# Experimental Observations on the Geometry and Stability of a Laminar Diffusion Flame in Micro-Gravity

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## ABSTRACT

An experimental study is conducted on a laminar diffusion flame established over a 50 mm x 50 mm x 10 mm slab of PMMA subject to a forced oxidizer flow parallel to the surface. The parameters varied are the oxygen concentration, the forced flow velocity and the length of pyrolyzing fuel. Experiments are conducted in micro-gravity to simulate the conditions on board spacecraft and to better approximate the assumptions of classical theoretical developments. The experimental results showed a low oxidizer velocity stability limit linked to a minimum fuel supply to the flame and related to a decrease in the heat feedback from the flame to the fuel surface. The importance of convective transfer of fuel to the flame is underlined and is evidenced by soot glowing (yellow flames) as opposed to blue flames where diffusion of fuel is dominant. Soot particles are convected towards the flame. A qualitative correspondence of blue flames with theory is observed and significant discrepancies are evidenced as the importance of convection increases and the flames become yellow.

**KEYWORDS:** Flame Stability, Flame Geometry, Flame Length, Micro-gravity

## INTRODUCTION

Once a fuel is ignited the flame propagates across its surface establishing a diffusion flame. The flame transfers heat to the surface and the combustible material pyrolyzes providing the necessary gaseous fuel to sustain the flame, this process is commonly referred as mass burning. In normal gravity, temperature gradients result in natural convective flows that are laminar when the scale is small, and transition to turbulence as the size of the fuel increases. In spacecraft, where buoyancy is negligible, the flow is limited to that induced by the ventilation system. Characteristic ventilation system velocities are of the order of 0.1 m/s, therefore the flow is expected to be laminar and parallel to the surface. The complex mixed flow (often turbulent) fire scenario observed in normal gravity is reduced to the classical combustion problem generally described in the literature as "The Emmons Problem" [1]. The problem of a chemically reacting boundary layer flow over a flat plate, as described by Emmons, is that of an incompressible boundary layer flow with blowing. The assumptions correspond to a classical Shvab-Zeldovich approach where gravity is neglected. Extensive research has been done following this pioneering work to use the theoretical framework to explain different fire scenarios. The natural constraints imposed by buoyancy and the differences between normal gravity fires and the laminar diffusion flame studied by Emmons have prevented complete validation of this model. The advent of long term manned space facilities motivates revisiting the work of Emmons under its original assumptions since this configuration represents a plausible fire scenario on board spacecraft.

Many theoretical developments have used the methodology proposed by Emmons. Lavid and Berlad [2] incorporated the effect of buoyancy for a horizontal plate and Fernandez-Pello and Pagni [3] extended this analysis presenting a mixed flow parameter that applied to any orientation. Pagni and Shih [4] used the Emmons analysis to study the flame length for a pure forced flow and a vertical wall. The solution to the reacting boundary layer problem provides an expression for the "excess pyrolyzate" that serves as a boundary condition for an integral analysis that leads to a flame length. Since all these studies relied on the assumption of infinitely fast chemistry, none of them addressed the issue of stability. Theoretical work dealing with the stabilization of a boundary layer diffusion flame has been restricted to establishing a blow-off limit for the free stream velocity and the oxygen concentration [5,6].

Experimental work, using a gas burner to simulate the fuel, conducted by Hirano et al. [7,8] explored the issues of stability and flow structure for forced flow velocities between 0.2 and 1.4 m/s. Velocity profiles at different locations showed overshoots when close to the flame. The authors attribute the velocity overshoots to thermally induced pressure gradients. Lavid and Berlad [2] attributed the pressure overshoots to buoyancy and defined non-dimensional length scales that incorporated the Grashoff number and served to describe buoyantly induced perturbations in the pressure field. Hirano et al. [7,8] addressed stability showing an upper limit for the free stream velocity and a lower limit for the fuel injection velocity. No mention of a lower limit for the oxidizer flow is made throughout this work. A study, of similar nature, conducted by Torero et al. [9] extended the range of velocities explored by Hirano et al. Conducting experiments under micro-gravity conditions the dominant effect of buoyancy was avoided and free stream velocities below 0.2 m/s could be studied. Ethane injected through a sintered bronze plate simulated the combustible fuel and showed that for velocities of the order of 0.1 m/s thermal expansion and fuel injection resulted in separation of the boundary layer and the formation of three dimensional flow patterns. These effects significantly altered the flame geometry but seemed to have only a minor stabilizing effect on the flame and extinction at low strain rates was only observed for a minimum fuel injection velocity.

The subject of flame stability under micro-gravity conditions for free stream velocities smaller than 0.2 m/s has been addressed extensively through flame spread studies. Olson et al. [10] showed that a flame ceases to spread over a thin fuel at approximately 17% oxygen concentration in normal gravity and approximately 26% in micro-gravity. Different experiments conducted in short term micro-gravity facilities and the Space Shuttle have further studied the stability of a diffusion flame over a thin fuel and are reviewed in Ref. [11 and 12]. Experiments and computations have attempted to demonstrate that radiative heat losses are responsible for the higher limiting oxygen concentrations.

Experiments with thick fuels under this velocity regime are not very common, since in most cases, the micro-gravity time required is much longer than that available in ground based facilities. West et al. [13] conducted a series of quiescent flame spread studies over thermally thick PMMA and observed that the flame spread rate decreases with time never reaching steady state conditions with non-propagation attributed to radiative losses. This study does not address aerodynamic effects on the flame stability.

The present work addresses the stability of a diffusion flame under micro-gravity conditions for free stream velocities smaller than 0.2 m/s. The fuel used is PMMA and the experiments are conducted under normal and micro-gravity conditions. Emphasis is given to the aerodynamic structure of the flame (flame geometry) and the effect of fuel injection on the heat feedback from the flame to the fuel. The parameters varied are the oxygen concentration, the length of the pyrolyzing fuel and the free stream velocity.

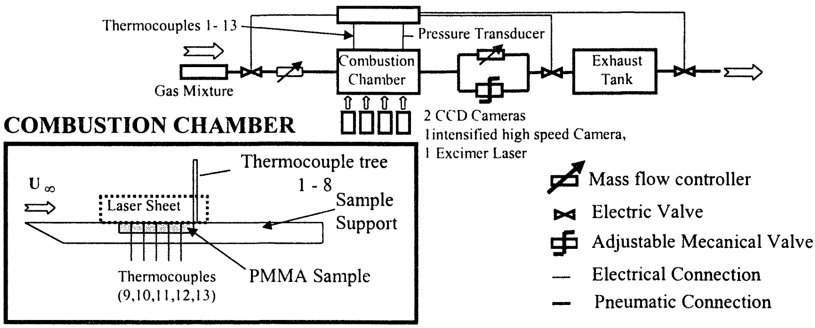


FIGURE 1 - Schematic of the experimental apparatus.

## DESCRIPTION OF THE EXPERIMENTAL APPARATTUS

A PMMA plate (50 mm x 50 mm x 10 mm) is mounted on a stainless steel plate which is placed inside a horizontal combustion chamber (300 mm diameter). Different mixtures of $O_2$

and $N_2$ are supplied by a controlled mass flow meter through a chamber that serves to assure an homogeneous laminar flow. Two CCD cameras provide a side and top view of the flame. Temperatures are recorded by means of 5 type-K thermocouples melted into the top surface of the PMMA plate and 8 thermocouples placed vertically at the trailing edge of the plate. All thermocouples are 0.05 mm in diameter and their tip is placed at the plane of symmetry of the plate. The surface thermocouples are placed at 12, 20, 28, 36 and 44 mm from the trailing edge of the sample and the vertical thermocouples at 2, 5, 10, 15, 23, 31, 41, 53 mm from the fuel surface. Details of this configuration are described in Figure 1. Experiments were conducted on ground, on board of the Airbus A300 from CNES (25 sec. of μg) and at the ZARM Drop Tower (4.7 sec. of μg). The combination of a large volume exhaust reservoir and a controlled mass flow meter maintained the pressure in the chamber within a maximum deviation of 30 mbar throughout the parabolic trajectories and in a closed loop system at the tower. During 15 tests at the drop tower a Planar Laser Induced Fluorescence system powered by an UV-Excimer Laser was used to trace OH radicals. A detailed description of the hardware and protocol followed is described in reference [13]. Ignition was accomplished by means of a homogeneously distributed NiCr coil embedded in the fuel sample at the trailing edge. The propagation front was observed to be one dimensional for almost the entirety of the sample, curving only 3-5 mm at the lateral edges of the sample. For all tests conducted at the drop tower, ignition was conducted in normal gravity and the flame was allowed to propagate under identical conditions to a pre-defined position. A few seconds before the drop, parameters were adjusted to those corresponding to the specific experiment. During parabolic flights ignition was also performed in normal gravity and the flame was allowed to propagate throughout successive parabolas with the experimental conditions changed for each micro-gravity period. Ignition was accomplished in micro-gravity for a few tests that show no significant difference with normal gravity ignition.

## EXPERIMENTAL RESULTS

### General Description

The different experimental conditions studied are presented in Figure 2. The oxygen concentration and free flow velocity were varied as indicated in the figure. As shown by Figure 2, three different regimes can be observed which depend on the free stream velocity and oxygen concentration. For oxygen concentrations above that of ambient and oxidizer velocity greater than 10 mm/s the flame is stable, is mostly yellow in color (significant soot glowing) and remains very close to the fuel surface. Decreasing the oxygen concentration or the free stream velocity reduces the soot glowing resulting in a bluer and less luminous flame. Oxygen concentration has a significant effect on the luminosity of the flames, but the free stream velocity seems to control the color. As the velocity approaches the stability limits for 20-25% oxygen concentration the flame is almost invisible. A further decrease in the free stream velocity results in a sudden decrease in gas and solid phase temperatures which leads to extinction of the flame. Extinction was not observed in normal gravity for any of the conditions shown in Figure 2.

Extinction experiments under micro-gravity conditions are very complex, thus explaining the presence of only three points on Figure 2. A number of tests were required to approach extinction conditions reducing the number of data points. Reliable extinction experiments can be obtained only on the drop tower since the perturbations in the gravity level common during parabolic flights tend to have a significant effect on the results. The data points labeled as extinction, thus, represent extinction in less than 4.7 seconds, therefore can not be taken as an absolute extinction limit although, temperature traces clearly discriminated between stable and non-stable flames.

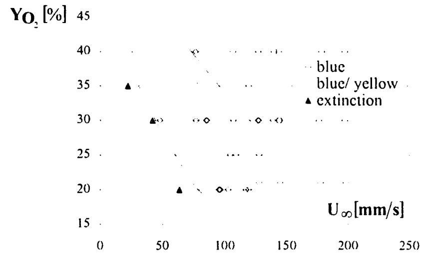


FIGURE 2 - Micro-gravity tests conducted showing the extinction limits and two different stable regimes. Tests correspond to different lengths of pyrolyzing material ($L_P$) and to drop tower and parabolic flights.

Tracing of OH radicals allowed validation of the visual observations provided by the CCD camera. The broad band emission of glowing soot particles and the methyl-methacrilate monomer precluded a quantitative evaluation of the OH concentration but allowed comparison of the zone where OH radicals were present with the visible flame. Significant traces of OH radicals were observed at the fuel side of the flame and there is a clear correspondence between the boundary of this zone and the boundary of the visible flame emission. Comparison between stand-off distance and flame length showed that the differences between the boundary of the zone where OH radicals were present and the visible flame (as determined by the CCD camera images) were always < 5%. Supported by these results the following discussion will be based on the visible images of the flame.

Transition Regime

It is impossible to discuss the different parameters that affect the stability of the flame without describing in detail the transition regime. During parabolic flights the transition period remains mostly undefined and oscillations between negative and positive fractions of normal gravity follow a period of almost 1.8 $g_0$ ($g_0$=9.81 m/s$^2$). In contrast, during drop tower tests, the transition corresponds to a sudden change between $g_0$ and $10^{-5}g_0$. Therefore, a characteristic drop tower test will be used to describe the transition process.

A series of six images corresponding to a 4.7 second drop (30% oxygen concentration and a free stream velocity of 110 mm/s) is presented in Figure 3. Figure 3 (a) shows the flame in normal gravity immediately before the drop. Buoyancy dominates over the forced flow therefore the flame is only slightly tilted towards the right due to the oxidizer flow coming from the left. The flame is mostly yellow and bright (due to the enriched oxygen flow) and only the area very close to the leading edge is blue. Figure 3 (b) corresponds to an image of the flame 0.1 sec. after the drop. The plume has fully disappeared and the flame remains mostly yellow and bright. The flame is close to the fuel surface resulting in large production of volatiles which are then carried away by the forced flow as they burn. A free flow of this magnitude will cover the entire length of the plate in approximately 1 sec. Figure 3 (c) shows an image at this point, flame length has increased almost two fold as a result of the change from a buoyantly driven to a forced flow. The stand-off distance has also increased significantly reducing the heat feedback to the surface.

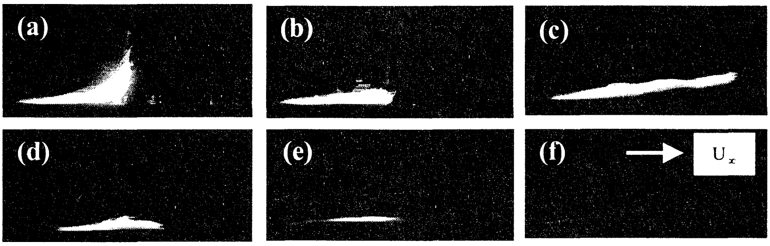


FIGURE 3 - Photographs of a drop tower test for an oxygen concentration of 30% and 110 mm/s velocity. (a) - 1 s , (b) +0.1 s , (c) +1 s , (d) +1.5 s , (e) +2.5 s , (f) +4 s.

For flow velocities of <120 mm/s a deformation of the flame accompanies this transition. As the residual flow moves across the flame a region of the flame is pushed against the fuel creating, in many cases, pockets of fuel vapor that escape through the flame (Figure 3 (d)). This phenomena has been observed many times with PMMA [12] and its detail description escapes the objectives of this work.

As time progresses the flame slowly reduces its size and its luminous (figure 3 (e) and (f)) intensity until it attains an almost steady position. Depending on the experimental conditions, steady state conditions might not be attained. This consideration is a limiting factor of this study. For cases close to the extinction limit, as the flame exits the transition period it reduces rapidly and becomes unstable. Periodic fluctuations of the leading edge and a monotonic decrease of the surface temperature precede extinction.

## Surface Temperatures

Temperature measurements of the solid phase by means of thermocouples are difficult since the exact placement of the thermocouple varies as the fuel pyrolyzes. For these experiments the surface temperatures will be used as a reference value but should not be taken necessarily as the pyrolysis temperature but as an unknown combination of the gas phase and pyrolysis temperatures. For this same reason no correction for radiation is included in this work. Temperature recordings show that as the fuel surface regresses the thermocouple is exposed to the flow increasing the recorded temperature. The increase is significant (>100°C) close to the flame (at the leading edge) and less important further downstream (~ 20°C).

A series of representative surface temperature histories are presented in figure 4. The temperature traces correspond to thermocouples placed at identical relative positions from the flame leading edge. Figure 4 (a) shows the temperature evolution for three different forced flow velocities. For 75 and 105 mm/s, the residual flow perturbation brings the flame towards the surface resulting in an increase in temperature. The increase in temperature is followed by a decay that leads to a steady-state value. The passage of the flow perturbation correlates well with the forced flow velocity, arriving earlier as the velocity increases. For the higher velocity (200 mm/s) the flame remains unaffected by the perturbation and the surface temperature decays as the stand-off distance increases. A stationary value is attained after less than one second. In the stationary region it can be observed that the surface temperature increases with the flow velocity which is consistent with boundary layer assumptions.

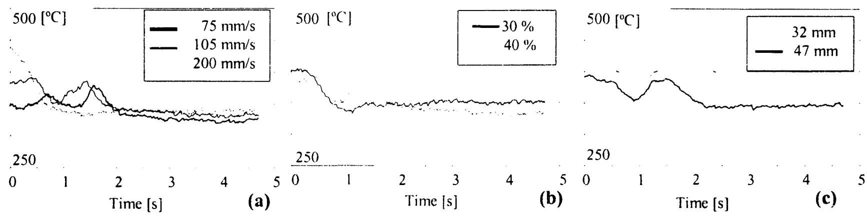


FIGURE 4 - Temperature histories as recorded by a surface thermocouple 14 mm downstream of the leading edge. (a) The effect of the forced flow velocity, (b) the effect of the oxygen concentration, (c) The effect of the size of the pyrolyzing zone.

The flow perturbation responsible for the temperature peaks observed in Figure 4 (a) can be attributed to residual buoyant flows, therefore is expected to be more severe at higher oxygen concentrations since the flame temperatures, as recorded by the thermocouple array, were observed to increase in approximately 200°C when the oxygen concentration was increased from 20% to 40%. Figure 4(b) shows this to be the case. The characteristic length scale of the pyrolisis region seems to have an effect only on the time interval of the perturbation (Figure 4 (c)). The smaller size of the sample leads to a smaller buoyantly induced velocity, thus, to a longer characteristic time. It needs to be noted that the temperatures presented show differences of 5- 30°C. This can be attributed to a different placement of the thermocouple relative to the surface.

## Heat Feedback to the Fuel Surface

Following boundary layer assumptions an estimate of the heat feedback from the flame to the fuel surface can be obtained by means of the following expression

$$\dot{q}'' = -\lambda \frac{(T_P - T_F)}{\delta_F}$$

where $\dot{q}''$ is the heat feedback per unit area, $\lambda$ is an average thermal conductivity for air ($\lambda$=0.0257 W/m.K), $T_P$ the surface pyrolysis temperature, $T_F$ the flame temperature and $\delta_F$ the stand-off distance.

Single thermocouple histories do not allow a proper estimate of the pyrolysis temperature of the fuel therefore and average value of 330°C was used. It is important to note that the average pyrolysis temperature, for the conditions studied, was not a function of the flow velocity or oxygen concentration. The thermocouple tree determined an average flame temperature for the different experimental conditions. Both pyrolysis and flame temperatures were in agreement with values commonly found in the literature. The flame stand-off distance can be obtained by digitizing the video recordings and establishing a luminosity threshold to determine a flame boundary. Averaging at least 25 consecutive images provides an average flame boundary that is considered to be representative of the stand-off distance. All values were obtained after the transition regime was over.

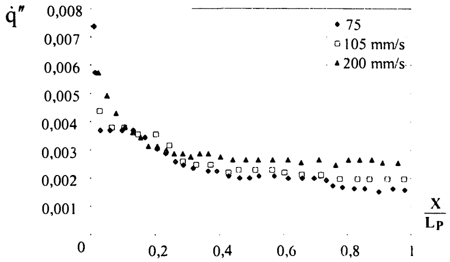


Figure 5 - Estimated heat flux (W/mm$^2$) for different forced flow velocities. The oxygen concentration in the oxidizer flow is 40% for all cases.

It is clearly possible to determine a more accurate estimate by evaluating the temperature gradient at the surface but due to the difficulty in obtaining proper temperature measurements this simple estimate was considered adequate to describe the experimental tendencies.

The estimated heat feedback to the fuel surface as a function of a scaled length, $x/L_P$ , where $L_P$ is the length of the pyrolyzing region and x the coordinate axis is presented in Figure 5. The heat flux to the surfaces reaches a maximum at the leading edge and decreases towards an almost constant value as the distance from the flame tip increases. The values presented are only for 40% oxygen concentration but are representative of all other experimental results. The more luminous nature of these flames made these results easier to interpret and are preferred to explain the experimental results.

Close to the leading edge the heat flux is very high because the flame is very close to the fuel. For 200 mm/s the heat flux decreases smoothly with the distance from the leading edge reaching a constant value for $x/L_P>0.4$. For 105 mm/sec and the 75 mm/sec the increase in heat flux at the leading edge is not as obvious. For the lower velocities, an initial peak is followed by a plateau leading again to an almost constant value further downstream. The heat flux plateau initially increases in size as the forced flow velocity increases, but a further increase in the oxidizer velocity leads to a smooth decrease as show for 200 mm/s. It is relevant to add that the absolute magnitude of the heat flux peaks close to $x/L_P=0$ are somehow artificial since they depend on the accuracy of the image processing. As expected, away from the leading edge the heat flux increases with the oxidizer flow velocity.

A further decrease in the forced flow velocity results in a lower heat flux to the surface that eventually will lead to a smaller mass flow of fuel towards the flame and consequently to extinction. This observation agrees well with the minimum fuel injection velocity extinction observed by Hirano et al. [7,8] and by Torero et al. [9]. Heat losses by emission from the fuel surface and by radiative losses from the flame, as argued by West et al. [12], will further support this observation.

## Mass Transfer

Fuel mass transfer from the surface to the flame has been generally assumed to occur by diffusion [1-6] and the self similar solution proposed by Emmons [1] requires a specific velocity profile at the surface, which is proportional to $x^{-0.5}$, where x is the distance in the stream wise direction. A mass balance leads to the determination of the fuel mass fraction at the surface [4]. Emmons [1] discusses the possibility of separation of the flow at the surface if fuel injection increases beyond a specified threshold value, but concluded (based on the diffusive nature of the heat feedback) that this will lead to extinction. Experimental work with constant fuel injection, under similar conditions to those of the present work, showed the possibility of separation of the free stream due to fuel injection velocity [9]. The strong heat flux close to the leading edge, as presented in Figure 5, seems to further support these observations.

The Blasius definition gives the following expression for the boundary layer thickness:

$$\delta_B = \frac{5.5\ x}{Re_x}$$

where $Re_x = U_\infty x / \nu$, $U_\infty$ is the free stream velocity and $\nu$ the kinematic viscosity. All properties are those of air and have been taken at ambient temperature. Following the analysis by Emmons [1] the flame stand-off distance can be considered a constant fraction of the boundary layer thickness, therefore, the stand-off distance will be presented normalized by $\delta_B$. The appropriate scaling should use the solution to the stand-off distance as can be derived from the Emmons formulation. This solution includes the effects of thermal expansion and thickening of the boundary layer due to the fuel mass addition. Although solutions are available in the literature [1, 4, 14] the dependency on the streamwise co-ordinate remains the same as that of the $\delta_B$. Instead, proper definition of parameters such as the mass transfer number and radiative feedback/loss contributions [4] are of a level of complexity that goes beyond the scope of this work. Thus, the discussion presented in this section will use $\delta_B$ as a scaling length and therefore the conclusions are of a qualitative rather than a quantitative nature.

Figure 6 shows the non-dimensional stand-off distance as a function of the normalized distance from the leading edge. The same three sample cases have been considered and a fourth intermediate velocity (145 mm/s) with a shorter pyrolysis length ($L_P$=39 mm) has also been incorporated for validation. For the lower velocities, for $x/L_P<0.2$ the stand-off distance increases faster than the boundary layer thickness and for $x/L_P>0.2$ the stand-off distance is proportional to $\delta_B$, as can be concluded from the constant value of $\delta_F/\delta_B$ (Figure 6). The increase in the constant of proportionality with the flow is related to the increase of the fuel mass transfer (incompressible boundary layer with blowing at the surface, as proposed by Emmons [1]). As the velocity increases together with the heat flux to the fuel surface, the mass flow of fuel into the boundary layer is controlled by momentum at the fuel surface and the stand-off distance is not anymore proportional to $\delta_B$. This regime corresponds well to the "convective regime" described by Torero et al. [9].

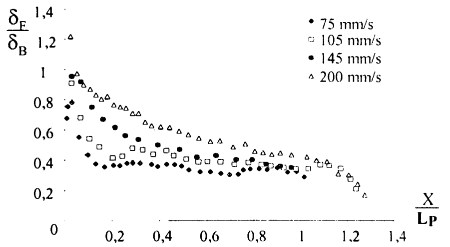


FIGURE 6 - Non-dimensional stand-off distance for four different forced flow velocities. The oxygen concentration in the oxidizer flow is 40% for all cases.

The former case corresponds to the zone defined earlier as the blue flame regime and the latter to the blue/yellow zone. As described by Law and Faeth [11] for soot glowing to occur, and thus for a flame to emit yellow light, it is necessary for the flow stream lines to carry the soot particles formed at the fuel side across the flame. The results of Torero et al [9] and the present work support this theory since yellow flames occur only in a regime where fuel transport by convection towards the flame is not negligible. In the case where only diffusion controls fuel transport towards the flame the flame becomes blue and almost invisible to a standard CCD camera.

As the flame exits the trailing edge of the fuel, the stand-off distance decreases as the fuel is consumed. This observation corresponds well with the concept of "excess pyrolyzate" proposed by Pagni and Shih [4].

## Flame Length

An important parameter related to fire safety is the flame length, $L_F$, since it affects flow aided flame spread and, thus, the involvement of flammable materials adjacent to a flame. For this work the flame length provides a global manifestation of the issues discussed above.

The flame length was obtained in a similar manner to the stand-off distance and $L_F$ is defined as the distance between the leading edge and the end of the visible flame zone. Figure 7 shows that the flame length undergoes an initial growth that leads to a constant value. The flame length is defined as the average value for the last second of the drop. In the case of parabolic flights, the flame length was recorded as the average value of the longest period without significant perturbations. For several experimental conditions the flame length did not fully attain a steady state value. If the decreasing slope was smaller than 1 mm/s the data points were still recorded.

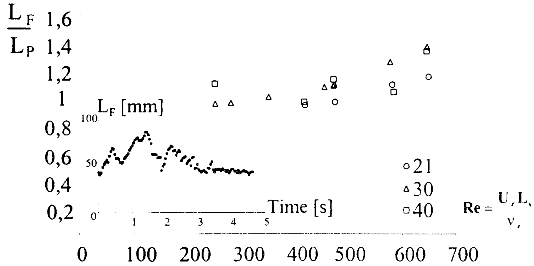


FIGURE 7 - Non-dimensional flame length for three different oxygen concentrations. The inner figure shows the time evolution of the flame length for drop tower test with 30% oxygen concentration and Re = 450.

Under the assumptions of Emmons [1], Pagni and Shih [4] determined that the flame length for a combustible plate subject to a flow parallel to the surface is independent of the Reynolds number, where the characteristic length scale is that of the fuel sample ($L_S$). Figure 7 shows the flame length normalized by the pyrolysis length ($L_F/L_P$) as a function of the Reynolds number. As with the stand-off distance, the flame length follows the theoretical predictions with good qualitative agreement for the blue flame zone (Re<400) but shows an increasing trend for Re>400 when convective transport of fuel leads to a yellow flame.

## CONCLUSIONS

A series of experiments have been presented and it has been shown that at least for the experimental conditions studied:

- Laminar diffusion flames were found to be unstable in the absence of a minimum oxidizer forced flow. Absolute stability limits seem to be a function of the oxygen concentration but could not be determined due to the short duration of the micro-gravity time.
- The low velocity stability limit of the flame seems to be linked to a minimum fuel production, below this value extinction will abruptly occur. Since fuel pyrolysis depends on the heat feedback from the flame, it is intimately related to the characteristics and geometry of the flame and, thus, to the magnitude of the flow.
- Two different regimes of stable flames have been identified, blue flames and yellow flames. Fuel supply is dominated by diffusion for blue flames, therefore, stand-off distance and flame length correspond well with classical theory [1,4]. Convection of fuel towards the flame is of importance in yellow flames leading to discrepancies between theory and the present experiments.

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## REFERENCES

1. Emmons, H. "The Film Combustion of Liquid Fuel," Z. Angews. Math. Mech., 33, 60, 1956.
2. Lavid, M. and Berlad, A.L. "Gravitational Effects on Chemically Reacting Boundary Layer Flows over a Horizontal Flat Plate" 16th Symposium (International) on Combustion, The Combustion Institute, 1157-1568, 1976.
3. Fernandez-Pello, A.C. and Pagni, P.J., "Mixed Convective Burning of a Vertical Fuel Surface", ASME-JSME Thermal Engineering Joint Conference Proceedings, Honolulu,4,1993.
4. Pagni, P.J. and Shih, T.M., "Excess Pyrolyzate" 16th Symposium (International) on Combustion, The Combustion Institute, 1329-1343, 1976.
5. Chen, H.C. and T'ien, J.S., "Diffusion Flame Stabilization at the Leading Edge of a Fuel Plate," Combustion Science and Technology, 50, 283-306, 1986.
6. Kodama, H., Miyasaka, K. and Fernandez-Pello, "Extinction and Stabilization of a Diffusion Flame on a Flat Combustible Surface with Emphasis on Thermal Controlling Mechanisms," Combustion Science and Technology, 54, 1-6, 37-50, 1987.
7. Hirano, T. and Kanno, Y. "Aerodynamic and Thermal structures of the Laminar Boundary Layer over a Flat Plate with a Diffusion Flame," 14th Symposium (International) on Combustion, The Combustion Institute, 391-398, 1972.
8. Hirano, T., Iwai, K. and Kanno, Y., "Measurement of the Velocity Distribution in the Boundary Layer over a Flat Plate with a Diffusion Flame ," Astronautica Acta, 17, 811-818, 1972.
9. Torero, J.L., Bonneau, L., Most, J-M and Joulain, P., "The Effect of Gravity on a Laminar Diffusion Flame Established over a Horizontal Flat Plate," 25th Symposium (International) on Combustion, The Combustion Institute, 1701-1709, 1994.
10. Joulain, P., "Diffusion Flame Combustion in Oxidizing Flow," Micro-Gravity Science and Technology, 4, 178-191, 1993.
11. Law, C.K. and Faeth, G. M., "Opportunities and Challenges of Combustion in Micro-Gravity," Progress in Energy and Combustion Science, 20, 1, 65-113, 1994.
12. West, J., Tang, L., Altenkirch, R.A., Bhattacharjee, S., Sacksteder, K. and Delichatsios, M.A., "Quiescent Flame Spread over Thick Fuels in Micro-Gravity," 26th Symposium (International) on Combustion, The Combustion Institute, 1335-1343, 1996.
13. Koning, J., Dinkelacker, F., Eigenbrod, C., Rath, H.J., Schroder, T. , Albrecht, H., Muller, D. and Triebel, W., "Application of UV-Laser-Diagnostics to Combustion Research under Zero-Gravity," Advances in Space Research, 16, 7, 145-148, 1995.
14. Pagni, P.J., "Diffusion Flame Analysis," Fire Safety Journal, 3, 273-285, 1980/81.