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ON THE EFFECT OF PRESSURE, OXYGEN CONCENTRATION, AIR FLOW AND GRAVITY ON SIMULATED POOL FIRES

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Introduction

The initial development of a fire is characterised by the establishment of a diffusion flame over the surface of a the condensed fuel and is particularly influenced by gravity, with most of the gaseous flow induced by natural convection. Low initial momentum of the fuel vapour, strong buoyant flows induced by the hot post-combustion gases and consequently low values of the Froude number (inertia-gravity forces ratio) are typical of this kind of scenario. An experimental study is conducted by using a porous burner to simulate the burning of a horizontal combustible surface. Ethane is used as fuel and different mixtures of oxygen and nitrogen as oxidiser. The magnitude of the fuel injection velocities is restricted to values that will keep the Froude number on the order of 10^{-5}, when calculated at normal gravity and pressure, which are characteristic of condensed fuel burning. Two different burners are used, a circular burner (62 mm diameter) placed inside a cylindrical chamber (0.3 m diameter and 1.0 m height) and a rectangular burner (50 mm wide by 200 mm long) placed in a wind tunnel (350 mm long) of rectangular cross section (120 mm wide and 90 mm height). The first burner is used to study the effect of pressure and gravity in the absence of a forced flow parallel to the surface. The second burner is used to study the effect of a forced flow parallel to the burner surface as well as the effect of oxygen concentration in the oxidiser flow. In this case experiments are also conducted at different gravity levels (micro-gravity, 0.2 g_0 , g_0 and 1.8g_0) to quantify the relative importance of buoyancy.

The Effect of Gravity

The gravity level was varied systematically to observe the effect of gravity on the flame characteristics. Experiments were performed in reduced and micro gravity conditions in an aircraft (Caravelle) following a parabolic trajectory. The aircraft provides up to 20 sec. of $10^{-3}g_0$ per parabola. By performing special manoeuvres, 20 sec. of reduced gravity (0.2g_0) were also obtained. Tests in over gravity conditions are conducted in a centrifuge facility and experiments were conducted for 3, 6, 9 and 12 normal earth gravity conditions. The maximum value of the ratio of the velocities induced by coriolis and centrifugal accelerations and the hot products velocity is of the order of 10^{-2} at $3g_0$, decreasing as the g-level increases, thus their effect is neglected.

At normal gravity the flames examined show the three main zones characteristic of buoyant diffusion flames [1]. Close to the burner surface edge, the flame presents a luminous annular zone around a fuel rich central region. The flame appears to be laminar with a light blue colour. Most of the chemical reactions occur in the luminous zone, due to the availability of oxidiser brought by buoyant air entrainment. The large heat release induces a drastic increase in the gas velocity and temperature in this region. Downstream (second zone) the flame has an intermittent character and turns yellow as the temperature maximum reaches the burner axis. Above the visible flame tip is the buoyant plume (third zone), which is characterised by decreasing gas velocities and temperatures.

It was observed from the video images that by increasing gravity the flame behaviour is clearly modified. As gravity is increased above normal level, the flame colour in the second zone changes from yellow towards blue (at $12g_0$ the whole flame is blue). Also the flame becomes compact, its neck is less visible, its height decreases, and its fluctuation increases. In reduced gravity, at $0.2g_0$, the flame is compact cylindrical, yellow and stable. During the micro-gravity period, a flattened flame is seen to float over the burner, periodically moving outward towards the air side, apparently seeking fresh air. The observed flame behaviour as the gravity is increased is interpreted as being the result of the increase in the air entrainment with gravity. A larger air entrainment results in better mixing and shorter residence times, both of which tend to reduce soot formation [2]. Furthermore, the soot particle pathlines and velocity distributions as well as the soot production regions are also affected by buoyancy [2]. The pathlines are wider, the velocities lower, and the soot containing volumes are broader as gravity is decreased. All these effects tend to reduce soot formation and increase soot oxidation as gravity is increased, and consequently to change the flame colour from yellow to blue.

The measured variation of the flame length (L_f) with gravity is presented in Figure 1. The flame height presented corresponds to the boundary of visible gas emission and is related either to the end of soot oxidation or the hydrocarbon radicals burning. It is obtained from the processing of 120 video images and is defined by the 50% flame tip appearance rate. The results show that the flame height has a -1/3 power law dependence on the gravity vector, g, from $0.2g_0$ to $12g_0$, i.e.

$$L_f \propto g^{-1/3} \qquad (1)$$

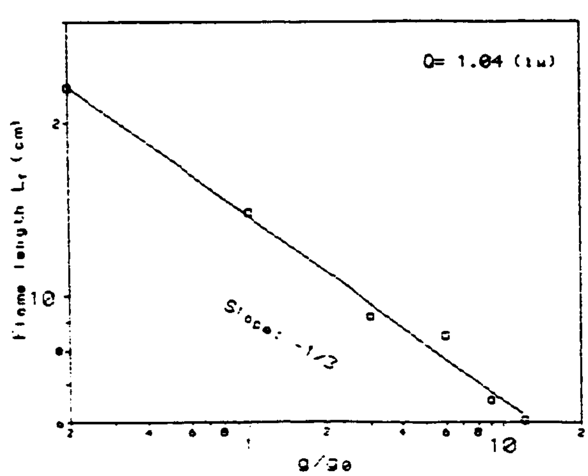

Figure 1
Variation of the flame length with gravity

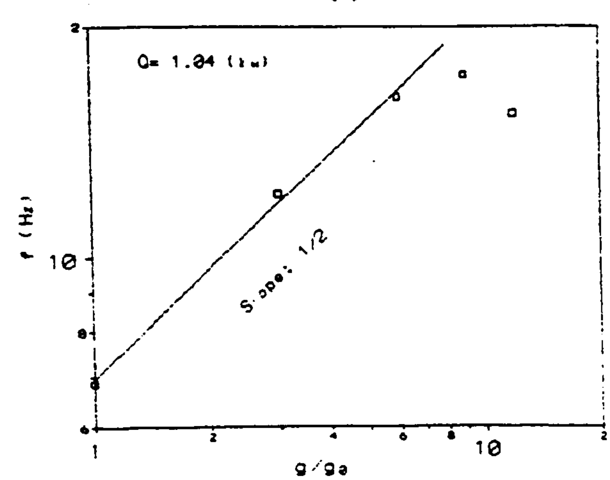

Figure 2
Variation of the pulsation frequency with gravity

These results agree well with the flame height predictions of the fire plume dimensionless analysis of Quintere [3]. The results are also in agreement with the experimental correlation of Zukoski et al. [4] and the work of Altenkirch et al.[5].

The flame pulsation frequencies are obtained from the flame video recordings by applying fast Fourier transformation of the analog output signal of a photo detector placed on the video monitor screen. The measured variation of the flame pulsation frequency with gravity is presented in Figure 2. For gravity levels smaller than $8g_0$ the results of Figure 2 give a 1/2 power law dependence of the flame pulsation frequency on gravity. For gravity levels larger than $8g_0$ limitations a significant deviation from this power law is observed and might be due to limitations in the video sweeping rate. Theoretical derivation of this 1/2 power dependence was previously conducted by Baum and McCaffrey [6]and independently by Bejan[7]. If the velocity at the surface is negligible the equation proposed by Baum and McCaffrey [6] can be simplified to

$$f \propto \sqrt{g/D} \qquad (2)$$

For normal gravity the results of numerous experimental studies for various fuels and pool diameters are well correlated with equation (2) [8].

Other parameters studied are the maximum temperature as measured by a 75μm diameter Cr/Al thermocouple and the radiative heat flux.

The Effect of Pressure

The effect of pressure was studied by changing the pressure inside the cylindrical chamber from 0.03 to O.3 MPa. All tests were conducted at normal gravity. It was observed that pressure had a significant effect on the flame physical appearance, temperature and pulsation frequency.

Video images of the flame were obtained by using a CCD camera and from these images it could be observed that as the pressure is increased above atmospheric levels the flame turns yellower and its height and width decrease. Small eddy structures appear and the soot formation increases visibly. Heat transfer to the vessel wall is drastically intensified. When decreasing the pressure below atmospheric levels, the flame turns blue and becomes more laminar, the central fuel rich zone grows, and the flame height decreases. these observations agreed qualitatively with those of Faeth et al. [2], for the effect of pressure on jet diffusion flames. It is interesting to note that the effect of pressure on soot formation in these types of flames is opposite to that of gravity. Since increasing pressure increases buoyancy, one would expect that according to the above arguments soot formation should decrease rather than increase as observed experimentally. This result seems to be due to the stronger effect of pressure on the soot formation reaction rate (a square power law dependence on pressure [2]), than on the other soot formation factors (soot residence time, pathway, containing volume).

Concerning the variation of the flame height with pressure, the results of Figure 3 show that for pressures below 0.08 MPa, the flame height increases with pressure according to a 0.16 power law. However, for pressures above 0.08 MPa, the flame height decreases with pressure, according to a -0.5 power law. The pressure at which the height maximum is observed (0.08 MPa) is higher than that observed by Hirst and Sutton [9] in experiments with a liquid pool fire of small diameter. At low pressures air entrainment is small, thus, transport of oxidiser to the reaction zone is mainly by diffusion, as pressure increases air entrainment becomes dominant over diffusion. For the former a Burke-Schumann [6] applies and for the latter an analysis such as the one of Quintere [3] is more convenient. The Burke-Schumann analysis predicts that for a diffusion dominated flame the flame length will increase with pressure, instead the buoyant analysis predicts that the flame length will decrease with pressure according to a -2/3 power law. The experimental results have a qualitative similarity with the theoretical predictions but quantitatively they differ significantly. Both diffusion and buoyancy seem to be significant transport mechanisms for all conditions studied therefore the opposing dependencies on pressure seem to explain the differences between the experimental results and the predictions derived by neglecting one of the effects.

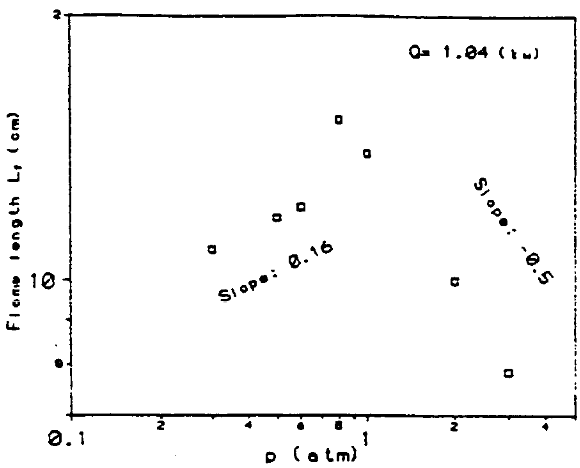

Figure 3
Variation of the flame length with pressure

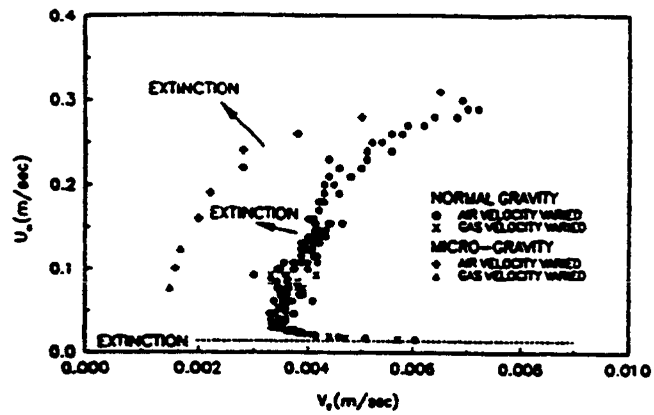

Figure 4
Effect of the oxidiser flow and fuel injection on the stability of the flame

The Effect of Oxygen Concentration and a Forced Flow Parallel to the Surface

The results presented above attempt to explain the effect that gravity and pressure have upon a flame established in a quiescent environment. This kind of environment is seldom found in real situations, in general, a forced flow is always present parallel to the burning surface. The objective of this work is to try to improve the knowledge on fire safety as related to micro-gravity environments therefore the effect of a forced flow of magnitude comparable to those induced by a spacecraft ventilation system (in spacecraft the ventilation system generates a flow of the order of 0.1 m/s) was systematically studied. The effect of oxidiser concentration on fire safety is also of great importance when determining the atmosphere of a spacecraft, thus, experiments were conducted with oxidiser flows ranging from 18% to 62% oxygen concentration.

The geometry of the experimental set up was changed to the above mentioned rectangular burner and a forced oxidiser flow was generated inside a wind tunnel. The burner geometry was changed to keep the two dimensional approach used when analysing the previously explained experiments. Video recordings of the flame allowed the observation of the flame geometry and extinction limits and six 75μm diameter Cr/Al thermocouples provided estimates of the flame temperature.

To study on the effect of gravity on the extinction limits, the flame was established and then the air flow velocity (U_∞) was increased until extinction occurred. For low air flow velocities, the fuel injection velocity (V_F) was varied until the flame extinguished. The results are presented in Figure 4, the data points represent the values of air and fuel velocities at which extinction occurred. In normal gravity, for $U_\infty < 0.03$ m/s all flames extinguished. Close to the extinction limit the flames where almost vertical and very close to the leading edge of the plate. For 0.03 m/s $< U_\infty <$ 0.1 m/s flames extinguished at an almost constant value of V_F. For $U_\infty >$ 0.1 m/s the extinction limit depends on both fuel and oxidiser velocity, with the dependence on the former becoming less significant as U_∞ increases. The extinction curves, in normal and micro-gravity, are similar with the latter significantly displaced towards the left. It is important to note that the difference between normal and micro-gravity extinction limits decreases as U_∞ increases. For $U_\infty<0.07$ m/s, perturbations in the gravity level become important rendering the micro-gravity extinction limits unreliable.

As mentioned before, oxygen concentration, oxidiser flow velocity and injection velocity were systematically varied. The influence on the flame geometry and appearance was observed. In normal gravity the flame consisted of two distinctive zones, a first zone, close to the leading edge, where a boundary layer flame can be observed and a second zone, further upstream, where a buoyantly induced plume is present. The first zone is characteristically blue and the second zone yellow.

Changing the oxygen concentration in the oxidiser flow has a significant effect on the appearance of the flame. As the oxygen concentration increases the flame becomes more stable and brighter. The first zone remains blue and the second yellow, but both colours become more intense. The distance from the leading edge at which the plume appears remains constant with the oxygen concentration, but the size of the plume decreases significantly.

The fuel injection velocity also exerts a significant effect on the appearance of the flame. There is a minimum injection velocity that will sustain a flame (as described before). For very low injection velocities the flame appears close to the burner and is very unstable. Almost the entire flame is blue and only slight traces of yellow can be observed. As the fuel injection velocity increases the plume increases in height and the presence of a yellow zone becomes more evident. The distance from the leading edge at which the plume becomes evident remains almost invariable with the fuel injection velocity.

The oxidiser forced flow velocity has an effect on the stability, stand-off distance and colour of the flame. The relative importance of the boundary layer and plume zones is also affected by the forced flow velocity. Increasing the forced flow velocity results in a bluer and more unstable flame. The flame appears closer to the burner, the plume becomes smaller and the size of the boundary layer zone increases with the plume appearing further down stream.

In micro-gravity three distinctively different flames can be observed. For low fuel injection velocities the flame adopts a parabolic geometry. The stand-off distance and the colour of the flame can be varied by changing the oxidiser flow velocity and oxygen concentration. The shape of the flame can be varied by increasing the fuel injection velocity. Far away from the leading edge, a change in the geometry of the flame can be observed when the injection velocity increases. The parabolic flame turns linear towards the end of the plate. A further increase on the injection velocity increases the presence of the linear flame. Finally, a third type of flame can be observed for high injection velocities, this flame is almost entirely linear and a curved flame is only present very close to the leading edge. The colour and stand off distance for the last two flames follow the same pattern as for the first type of flame.

It was also observed that all flames are blue on the lean side and yellow on the rich side and that there is a significant effect of the ceiling on the flame shape. The ceiling reflects the flame, when it gets to close, generating a point of maximum stand-off distance. The geometrical limitation of the chamber has a significant effect downstream but no observable effect upstream of the point of maximum stand-off distance.

For low oxygen concentrations significant three dimensional effects could be observed, this effects along with the influence of the lateral walls are extensively discussed in the work of Torero et al. [10] and will not be treated here.

Conclusions and Perspectives

The influences of gravity, pressure, oxygen concentration and wind have been studied experimentally on a small scale simulated pool fire, conclusions regarding several fundamental parameters have been drawn from mainly video images and thermocouples. Verification of existing dimensionless laws has been accomplished and phenomena such as blow-off limits has been explored. Numerical simulations and theoretical analysis are being developed and comparison with the experimental results should be expected for the near future. Further experiments with gas burners as well as liquid and solid fuels have been planned for different gravity levels. Comparison between the idealised cases and the more realistic ones should shed further light on the fundamental mechanisms controlling pool fires.

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