camera which showed it to be uniform within 0.75 $^{\circ}\text{C}$. Upon reaching temperature, methanol is poured over the bronze until it wets the entire top surface. A stainless steel lid with a rubber gasket around the edge is slid over the tray by lifting up the duct aluminum wall which slide in slots in the duct end walls (cf fig. 2). This prevents evaporation and an accumulation of fuel vapor above the tray. After waiting for the methanol to equilibrate in the

tray, the lid is pulled out, the side wall lowered, and after a specified time for fuel evaporation and diffusion, the fuel-air mixture is ignited.

In order to measure the fuel vapor concentration ahead of the flame we have been experimenting with a rainbow schlieren deflectometry system capable of detecting the fuel concentration gradient. The test system presently consists of a collimating lens of 550 mm focal length and a decollimating lens of 1550 mm focal length with the light supplied by a fiber-coupled arc lamp passing through a 75 μm wide slit. A small test pool 15 cm long was placed in the test section. At the secondary focus we placed a standard 2 mm Cartesian rainbow filter [15] oriented to detect vertical concentration gradients and recorded the images with a color CCD camera as the tray lid was removed. No flame spread tests have been done in this system. Currently we are building a 4 m focal length system which will give increased sensitivity to better record any changes that occur during flame spread.

Results and Discussion

Figure 3 contains the result of using the rainbow schlieren system to measure the fuel vapor layer 1.0 sec. after removing the test tray lid. Knowing the initial pool temperature, and using the procedure described in [15] we integrated the hue variation in the schlieren image to obtain the fuel concentration as a function of height above the pool. Figure 3 shows a calculated profile based on the 1-D diffusion equation along with our experimentally determined profile. As can be seen, the agreement is good except that the measured profile dips below zero. Unfortunately, the apparatus at the time did not have schlieren quality windows, so the side walls were removed for the measurement. This allowed fuel vapor to diffuse outside the test region (changing the path length) and skew the measurement, a condition that will be remedied in the future. As part of this project, we plan to develop an independent experimental measurement technique based on laser light absorption to provide a second check of this measurement. The schlieren system will then be used for real-time measurements of the layer thickness ahead of the flame during spread.

Flame spread tests have been conducted in normal gravity as described above for methanol at temperatures between 21 $^{\circ}\text{C}$ and 11 $^{\circ}\text{C}$. (For reference, the for methanol $T_{\text{flash}} = 11^{\circ}\text{C}$ and $T_{\text{st}} = 21^{\circ}\text{C}$). Representative flame position vs. time data as determined by flame tracking are shown in Fig. 4. Initially we had some problems achieving a flat flame front during spread (i.e. flame front perpendicular to spread direction), but those were overcome by more care in removing the lid, so that all of the data shown are from flames that propagated with flat fronts (except for a small amount of curvature near the wall due to heat loss). The ignition delay (the time between removing the lid and igniting) was approximately 3.5 sec for these cases. As can be seen, the flame spread is very uniform (i.e., no pulsations) with the higher temperature cases spreading faster.

In Figure 5 we present a compilation of all of the runs showing the effect of the initial temperature on spread rate. At least three runs are represented at each temperature. The data as shown in Fig. 4 are fit with a straight line to get the flame velocity. Points that did not track well due to ignitor interference or tray end effects were first eliminated. This graph shows the spread rate for substoichiometric conditions has an exponential dependence on temperature when the diffusion time is held constant. Once T_{st} is reached, the flame speed increases only slowly, if at all with temperature. The data agree well with that taken previously by Hirano for spread over pure liquids [16], who also found that at higher temperatures the flame spread at rates well above the laminar burning velocity for stoichiometric, homogeneous mixtures. In contrast to Hirano we were unable to achieve ignition below 11 $^{\circ}\text{C}$, presumably due to heat loss to the bronze which is higher than the pure liquid fuel he used, and which also may account for somewhat lower spread rates at the lower temperatures.

Since some previous flame spread studies were conducted in ducts with either one of the ends closed, we performed a few preliminary tests to determine what effect the duct might be having on the flame spread. For a temperature of 15 $^{\circ}\text{C}$ and short diffusion times (a few sec.) the flame spread rate was unchanged; for diffusion times of ~ 20 sec. we were unable to get straight flame fronts; for long times (~ 1 min.) the flame spread very rapidly (estimated from a few video frames to be 3.5 m/s). In the latter case, hot gas expansion behind the flame front drives it forward at a faster rate than would otherwise be expected. This effect also explains the high propagation rates seen by Hirano [17] for uniform mixtures, since he ignited in the center of an axisymmetric chamber and the hot gases had no escape path

The side view of the flame is shown in Figure 6. This is representative of the flames we saw. It appears to be a triple flame with the lower leg quenched. We believe the upper leg of the flame - which is much higher than the height of the lean layer limit prior to the flame arrival - to be burning at or near the lean flammability limit, and the middle or horizontal leg behind the flame to be burning closer to stoichiometric conditions as heat from the flame passage evaporates more fuel behind it and excess air due to the fuel lean condition above diffuse together. The overall height of the flame was found to increase as the diffusion

time increased for a given temperature.

Conclusions and Future Plans

We have built an apparatus for measuring flame spread rates through non-homogeneous fuel-air mixtures as a function of layer thickness and concentration. The layer thickness is adjusted by controlling the diffusion time above a fuel-saturated porous media, while the concentration is controlled by the fuel temperature. Normal gravity tests with methanol have so far explored largely the effect of temperature, as well as the effects of various aspects of the apparatus. Good agreement with previous research has been obtained. We have also demonstrated the ability of a rainbow schlieren system to quantitatively measure fuel vapor concentrations in the static case. As the next step, we plan to implement this diagnostic into the flame spread tests, as well as the laser absorption method mentioned above. Though not described in the paper, we completed the design of a 2.2 sec drop tower rig for conducting experiments in microgravity, after establishment of the flammable layer profile in 1g. The rig design includes the rainbow schlieren measurement system, and a capability for high-speed cinematography, but not the line absorption technique. In addition, we plan to use diffusing gases in place of evaporating liquids for some tests in both normal and microgravity so that we can explore roof layers. For some tests, we hope to investigate the effect of oxygen concentration on the flame behavior in microgravity, since this has direct applicability to fire hazards aboard the International Space Station, and diluent type, since previous work has shown a dramatic effect on liquid flash point, for example. Finally, in the later years of this project, we will utilize a numerical model developed by Schiller et al [18] and apply it to the case for layered mixtures.

References

- [1] D. G. Talley, "Some Properties of Nearly Premixed Laminar Flame Propagation Along Weakly Stratified Layers in Combustible Gas Mixtures," *Combustion and Flame*, vol. 79, pp. 141-150, 1990.
- [2] P. D. Ronney and H. Y. Wachman, "Effects of Gravity on Laminar Premixed Gas Combustion: 1. Flammability Limits and Burning Velocities," *Combustion and Flame*, vol. 62, pp. 107-119, 1985.
- [3] C. K. Law and G. M. Faeth, "Opportunities and Challenges of Combustion in Microgravity," *Prog. Energy Combust. Sci.*, vol. 20, pp. 65-113, 1994.
- [4] R. A. Strehlow, K. A. Noe, and B. L. Wherley, *21st Symposium (Int'l) on Combustion*, pp. 1479-1494, 1986.
- [5] I. Liebman, H. Perlee, and J. Corry, "Investigation of Flame Propagation Characteristics in Layered Gas Mixtures," U.S. Bureau of Mines 7078, 1968.
- [6] M. Kaptein and C. E. Hermance, "Horizontal Propagation of Laminar Flames Through Vertically Diffusing Mixtures Above a Ground Plane," presented at 16th Symposium (Int'l) on Combustion, 1976.
- [7] H. Ishida, "Flame Spread over Ground Soaked with Highly Volatile Liquid Fuel," *Fire Safety Journal*, vol. 13, pp. 115, 1988.
- [8] C. C. Feng, S. H. Lam, and I. Glassman, "Flame Propagation Through Layered Fuel-Air Mixtures," *Combustion Science and Technology*, vol. 10, pp. 59-71, 1975.
- [9] I. Leibman, J. Corry, and H. E. Perlee, "Flame Propagation in Layered Methane-Air Systems," *Combustion Science and Technology*, vol. 1, pp. 257-267, 1970.
- [10] T. Hirano, T. Suzuki, and I. Mashiko, "Flame Behavior Near Steps Bounding Layered Flammable Mixtures," *Eighteenth Symposium (Int'l) on Combustion*, pp. 647-655, 1981.
- [11] T. Suzuki, I. Mashiko, N. Tanabe, and T. Hirano, "Flame Jumping over obstacles on the surface of a flammable liquid at superflash temperatures," in *Combustion in Reactive Systems*, J. Bowen, Ed., 1981.
- [12] H. Phillips, "Flame in a Buoyant Methane Layer," presented at Tenth Symposium (International) on Combustion, 1965.
- [13] H. Phillips, "A three-colour quantitative schlieren system," *Journal of Scientific Instruments*, vol. 1, pp. 413-416, 1968.
- [14] F. J. Miller and H. D. Ross, "Further Observations of Flame Spread over Laboratory-Scale Alcohol Pools," *24th Symposium (International) on Combustion*, pp. 1703-1711, 1993.
- [15] P. Greenberg and R. Klimek, "Quantitative Rainbow Schlieren Deflectometry," *Applied Optics*, 1995.
- [16] T. Hirano, T. Suzuki, I. Mashiko, and N. Tanabe, "Gas Movements in Front of Flames Propagating Across Methanol," *Combustion Science and Technology*, vol. 22, pp. 83-91, 1980.
- [17] T. Hirano, T. Suzuki, I. Mashiko, and K. Iwai, "Flame Propagation Through Mixtures with Concentration Gradient," *Sixteenth Symposium (International) on Combustion*, pp. 1307-1315, 1976.
- [18] D. N. Schiller, H. D. Ross, and W. A. Sirignano, "Computational Analysis of Flame Spread Across Alcohol Pools," *Combust. Sci. Technol.*, vol. 118, pp. 205, 1996.

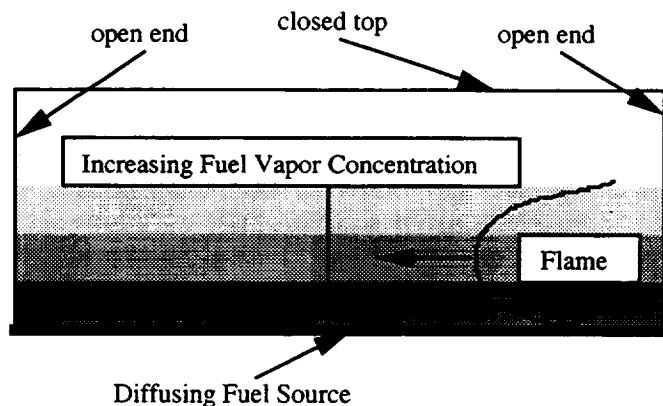


Figure 1. Schematic showing fuel vapor layers that develop above a fuel source. Flame leading edge spreads along a line near stoichiometric.

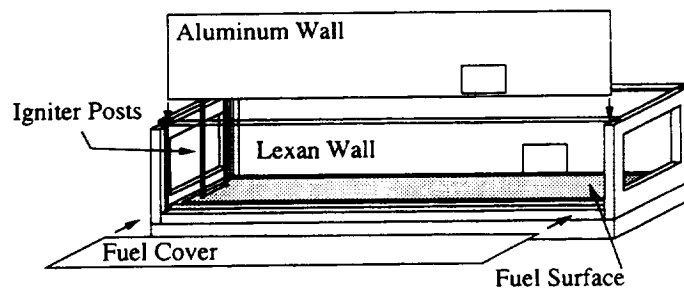


Figure 2. Experimental Apparatus.

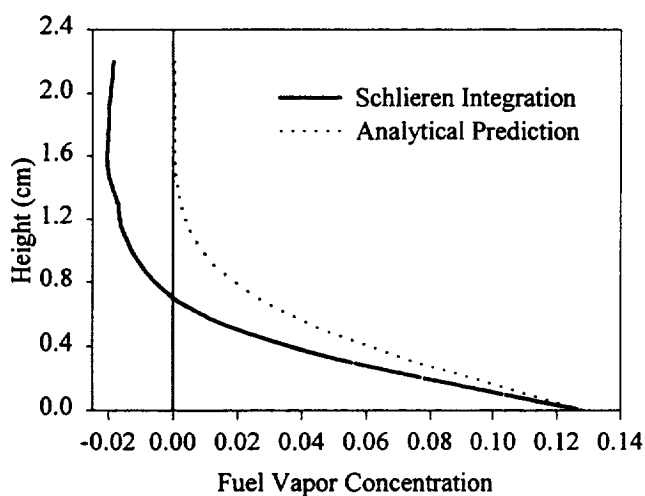


Figure 3. Fuel vapor concentration above the fuel bed as measured by Rainbow Schlieren compared to calculated distribution.

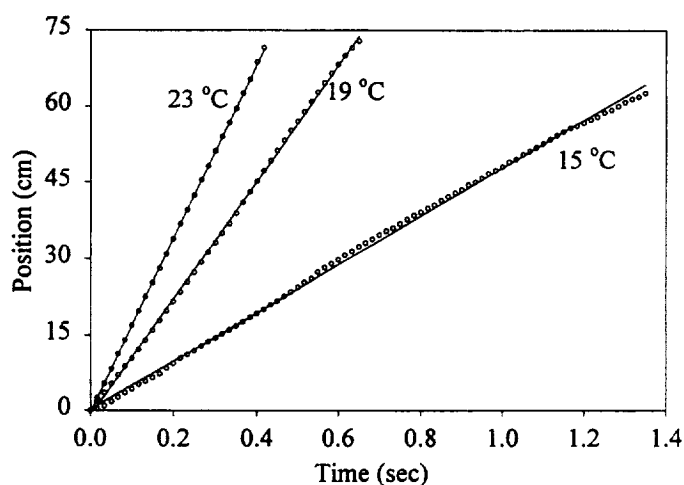


Figure 4. Flame position vs. time for several sub-stoichiometric temperatures.

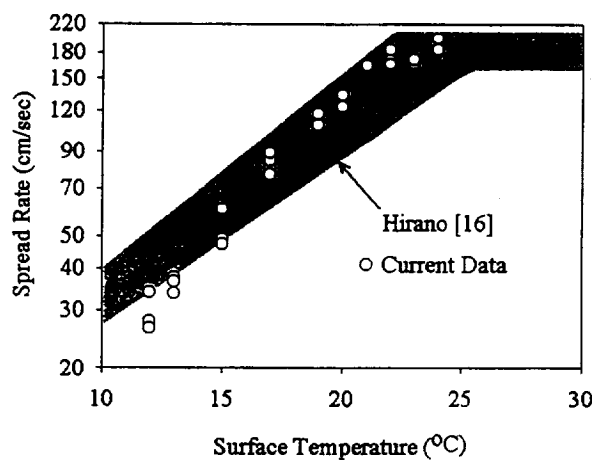


Figure 5. Flame velocity over methanol-soaked porous bronze vs. temperature compared to data for pure methanol [16].

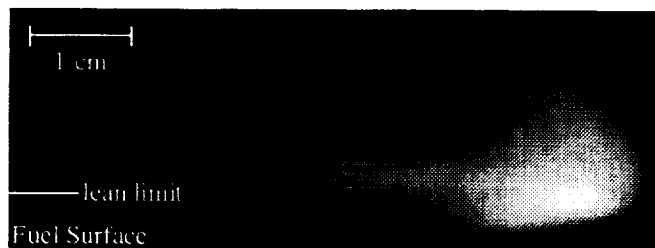


Figure 6. Side View of 1g flame for $T_0 = 21^\circ\text{C}$ and a diffusion time of 3.1 sec.. Flame is all blue (no soot).