The Effect of Reduced Pressure and Airflow on Liquid Surface Diffusion Flames

R. Hirst* and D. Sutton

Rocket Propulsion Establishment, Westcott, Aylesbury, Bucks.

(*Received February 1961*)

A general investigation into diffusion flames burning from a liquid surface at low pressure has been made, as this type of problem is relevant to the question of the persistence of fires in aircraft flying at high altitudes. The fuels used were isododecane and aviation kerosine. Temperatures in the carbon-free parts of the flame and in the fuel were measured in various sizes of burner. The rate of consumption of fuel was measured and the effects of air velocity around the flame and of air vitiation were noted. Evidence was found of recirculation within the vapour space of the flame. The minimum air velocities required to extinguish flames from the fuel surface at low pressures were determined in a 16 in. diameter variable density wind tunnel. The effect on the extinction velocities of the fuel temperature, the presence of flameholders, and the presence of a metal plate above the flame was investigated. It is concluded that the probability of the persistence of fire in an aircraft remains high up to 40 000 ft, is much less at 50 000 ft, and may be negligible at 60 000 ft. The probability of its persistence at the higher altitudes may be greater in a damaged aircraft.

Introduction

Experience has shown that fires can be initiated and can persist in aircraft flying at altitudes up to at least 20 000 ft. Above this height flight information is meagre and it is not known to what extent the hazard diminishes at greater altitudes. This investigation was made to obtain some information on the persistence of fires at high altitudes, and was in fact concerned with the behaviour of liquid surface diffusion flames at low pressures.

Fires occur much more frequently in the engine nacelle than in any other part of an aircraft. This is due mainly to the proximity of a pressurized fuel system to highly stressed mechanical parts and both thermal and electrical ignition sources. On military aircraft, fires may also result from incendiary attacks on the fuel tanks.

Three modes of combustion can exist in an engine fire, each supported by the cooling air that passes through the nacelle: a 'spray' fire, supported by fuel escaping from a fractured pipeline; a 'wick' fire, burning from fuel streaming over a hot metal surface; and a 'puddle' fire established above the surface of a pool of fuel. Flameholding in the airstream can occur in the wake of any of the obstructions and protrusions that are inevitably present within a nacelle. In a damaged tank bay, the spray fire that may exist momentarily following a strike must pass over to a puddle fire burning from the spilled fuel (unless the tank is destroyed by a vapour–air explosion).

The experiments reported here are concerned only with puddle fires, which were expected to be the most difficult to extinguish on an aircraft. It was assumed that a liquid surface diffusion flame burning in the wake of a bluff body represents the most stable mode of combustion in this environment, but further testing is needed to establish this point fully. An investigation of combustion in spray fires and wick fires will be reported later.

A considerable amount of work has been reported on the effect of reduced pressure on premixed flames and, more recently, on gaseous diffusion flames, but there is little information about diffusion flames burning from a liquid surface under these conditions. G. N. Khudiakov[1] has reported an investigation into liquid surface diffusion flames in which he recorded flame temperatures, temperature profiles within the liquid, and gas composition inside the flame, but the effect of reduced pressure was not discussed. Measurements of the fuel temperature and its rate of consumption in large burners have been made by J. H.

*Present address: Group Research, Wilkinson Sword Ltd, Colnbrook, Slough, Bucks.

BURGOYNE and L. L. KATAN[2], and by D. J. RASBASH, Z. W. ROGOWSKI and G. W. V. STARK[3]. In the work reported here, measurements were made of temperatures in the carbon-free part of the flame, temperature profiles in the liquid, the rate of consumption of fuel, and flame dimensions, with respect to such variables as pressure, burner diameter, air flow around the burner, and vitiation index. In a second series of experiments, measurements were made of the minimum air velocity required to sweep the flame from the fuel surface at low pressures. The experiment was then repeated in the presence of simple flameholders, and of a metal plate above the fuel surface. The results indicate some of the critical ambient conditions for the persistence of flames at reduced pressures.

This study was primarily concerned with the behaviour of flames at high altitudes, and many of the results are therefore expressed in terms of altitude. The pressures at which tests were made, and the corresponding altitudes, are indicated in *Table 1*. Graphs in the figures have been scaled in both pressure and altitude.

Table 1. Pressures at which tests were made

Approximate pressure atm	*Altitude* ft
0·50	18000
0·30	30000
0·19	40000
0·11	50000
0·07	60000
0·04	70000

Effect of Reduced Pressure on Liquid Surface Diffusion Flames

Apparatus and technique

The experiments were made in a cylindrical decompression chamber of 200 ft^3 capacity which could be pumped out to a low pressure limit of about 0·04 atm, corresponding to an altitude of 70000 ft. A window was fitted at one end of the chamber and along its centre axis, through which the flame could be seen directly. A cathetometer was placed in line with this window to facilitate the accurate alignment of the burner. The burners used were 28, 41, 66 and 96 mm in diameter, about 50 mm in depth and with a wall thickness of 1 mm. The burner was supplied with a laminar airflow from a 16 cm diameter tube, the air being metered through a rotameter. The arrangement of the burner and air supply is illustrated in *Figure 1*.

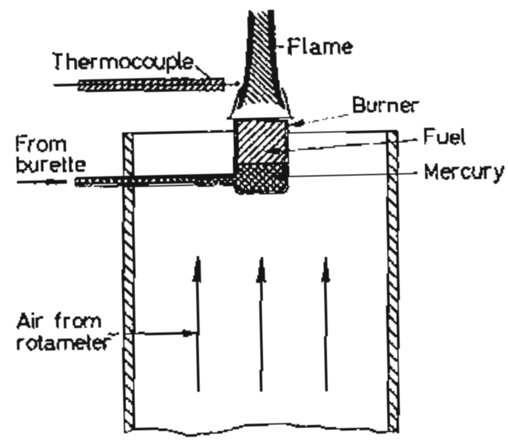

Figure 1. Diagram of burner

During the course of an experiment it was necessary to keep the fuel level with the rim of the burner, and this was done by running in mercury at the same rate as the fuel was consumed, from a burette located outside the chamber. Mercury was used instead of fuel as experience showed that bubbles formed in the supply tube when it contained fuel, which caused troublesome splashing in the burner.

Temperature measurements were made with a platinum/platinum–rhodium thermocouple, which could be moved to any position within the flame or liquid by operating three handles fixed outside the chamber, a complete turn of any one handle resulting in a movement of 1 mm along a cartesian coordinate.

Since kerosine is a mixture of hydrocarbons, it seemed probable that fractionation of the fuel would occur at low pressures, with a consequent change in properties. For this reason most of the experiments were made with *iso*dodecane as the test fuel. Sufficient tests were made with kerosine (DERD/2482) to show that differences between the two fuels were only slight.

Effect of air flow on burning rate

The effect of air flow on the rate of consumption of *iso*dodecane was studied using the 28, 41 and 66 mm burners at the pressures shown in *Table 1*. The maximum air flow used was 100 l./min. Considerable turbulence of the flame occurred in this flow, which corresponded to a linear velocity of 80 cm/sec at 0·1 atm. On the other hand, for very small air flows (e.g. 1 to 5 l./min with the 66 mm burner) insufficient oxygen was being supplied to maintain combustion, and general vitiation of the chamber atmosphere then played a part in extinguishing the flame after a certain time of burning.

In general it was found that the rate of consumption of fuel was independent of air flow above a certain lower flow limit. Flow rates well above this limit were used in all subsequent experiments.

Temperature measurements in the flame

The procedure was to traverse a diameter of the flame with the thermocouple from a position 10 or 20 mm outside the burner edge to a corresponding position at the other side of the burner. Measurements were started at a distance of 1 mm above the burner rim, and the procedure repeated at increasing distances above the burner until the carbon zone was reached. Measurements were then discontinued because deposition of solid carbon particles on the thermocouple made the temperature readings inaccurate. In this way the temperature field in the carbon-free zone of the flame was obtained using kerosine and *iso*dodecane in the 28 mm burner at atmospheric pressure and at all the pressures listed in *Table 1*.

Isothermals at 200°C intervals were then drawn and superimposed on outline drawings of the visible region of the flame that had been copied from photographs. The results obtained from the two fuels were almost identical. Measurements made in *iso*dodecane flames at four pressures are shown in *Figure 2*.

During these experiments the mass air flow was so adjusted that the linear flow around the flame was roughly the same at the different pressures.

Temperature measurements in the liquid

Temperatures below the liquid surface were measured at 1 mm intervals in *iso*dodecane in the four burners and over the pressure range previously mentioned. It was found in practice that the liquid quickly attained thermal equilibrium, and also that the temperature gradient at the edge was the same as in the centre. Readings were taken in the centre down to the depth where the temperature was constant, which was usually at between 10 and 20 mm. The results for the 41 mm burner are typical and are shown in *Figure 3*.

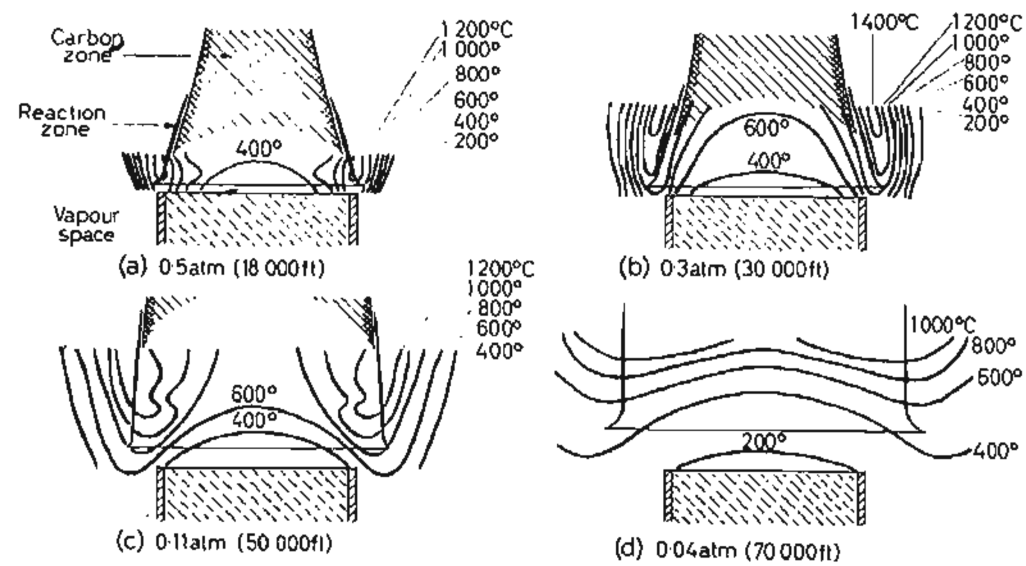

Figure 2. Isothermals in isododecane, 41 mm burner

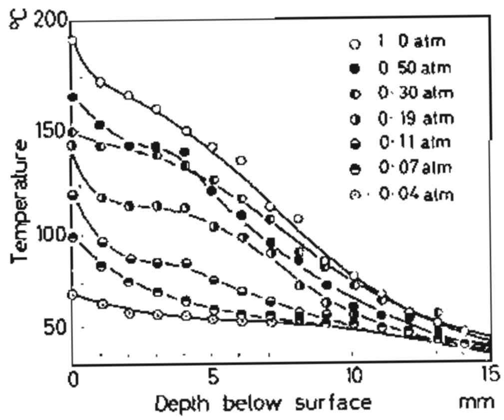

Figure 3. Temperature profiles in isododecane, 41 mm burner

Rate of fuel consumption

This was measured by observing the volume of mercury let in from the burette to replace the fuel consumed in a given time, usually 5 or 10 minutes. Values were obtained from the four burners at pressures down to 0·04 atm (70 000 ft).

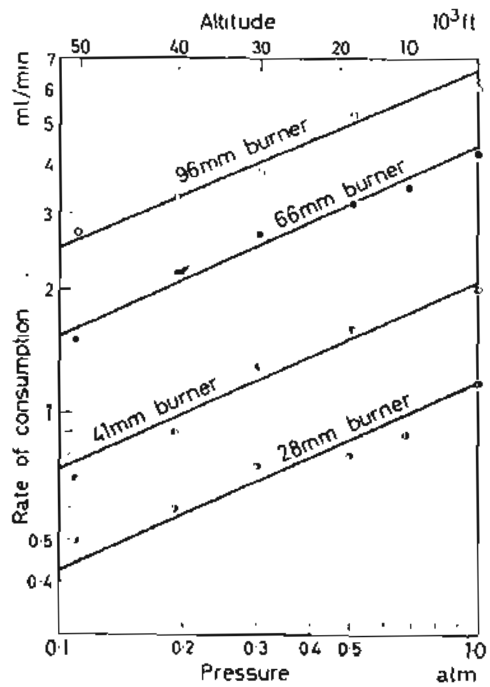

Figure 4. Rate of consumption of isododecane

The results are plotted in *Figure 4* on a log-log scale. They show that the relationship between the rate of consumption and the pressure was approximately the same for each burner, and can be expressed by $C \propto p^{0.46}$, where C denotes consumption and p the pressure.

When the relationship between the rate of consumption and the radius of the burner, r, was examined, it was found that at each pressure the result was approximately the same: the rate of consumption was proportional to $r^{1.5}$.

Effect of vitiation on burning rate

Vitiation experiments were made by measuring the rate of consumption of fuel when the incoming air was mixed with nitrogen in increasing proportions, the total gas flow being kept constant. The fuel consumption was found to fall off rapidly with an increasing admixture of nitrogen, until a point was reached where the flame was extinguished. Using the 28 mm burner, the limiting oxygen concentrations were found to vary between 12·5 per cent at 0·5 atm and 18 per cent at 0·07 atm. For the largest burner the corresponding values were 15 and 18 per cent. These results may be compared with R. F. SIMMONS and H. G. WOLFHARD's values for liquid surface diffusion flames at atmospheric pressure[4]. Their flames were burning beneath an inverted sintered metal hemisphere. The limiting oxygen concentrations for *n*-hexane, *n*-octane and *n*-decane were all about 13·4 per cent.

Flame dimensions

The flame height was measured by means of a scale fixed by the side of the flame. Results for both fuels in the 25 mm burner are shown in *Figure 5*.

The height of the vapour space between the top of the burner and the lowest visible part of the flame was also measured. The results were the same for both fuels: the height varied inversely as the pressure, from 0·50 mm at 0·5 atm to 5·5 mm at 0·04 atm.

General character of the flame

A diffusion flame burning from a liquid surface is similar in appearance to that of a gaseous fuel burning from the top of a circular pipe, and can be divided into three distinct regions:

(i) A vapour space directly above the liquid surface which includes a pyrolysis zone
(ii) A blue reaction zone forming a sheath around the flame at the base and extending well up its side
(iii) A carbon zone starting some way up and inside the reaction zone and extending to the top of the flame, this zone being characterized by the emission of yellow or orange light.

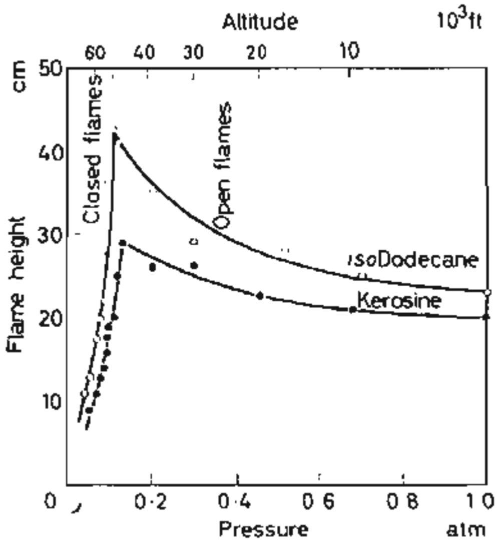

Figure 5. Flame height, 28 mm burner

In addition there is a thin sheath of weak blue radiation surrounding most of the flame. This is difficult to distinguish except near the base of the flame where it merges with the reaction zone. The flame is hollow, and may be either open at the top, with the production of grey soot particles, or closed, depending on the nature of the fuel and the size of the burner. In this investigation all the flames were open at the top at pressures down to about 0·12 atm (see *Figure 5*). In general, the effect of decreasing pressure was as follows:

(a) The depth of the vapour space was extended, i.e. the flame moved away from the surface
(b) The diameter of the reaction zone increased until it was outside the edge of the burner
(c) At pressures down to 0·1 atm the height of the reaction zone increased and the luminosity of the carbon zone was also extended. Below this pressure the top closed and the flame height decreased rapidly at the expense of the carbon zone.

At about 0·05 atm the flame changes its general shape to become more of a hemisphere than a cone, the carbon zone then being quite

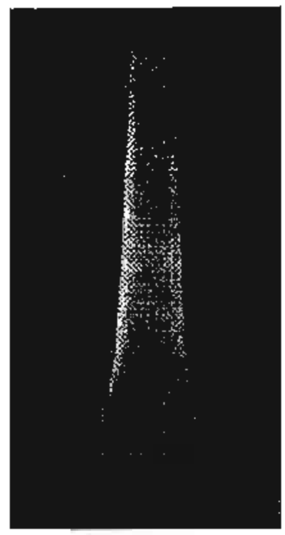

Figure 6(a). *isododecane flame at 0·5 atm showing condensate*

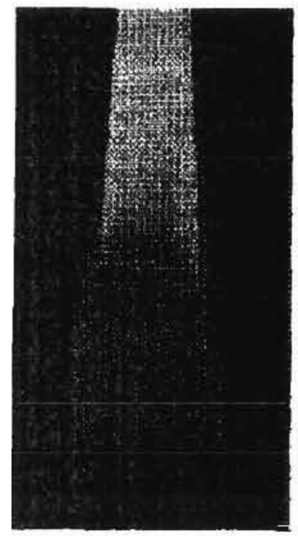

Figure 6(b). *isododecane flame at 0·11 atm*

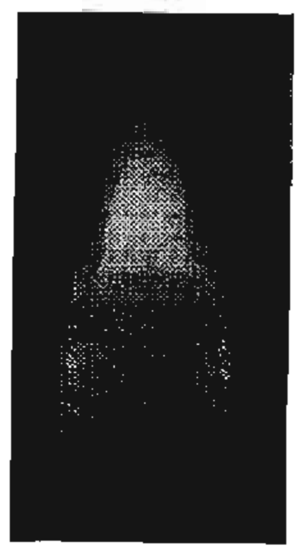

Figure 6(c). *isododecane flame at 0·04 atm*

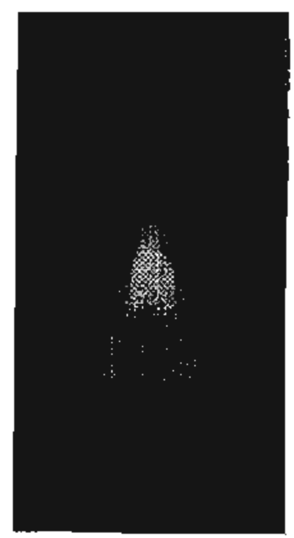

Figure 6(d). *isododecane flame at 0·11 atm in air containing 16·2 per cent oxygen*

small. At the lowest pressures the carbon zone contracted to a yellow patch within the reaction zone.

The size of the flame was found to decrease with increasing vitiation, the whole flame contracting towards the centre of the burner, with an increase in the depth of the vapour space. The general shape of the flame remained the same, but there was considerable diminution in brightness with increasing vitiation. As the limiting conditions for a low pressure vitiated flame were approached, the flame became a small faintly-luminous cusp that tilted slowly from side to side at some distance above the burner.

Three photographs of flames burning at different pressures, and one showing the effect of vitiation, are shown in *Figure 6*. Outline drawings of the flames can be seen in *Figure 2*.

Gas flow within the flame

The accidental use of a sample of 'leaded' *iso*dodecane in these experiments provided interesting evidence of the gas flow within the flame. A white condensate, apparently solid, was observed inside the vapour space of the flame at pressures between 1·0 and 0·1 atm. This can be seen in *Figure 6*(a), and is sketched in *Figure 7*. The condensate formed a toroidal vortex which rolled slowly (as shown in *Figure 7*) at about one revolution a second. Small flocculent particles continuously formed and attached themselves to the main stream, made two or three revolutions, and finally escaped up into the carbon zone of the flame. The condensation was most marked at about 0·4 atm, and then decreased with decreasing pressure, though traces were sometimes seen at 0·07 atm. A small amount of the condensate was collected on a probe for analysis. It was found to contain a high proportion of lead.

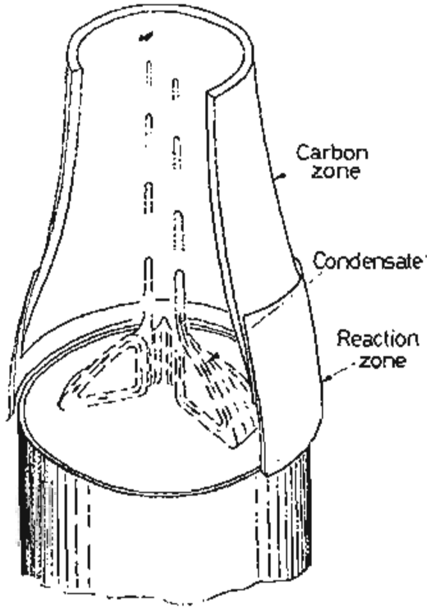

Figure 7. Condensate flow pattern

Limiting Air Velocities for Liquid Surface Diffusion Flames at Low Pressures

Apparatus and technique

The effect of airflow on low-pressure liquid-surface diffusion flames was studied in a small variable-density wind tunnel. This was connected to the vacuum main of a very large high-altitude test facility. The incoming air passed through an orifice plate flowmeter and a gate valve into a cylindrical settling tank. From this it passed through a converging bell-mouth section into a 16 in. diameter pipe. A second gate valve controlled the flow into the vacuum main. By suitable adjustment of the two valves a wide range of airflows could be obtained at pressures down to about 0·07 atm.

The 16 in. pipe formed the working section and was fitted with observation windows. An aerofoil-section model containing a tray of fuel

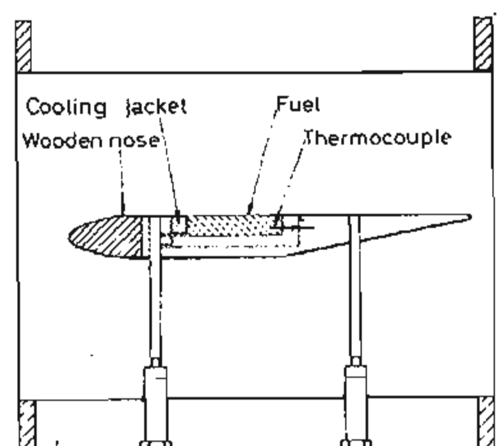

Figure 8. Section of model and working section of wind tunnel

was mounted at the axis of this pipe: this is shown in section in *Figure 8*. The fuel tray was 5 in. × 5 in. × 0·8 in. deep (12·7 cm × 12·7 cm × 2·2 cm) and was surrounded by a cooling jacket. The model was supported in the tunnel by two vertical tubes passing through the underside. These legs were threaded and permitted adjustment to be made to the height of the model. They also acted as conduits, for tubes supplying fuel and coolant, and for the leads of a thermocouple located ½ in. below the surface of the fuel.

The velocity profile within the working section was examined by Pitot traverses and found to be very uniform. Checks with cotton tufts showed that the airflow was substantially laminar and free from any major turbulence.

Both kerosine (DERD/2482) and *iso*dodecane were tried as fuels, but no differences in behaviour could be detected. There was little evidence of fractionation of the kerosine and it was therefore used for most of the experiments.

The fuel was drawn into the tray by reducing the pressure in the tunnel. The surface was then ignited in a small airflow with the aid of a hydrogen pilot flame, which was then turned off. The pressure in the tunnel was adjusted to the desired value and the airflow gradually increased at constant pressure until the flame was extinguished. The fuel temperature, working pressure, and flowmeter manometer were read at the time of blowout, and the test then repeated at different pressure levels. In each test care was taken to maintain the fuel surface level with the surface of the model.

General nature of the flame

At low values of airflow the flame had the structure illustrated in *Figure 9*. It began near the leading edge of the fuel tray and lay nearly parallel to the surface of the model. It was very luminous over most of its surface, except for a blue reaction zone near the edge of the tray. A gap or vapour space existed between this blue zone and the edge, and the length of the gap increased as the ambient pressure decreased, in the same manner as the corresponding zone described in relation to *Figure 5*.

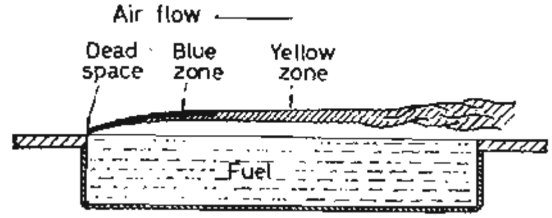

Figure 9. Flame structure in a low airflow at 0·1 atm

As the air velocity was raised the front of the flame became ragged; it then broke away suddenly from the edge of the tray and was extinguished. When obstructions to the airflow were placed at the front of the fuel tray the character of the flame was changed, particularly at the higher air velocities required for extinction. Recirculation over the fuel surface occurred, and conditions were established similar to those behind the flameholders of jet and ramjet engines. The flame was then no longer of the simple diffusion type, and the air and fuel vapour were to some extent premixed. The flame became more ragged, and less luminous.

Effect of model nose length

Since the stability of a diffusion flame depends very much on the conditions at its base (i.e. the blue zone and vapour space at the leading edge

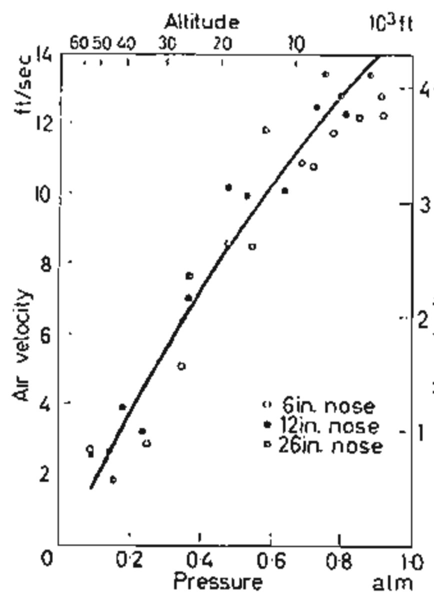

Figure 10. Variation of extinction velocity with pressure (kerosine)

of the laminar flame in *Figure 9*), it was thought that the boundary layer thickness might be important. To test this point, the elliptical-section nose of the model was made in three different lengths, measuring 6, 12 and 26 in. respectively from the leading edge to the front of the fuel tray. The observed extinction velocities for each nose at different pressures are plotted in *Figure 10*, and it is evident that within the experimental range studied the boundary layer thickness is not an important factor.

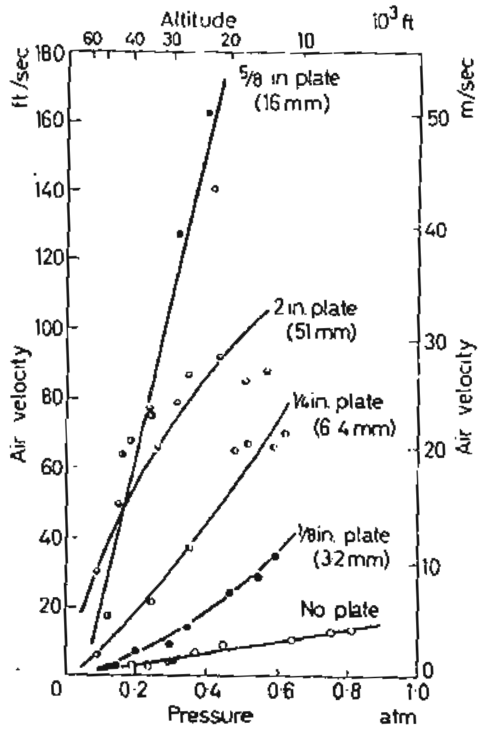

Figure 11. The effect of plates at the front of the fuel tank (kerosine)

At the low Reynolds number of the flow used in this part of the investigation the boundary layer would normally be laminar. An attempt was made to find the effect of a turbulent boundary layer by creating turbulence with a 20 s.w.g. wire stretched across the nose of the model. The results indicated that a small reduction in extinction velocity was produced in this way.

Effect of obstructions

In the experiments reported above, measurements were made of the air velocities needed to sweep the flame off the liquid surface at various pressures. The tests were now repeated with simple obstructions located at the upstream edge of the fuel tray. Metal plates, each the full width of the tray, were arranged to project $\frac{1}{8}$, $\frac{1}{4}$, $\frac{5}{8}$ and 2 in. (3·2, 6·4, 16 and 51 mm) above the surface of the fuel. Limiting airflows were determined at pressures down to about 0·1 atm. *Figure 11* shows that the extinction velocities increased with increasing height of projection up to an optimum size of plate, and then decreased. This is understandable as the flame was seen to burn from the top edge of the plate down to the fuel surface, and obviously the heat transfer became an important factor with the taller plates, where part of the flame was a considerable distance from the fuel surface.

The effect of obstructions in the form of plates and rods in the centre of the fuel surface was also tried. It was found that the flame burned in the wake of the obstructions after it had been extinguished from the rest of the fuel surface. With increased width of obstruction the flame had higher values of extinction velocity for any given pressure.

Effect of metal plate above the fuel surface

The effect on the extinction velocities was examined of bringing a horizontal metal plate down above the fuel surface. The plate measured 9 in. × 12 in. (22 cm × 31 cm) and was placed at distances of $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{2}$ and 2 in. (1·3, 1·9, 2·5, 3·9 and 5·1 cm) above the model. This had surprisingly little effect even when the plate was only $\frac{1}{2}$ in. from the fuel surface, although in this case the nature of the flame was radically changed: the flame burned only near the front of the fuel tray where the air entered and was used up, and again behind the back of the plate where fresh air could be obtained.

No other obstruction was present in these tests, and when the experimental results were plotted it was found that the curve drawn in *Figure 10* could be fitted to them, although the scatter was slightly greater than that in the figure.

Effect of fuel temperature

In the normal tests the fuel was cooled by forcing water through the cooling jacket, the temperature of the bulk of the fuel being maintained at between 30° and 40°C. The thermocouple, which was ½ in. below the fuel surface, was in the region of approximately constant temperature found in the earlier experiments (page 321). Tests were conducted at lower temperatures by pumping methanol at −70°C through the cooling jacket, the fuel temperature obtained with two different rates of flow of methanol being in the ranges −5° to 0°C and 2° to 8°C. The tests were made with the ⅛ in. obstruction at the front edge of the tank as this had been found to give the most reproducible results in the previous experiments.

The effect on extinction velocity was found to be negligible except at pressures below about 0·4 atm. At 0·2 atm (30 000 ft) the limiting velocities were these: fuel temperature 37° to 40°C, 12 ft/sec; 2° to 8°C, 8 ft/sec; −3° to 0°C, 4 ft/sec (3·7, 2·4 and 1·2 m/sec respectively). A further experiment conducted without any cooling, when the final fuel temperatures were between 55° and 70°C, again showed little change in extinction velocities, except at the lowest pressures.

Discussion

Simple diffusion flames

The temperature measurements made in the simple diffusion flames were not corrected for radiation and conduction losses and should therefore be regarded as purely relative, the true temperature in the hottest part of the flame being possibly about 200°C higher than those given. They correspond closely to similarly uncorrected measurements in a candle flame reported by A. G. Gaydon and H. G. Wolfhard[5]. The effect of lowering pressure was to reduce the temperature gradients, but the maximum temperature was not greatly affected. The presence of the thermocouple appeared to make little difference to the flame except at 0·04 atm, when the whole flame tilted away from the incoming probe. The flames became very unstable at pressures below 0·04 atm, which appeared to be near the limiting pressure for these flames. Unfortunately the apparatus was incapable of producing sufficiently low pressures to prove this point.

Temperature measurements in various liquid fuels burning at atmospheric pressure have been made by G. N. Khudiakov[1]. He found an exponential fall in temperature with depth below the surface. Assuming that heat penetrates the liquid by conduction alone, the heat conduction equation when thermal equilibrium has been attained is of the form

$$\lambda \frac{d^2T}{dx^2} + c\sigma R \frac{dT}{dx} = 0$$

where λ, c, σ and R are the thermal conductivity, heat capacity, specific gravity and rate of burning of the liquid respectively, and T is the temperature at distance x below the surface. The solution of this equation is of the form

$$(T - T_0) = (T_{max.} - T_0) \exp(-\beta x)$$

where $\beta = c\sigma R/\lambda$, $T_{max.}$ is the temperature at the surface, and T_0 is the temperature in the bulk of the liquid. A graph of $\ln(T - T_0)$ against x should therefore be a straight line. Plots of the results in the present investigation showed that the relationship was indeed linear, except for a region near the surface of the fuel. This disparity near the surface was due to a convection layer in the liquid, which is reflected in the shape of the temperature profiles in *Figure 3*. The movement in this convection layer could be observed through the window by watching the schlieren pattern in the liquid. The layer was most marked in the 28 mm burner at pressures between 0·5 and 0·1 atm, being about 5 mm deep. Very little convection was seen at other pressures, and at atmospheric pressure the layer was too thin to have been detected in Khudiakov's experiments. The layer was thinner in the larger burners, the maximum observed depth in the 96 mm burner being about 2 mm.

The rate of consumption of fuel over the range of pressures was found to be proportional to $r^{1\cdot5}$. This means that the evaporation of fuel lies between the two extremes of:

(*1*) evaporation from the perimeter of the burner only, when the rate of consumption would be proportional to r, and

(2) evaporation equally from the whole liquid surface, when the rate of consumption would be proportional to r^2.

This is a reasonable result and implies that the rate of evaporation at the edge of the burner, adjacent to the hot reaction zone, is higher than at the centre. There was some indication from the experimental results that the rate of consumption became more nearly proportional to r for the larger burners. V. I. BLINOV and G. N. KHUDIAKOV[6], and W. L. FONS[7], have already reported that the burning velocity of a number of liquid fuels decreases with increasing burner diameter up to about 5 in. It then increases with increasing diameter up to about 40 in., and finally becomes independent of diameter in larger burners.

The flames illustrated in *Figure 6* are markedly similar to those already reported for gaseous diffusion flames on circular tubes. The reduction of the carbon zone at reduced pressure, and its final withdrawal to within the reaction zone has been illustrated for an acetylene–air flame by A. G. GAYDON and H. G. WOLFHARD[8]. The flames of *Figures 6*(a) and (b) are similar to the 'laminar diffusion flames' described by J. BARR[9]. *Figures 6*(c) and (d) bear a close resemblance to the illustrations of vitiated flames in a paper by B. P. MULLINS[10]. Barr's flames show the effect of different air and fuel flow rates, Mullins's the effect of vitiation, and Gaydon and Wolfhard's the effect of pressure. In the present work both pressure and the degree of vitiation were varied, but the fuel flow rate varied with them (as was shown by variations in the rate of fuel consumption). A. G. GAYDON and H. G. WOLFHARD[11] have already pointed out this similarity that exists between the effects of pressure and vitiation on a diffusion flame.

The observation of an indication of the movement of fuel vapour within the flame has not been previously reported. The laminar flow that has previously been assumed in this zone is incorrect, at least for flames burning in the conditions reported here, and the actual transit time of the molecules in this zone may be many times greater than has been calculated on this basis. The toroidal movement is probably a result of the steeper temperature gradients, and hence flow velocities, near the edge of the burner. It is reflected in the displacement toward the centre of some of the isothermals in *Figure 2*. These flow conditions are in contrast to those existing in a gaseous diffusion flame, where the highest velocity is at the centre of the burner. Particle track studies in gaseous diffusion flames have in fact revealed no evidence of circuitous movement[12] (although A. LEVY and F. J. WEINBERG[13] did observe the presence of a toroidal vortex, but this was located outside the edge of a flat flame burner).

Flame in airstreams

The extinction velocities in the absence of any obstruction were found to be quite small, 15 ft/sec being sufficient to sweep the flame off the surface at pressures a little below atmospheric. A higher value was obtained by G. PALMER[14] in a full-scale test at atmospheric pressure. He found that a petrol fire could not persist on the surface of an aircraft wing in air flows above about 25 ft/sec. The difference between these results is explained by Palmer's observation that some flameholding occurred at the trailing edge of the wing.

It was found that at lower pressures the flame was even easier to dislodge, and as the limiting pressures for these flames were approached, the extinction velocity diminished rapidly. Thus at pressures of 0·1 atm or less (corresponding to altitudes of more than 50 000 ft) the extinction velocity was less than 2 ft/sec.

The presence of obstructions had a marked effect on the extinction velocities, a projection only $\frac{1}{8}$ in. high being sufficient to double the values previously obtained in its absence. Still greater increases were observed with higher obstructions. The flameholding properties of these simple obstructions were so marked that it was not considered necessary to make more elaborate experiments with many varied shapes.

The effect of varying the length of the fuel tray was not examined in these experiments, and this could have influenced the stability of the flame. Recirculation over the fuel surface would create some degree of premixing in the wake of the flameholder, and the stability of the flame would be affected by the composition of the mixture. The proportion of fuel vapour would be dependent on the length of travel of the reversed airflow over the fuel surface. Hence the length of the fuel tray would affect the mixture ratio and therefore the persistence of the flame.

The length of the recirculation zone behind a simple gutter baffle has been measured by J. P. LONGWELL[15], and it was found to be between 4 and 5 baffle heights for both 1 in. and 2¼ in. gutters. These results were obtained in a premixed gas stream, but the length of the recirculation zones in the present experiments might be expected to show a similar relationship to the baffle height. Hence a 5 in. tray should contain the whole of the recirculation zone existing behind a 1 in. plate. It has recently been shown[16] that this assumption is correct: liquid surface diffusion flames burning in a similar wind tunnel at atmospheric pressure were found to have maximum stability behind a 1 in. baffle when the tray length was between 4 and 6 in. Thus the choice of tray length in these experiments was correct for baffles up to about 1 in. high, but it is possible that a longer tray might have resulted in higher extinction velocities for the 2 in. plate.

At pressures above about 0·4 atm the temperature of the bulk of the fuel had no measurable effect on the extinction velocities, but at lower pressures the increased abstraction of heat from the surface layers of the chilled fuel was sufficient to decrease the extinction velocities, presumably by decreasing the rate of fuel vaporization. The depth of fuel in these experiments was 0·8 in., well in excess of the depth of steep temperature gradients shown in *Figure 3*. The conditions did not therefore cover the case of a relatively thin layer of fuel on a metal surface at low temperature, as might well occur in an aircraft.

Conclusions

The greatly enhanced stability of flames anchored to simple obstructions as small as ⅛ in. high serves to emphasize the importance of the effect of flameholders on the aircraft fire hazard. If it was possible to make an aerodynamically clean nacelle, the limiting conditions for the persistence of flight fires would be narrowed, and the fire protection problem greatly simplified. (The reduction in the quantity of chemical extinguishant required in such conditions has been demonstrated by C. A. HUGHES in a number of trials in modified engine nacelles[17].)

This work has shown quite definitely that it is possible for aircraft fuel to burn at altitudes up to 70 000 ft. The maximum temperatures in the reaction zone of the flame change very little with increasing altitude, and the flame still remains a dangerous source of heat even at the highest altitudes studied. However, as the altitude increases, the flame becomes more susceptible to the effects of vitiation and cooling, and at 70 000 ft it is unstable and readily extinguished. The conditions in an aircraft are not as favourable as those in the laboratory and the persistence of fire at this altitude is therefore improbable.

At pressures corresponding to 20 000 ft the laboratory flames were very stable and persisted in quite fast airstreams provided that some obstruction was present to act as a flameholder. At this altitude too we know from operational experience that fire can be readily started and will persist in an aircraft. The reason no doubt lies in the wide variation of conditions that a flame will tolerate at this pressure and in the fact that an aircraft structure can provide the necessary obstructions for flameholding.

Between the altitudes of 20 000 and 70 000 ft therefore, the probability that fire will persist declines from a high value to almost nil, and an important question is the way in which this change takes place. The laboratory tests indicate that the exinction velocity falls progressively as the pressure is reduced, but this is not necessarily the most important change affecting the persistence of the flame at low pressures. Air vitiation by the products of combustion, and the reduction of fuel volatility at low temperatures, have both been shown to have an enhanced quenching effect at low pressures. Hence the probability that a fire will persist in an aircraft must diminish more rapidly at higher altitudes than the laboratory results suggest.

On the basis of this argument, we suggest that in an aircraft the probability of the persistence of fire remains high up to say 40 000 ft and then begins to decline sharply. Thus it may be much less at 50 000 ft and negligible at 60 000 ft.

However, it has been pointed out[18] that there are two practical conditions which may favour the persistence of flames at high altitudes. Ram air entering a nacelle or a damaged wing may create local high pressure regions. The same effect can be produced by air leaking from a jet engine compressor, or from pressurizing air ducts. Small localized flames might therefore persist at altitudes unfavourable to a large fire. In the absence of any data it is difficult to say to what extent this should influence the argument given above, but as the normal flow of cooling air through a nacelle creates little change in pressure, the conclusion would appear to be valid for an undamaged aircraft.

References

1. KHUDIAKOV, G. N. *Izvest. Akad. Nauk S.S.S.R. Otdel tekh. Nauk*, 1951, **7**, 1015
2. BURGOYNE, J. H. and KATAN, L. L. *J. Inst. Petrol.* 1947, **33**, 158
3. RASBASH, D. J., ROGOWSKI, Z. W. and STARK, G. W. V. *Fuel, Lond.* 1956, **35**, 94
4. SIMMONS, R. F. and WOLFHARD, H. G. *Combustion & Flame*, 1957, **1**, 155
5. GAYDON, A. G. and WOLFHARD, H. G. *Flames, their Structure, Radiation and Temperature*, p 146. Chapman & Hall: London, 2nd ed. 1960
6. BLINOV, V. I. and KUDIAKOV, G. N. *Dokl. Akad. Nauk S.S.S.R.* (*N.S.*), 1957, **113** (5), 1094
7. FONS, W. L. *Combustion & Flame*, 1960, **4**, 279
8. GAYDON, A. G. and WOLFHARD, H. G. *Flames, their Structure, Radiation and Temperature*, p 140. Chapman & Hall: London, 2nd ed. 1960
9. BARR, J. *Fourth Symposium (International) on Combustion*, p 765. Williams and Wilkins: Baltimore, 1953
10. MULLINS, B. P. *Selected Combustion Problems*, p 477. Butterworths: London, 1954
11. GAYDON, A. G. and WOLFHARD, H. G. *Flames, their Structure, Radiation and Temperature*, p 149. Chapman & Hall: London, 2nd ed. 1960
12. See e.g. LEWIS, B. and VON ELBE, G. *J. chem. Phys.* 1943, **11**, 75
13. LEVY, A. and WEINBERG, F. J. *Seventh Symposium (International) on Combustion*, p 296. Butterworths: London, 1959
14. PALMER, G. Unpublished work, Farnborough, 1926
15. LONGWELL, J. P. *Combustion Researches and Reviews 1955*, p 58. Butterworths: London, 1955
16. EYRE, R. Unpublished work, Colnbrook, 1960
17. HUGHES, C. A. U.S. Department of Commerce: Civil Aeronautics Administration. *Tech. Dev. Rep. No. 205*, 1953
18. HANSOM, B. S. Private communication

NRC-CNRC

CISTI Document Delivery Order Form

Commande de service de fourniture de documents de l'ICIST

Combustion and flame.
89894

ORDER NO. : CI-776543-7

TECHNICAL CENTER LIBRARY
US FEDERAL AVIATION ADMINISTRATION
INTERNATIONAL AIRPORT
ATLANTIC CITY, NEW JERSEY
USA 08405

FIN NO. :
CISTI NO. : AZ138084
ACCOUNT NO.: DD705938
SENT VIA : GEOFOCLC

PHONE : 609/485-5124
FAX : 609/485-4329

SUBMITTED : 07-12-95 12:00:00 AM
PRINTED : 07-13-95 11:35:47 AM

2 Periodical Regular

TI : COMBUSTION AND FLAME.
AU : HIRST, R. AND SUTTON, D.
SO : -
V/I : VOL 5
DA : 1961
PG : 319
TI ART : THE EFFECT OF REDUCED PRESSURE AND AIRFLOW ON LIQUID SURFACE DIFFUSION FLAMES.
PE : NEW YORK ›ETC.! ELSEVIER ›ETC.!
NU : ISSN 0010-2180
SO : OCLC 1564277 OCLC
NO/CL : 9861476 /INGERSON, DOUG., X54945
MODE : GEOFOCLC

INSTR : MAX COST $WI. PAY SHIP TO: ILL DEPARTMENT/FAA TECHNICAL CENTER LIBRARY/ACL-1L TE

REPLY VIA: OCLC

The estimated copyright charge for this document based on 12 pages is $9.50 .

If you have any questions or problems, please contact our Client Assistant.

En cas de problèmes ou si vous avez des questions, communiquez avec le bureau d'aide aux clients.

Phone/Téléphone : (613) 993-9251
Fax/Télécopieur : (613) 952-8243