

Ignition and Fire Development Caused by Leaking Fuels onto Heated Surfaces

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ABSTRACT

How fires are initiated and sustained by the leaking of fuel onto heated surface is still a problem in many industrial applications, especially so for the military and commercial aircraft arena. The present experimental investigation aims at developing techniques to study the consequences of leaking hydrocarbon fuels onto heated surfaces. This initial work discusses the temperature and velocity fields immediately above a heated circular 20 cm diameter flat plate that could be heated to temperatures between 300⁰ C and 550⁰ C. A Schlieren and Laser sheet methodology has been used extensively to qualitatively and quantitatively examine these areas and it has been found that radial collision lines emanate from the edge of the plate towards the center and appear to be attached to the apex of a forming cellular structure, and that these cell-like structures appear to be either of 5 or 6 sided in construction. In addition, at certain surface temperatures, pool boiling of the fluid is initiated; whereas at even higher temperatures film boiling occurs that appear to lead to ignition and flame propagation.

INTRODUCTION

Propagation of a fire caused by fuel leaking onto hot surfaces is of real concern in a number of industrial applications, machinery, and transport, as well as in both the military and commercial aircraft arena. It is far from clear how leaking fuels however created, whether by poor joints, cracked fuel lines, or damage by extenuating circumstances, ignite and sustain a fire when it is sprayed or dropped onto a hot surface. Such surfaces are abundant within, for example, an aircraft engine nacelle, and if fire suppressants are to be used efficiently in their deployment, then it is essential that our understanding of the sequence of events leading up to sustainable fires be improved. To this end, work is in progress developing techniques to study the consequences of hydrocarbon fuels making contact with surfaces at elevated temperatures between 300⁰ C and 550⁰ C.

The ignition process of a fuel being introduced onto a hot surface is a complex phenomenon governed by various factors such as fuel flow rate, evaporation modes, equivalence ratio, convective heat transfer, etc, of which the effects of the convective flow field is least understood. In spite of the stipulation that admissible safe temperatures limits based on auto-ignition temperatures (AIT) and minimum hot surface ignition temperatures (MSHIT) should be accounted for in the respective design features, accidents still occur even when the temperatures are below the stipulated limits. This study aims at mapping the fluid flow field above a horizontally heated flat plate set at various surface temperatures, and investigating its effect on ignition limits and delay times, for a temperature range between 250°C – 550°C . However, the present study is restricted to a temperature range of 200°C – 350°C for observations of the flow field immediately above the heated surface, whereas a temperature range of between 350°C – 500°C has been conducted for some initial ignition studies.

The flow field over a heated flat plate is regarded as a result of buoyancy induced flow where a boundary layer flow is established as a result of pressure gradients induced by density gradients, which are, in turn, induced by the temperature gradient between the heated surface and the ambient fluid, Stewartson [1]. Instabilities in the boundary layer then cause separation from the surface as the fluid convects upwards, Pera and Gebhart [2]. Stewartson [1] also provided the first theoretical analysis of a buoyancy induced flow field on a semi-infinite heated horizontal surface placed in an expanse of fluid with $Pr = 0.7$. It was shown that the laminar boundary layer over such a plate is self-similar. Rotem and Claassen [3],[4] analyzed the problem using a semi-focusing Schlieren system, whereas Pera and Gebhart [2] used an interferometric technique to investigate the extent and separation of the boundary layer for horizontal and slightly inclined semi-infinite surfaces. The flow over a finite plate is fundamentally different to these surfaces since the laminar boundary layer originating from a leading edge would meet similar ones from every other leading edge, after which the flow turns upwards to feed into a thermal plume. The earliest visualizations of this kind of flow were provided by Croft [5], who used an interferometric technique for temperature measurements above a finite plate, and a shadow method to visualize the flow field. The observations indicated the existence of a cellular mode of convection near the surface, which was thought to be similar to the Bernard cells. Also, the observation of rising plumes above the cellular structure was thought to be due to a mushrooming effect of the cellular motion as it convects upwards. Husar and Sparrow [6] visualized the flow field over plates of various planforms, with the circular plate as a particular case, using an electrochemical technique. While they observed flow partitioning through collision lines for the boundary layer along the plate edges for each of the planforms, in the case of the circular plate, they found radially accelerating flow from the edges, which then transitioned into a billowing plume at the center. Ackroyd [7] investigated the edge flows and fluid property variations for rectangular horizontal plates and Al-Arabi and El-Riedy [8] conducted further heat transfer studies on plates of various shapes, and observed both edge and corner effects, whereas Garcia-Ybarra and Trevino [9] analyzed the thermal diffusion effects of hydrogen-air mixtures within the development of a boundary layer on a hot flat plate.

In this present study, the flow field above a horizontal hot plate was visualized using a Schlieren system and a Laser sheet methodology, while the temperature field was

mapped using high-speed thermocouples at suitable locations above and on the plate surface. Since the Schlieren image integrates the density gradients along the light path, it was used to gain a qualitative view of the overall flow structure, and was used extensively for examining the fuel impingement process, whereas a two-dimensional laser sheet was used to investigate the plume dynamics along a vertical central section of the plate, as well as using a horizontal laser sheet at different distances from the plate surface to observe the evolving plume.

EXPERIMENTAL ARRANGEMENT

A horizontal heated surface was constructed from a 20-cm diameter (1.27-cm thick) 316 stainless steel horizontal disk as shown in the figure 1. Surface temperatures up to 973K were produced by a tightly wound 18-cm CALROD heating coil embedded within the plate assembly. A series of K-type Chrome-Alumel thermocouples were embedded into the side of the plate to plot the plate thickness cross-sectional temperature. Temperatures measured across the plate surface area were found to be substantially uniform with temperature variability of 1% or less at a given distance radially from the center, with temperatures only 2% to 3% lower than the center at the half radial position, and some 5% lower at the plate perimeter. Further thermocouples were used to measure the temperature profiles above the plate using a linear traverse with an accuracy of ± 0.001 mm. The plate was also fitted with a stainless steel catchment gutter to contain any unburnt fuel that flowed across the surface.

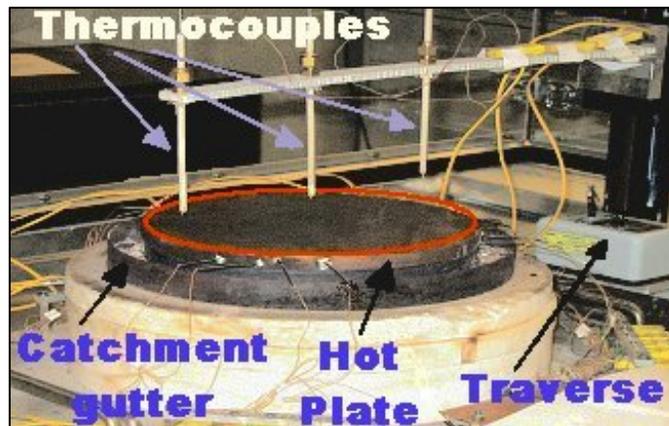


Figure 1: Hot plate set-up with thermocouples and traverse arrangement

A Z-type Schlieren configuration as shown in figure 2 was used to examine qualitatively the flow field above heated plate with and without fuel impinging onto its surface. Light, from a 5 mm diameter source, was placed at the focal point (2438 mm) of a 305 mm diameter parabolic mirror (M_1), which provided a collimated beam that was allowed to pass over the working section (the hot plate). This beam was then collected by a second parabolic mirror (M_2) of 349 mm diameter and 2946 mm focal length, and was refocused at a distance equal to its focal length, where a knife-edge was placed to

cut-off any unwanted refracted rays. A vertical knife-edge orientation was found to produce the best results for the hot plate setup. The flow field was captured with a 3-CCD Panasonic WV250B series NTSC color video camera and displayed on a Panasonic CT-1331Y color monitor and then recorded using a Panasonic AG-7750 SVHS recorder.

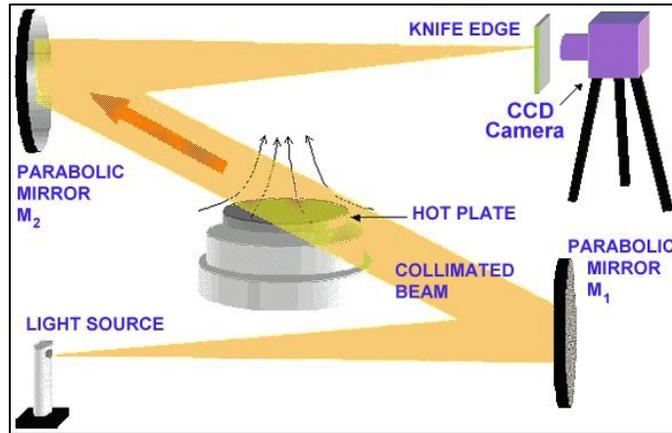


Figure 2: Z-type Schlieren System

The experimental arrangement used to generate the Laser light sheet is shown in figure 3, where an Argon-Ion Laser with a maximum output power of 4 Watts and with a wavelength range of 350-1100 nm was used as the laser source. The laser sheet was developed by reflecting the beam onto either a cylindrical lens, or a rotating mirror assembly spinning at 2358 rpm. The flow field above the hot plate was visualized by MIE scattering of the laser light sheet that was obtained by vaporizing a petroleum product on the hot plate surface. Images of the vertical flow field were captured using the imaging equipment arranged as shown in figure 3, and for observations of the development of the plume close to the heated surface, the laser sheet was arranged horizontally.

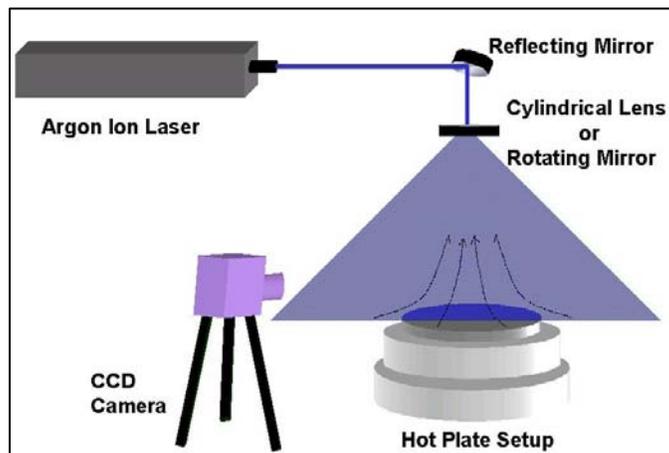


Figure 3: Laser sheet diagram

RESULTS & DISCUSSION

From a qualitative point of view, the images obtained from the Schlieren technique provided an overview of the plume mechanism for different plate temperatures. For example, figure 4. shows the image of a digitally enhanced plume that is seen to be evolving from the edge of the hot plate set at 250⁰ C , and is being convected radially towards the plate centre before rising vertically into the plume. This mechanism shows that there is a near and far region that governs the flow field, with a boundary layer being developed in the radial direction towards the center, *as distinguish by the light blue line*. Once these boundary layers converge upon one another, a transition region occurs (the near region) and the mixing process between the hot plume and entrained air evolves. This breaks down into, what appears to be, a fully developed turbulent flow (the far region) in the rising plume, *as demarcated with the dark blue line*.

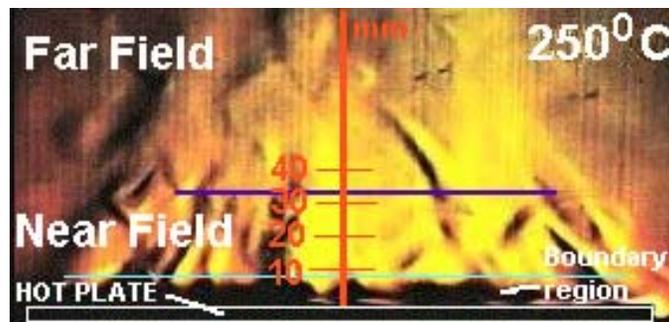


Figure 4: Development of the thermal plume over a hot plate at 250⁰C

The results of this type of analysis for different plate temperatures between 250⁰ C and 550⁰ C has shown that as the surface temperature increases so to does the pace of the boundary layer and this appears to increase the momentum within the near field region. This in-turn increases the turbulence within the far field at a lower elevation, which would imply that if fuel was to be dropped or leaked onto the plate at a higher temperature the likelihood of ignition would be that much greater. It is estimated that the transition zone between the near region and the far field region is reduced from 34 mm above the surface at 250⁰ C, to 20 mm at 550⁰ C as shown in the following table 1.

Table 1. Extent of the near field region above the hot surface

Plate Surface Temperature (°C)	Extent of the Near field Transition Zone (mm)
250	34
350	30
450	25
550	20

In contrast to this suggestion, temperature profiling above the hot surface appears to suggest that possible ignition may take place within the first 10 mm above the hot surface. For example, figure 5, shows an experimentally acquired temperature profile above the center of the plate set at 250⁰ C, together with a CFD acquired profile using a turbulent convective model. Here it may be observed that both methods shows there are two distinct temperature regions, one that shows a rapid decrease in temperature extending to less than 10 mm from the surface and is driven by conduction, and a second region that shows a much slower decrease in temperature over the following 190 mm to near ambient conditions that is related to the plume and is driven by convection. However, such profiles do not provide any insight into the mixing process that is evolving above the surface and it is this mixing and vaporizing of a leaked fuel within the high temperature region that will ultimately support and sustain ignition.

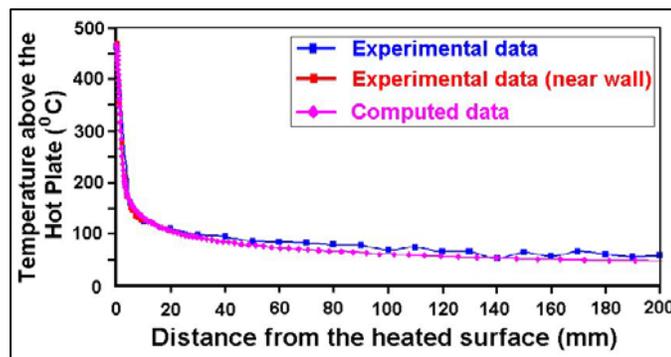


Figure 5: Temperature profile above a 250⁰C heated flat surface

The second method of flow visualization, that of using a Laser sheet set perpendicular to the heated surface, assisted in the interpretation of the fluid dynamics of the thermal plume and was undertaken by introducing a petroleum product on the hot surface. The resulting image, as shown in figure 6, provides a ‘snapshot’ of the plume as the vaporizing product rises above the plate. There is clearly a number of different mechanisms taking place at the surface where the flow tend to break away into well formed ‘mushroom’ type vortices before stretching and mixing with cooler air that is being entrained from outside the immediate heated zone. An estimate of the velocity of the flow field above the surface may be achieved by using a Lagrangian particle tracking approach to a number of frames, figure. 7. This figure shows how the velocity changes with height for different surface temperatures of 200⁰ C, 300⁰ C and 350⁰ C, with velocities reaching over 2 m/s at 500 mm or more above the surface for the 350⁰ C case. Although it was difficult to determine the plume velocities below about 100 mm with sufficient accuracy it is clear that the velocities are small (typically < 0.5 m/s) where vaporization of a leaking fuel will be crucial in the ignition process.



Figure 6: Visualization of the plume above a 250^o C heated surface

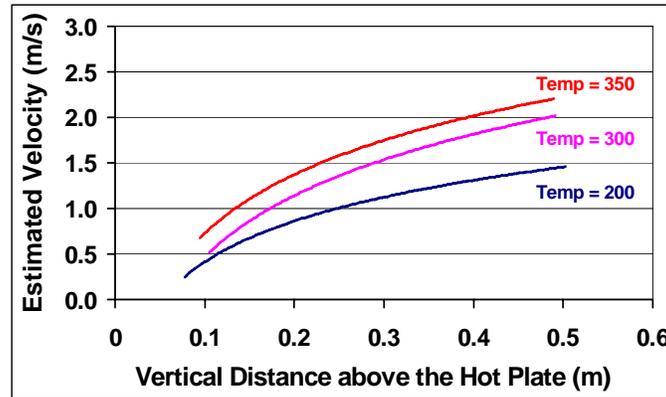


Figure 7: Velocity distribution in the plumes above heated surfaces

In addition to visualizing the plume rising vertically above the surface, it was also possible to visualize the flow field in the very near region above the heated surface using the laser sheet set parallel to the plate. In this case a horizontal laser sheet was set at different distances from the heated surface and the petroleum product, once again, introduced onto the plate. As an example, the ensuing images capture the radial movement of the boundary layer as it flows from the edge of the plate towards the center. However, the boundary layer collides and combines to form distinct cellular patterns that are very evident in figure 8. This figure shows two successive images (a and b) taken at 30 fps (0.03 seconds apart) and by using this frame capture rate and determining the position of the cell walls the velocity of the horizontal motion of the cell walls could be estimated. It should be noted that these cell walls are probably the rising thermals that may be observed in figure 6 and are being drawn towards the center of the plate by the entraining air.

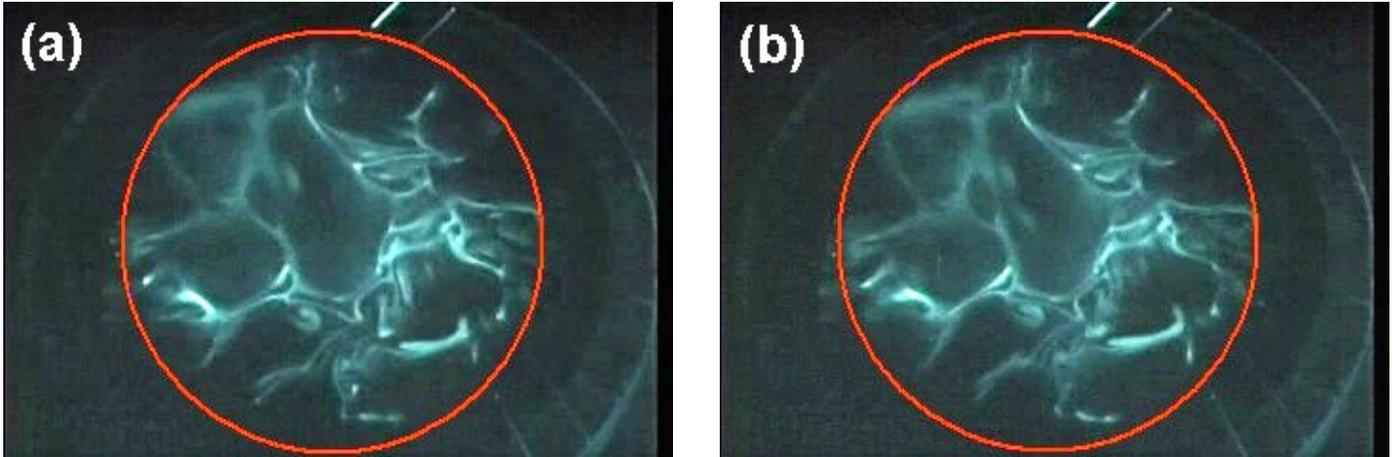


Figure 8: Two successive images of the evolving cellular pattern

How these cells form is unclear at present but they appear to originate from the edge of the hot plate and travel towards its center before rising into the center plume. Obviously this is part of a three dimensional pattern whereby the further away from the hot surface the more rapidly the vertical component of velocity will become. However, from an analysis of the size of these cells, based on their hydraulic radius ($H_R = A/P$), as a function of height above the surface, for different plate temperatures, it may be observed that for any given plate temperature the hydraulic radius is reduced in a linear fashion, figure 9. Furthermore, as the plate temperature rises the H_R is reduced for any given height. What is intriguing is that for plate temperatures above 250⁰ C the results tend to overlap at a height between 8 and 10 mm above the plate, which is synonymous with the edge of the boundary region as shown in figure 4.

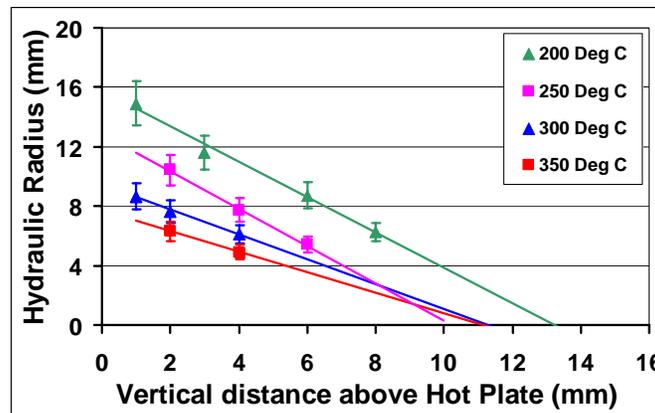


Figure 9: Hydraulic Radius of the cellular patterns at different vertical locations for each temperature

Although the H_R falls with increasing height for the 200° C plate temperature it is considered that in this case the thermal boundary layer is not as intensive as that produce at the higher elevated temperatures nor is the entrainment of the outside ambient conditions as vigorous. It should be noted that it was not possible to measure cellular structures below a H_R of about 4, a size that is comparable to a circle of 13 mm diameter.

This analysis is further supported by consideration of the local horizontal velocities of the cell walls at different heights above the surface for each plate temperature, figure 10, where a 3rd order polynomial has been fitted to the results. These results are shown with an error of about $\pm 10\%$ in their respective evaluations. For the cases where the surface temperature is above 250° C there is an increase in the horizontal velocity with height up to a maximum and then it is reduced. The reason for this is that the higher above the plate the cells are, the more they will be acted upon by the rising plume and their vertical velocity component will be increasing, thereby reducing the effect of their horizontal component. Furthermore, the higher the surface temperature the lower the distance will be for the plume to start to be effective. It should be noted that once again the temperature of 200° C appears not to follow this pattern and is considered to be because of insufficient thermal energy compared to the three other cases.

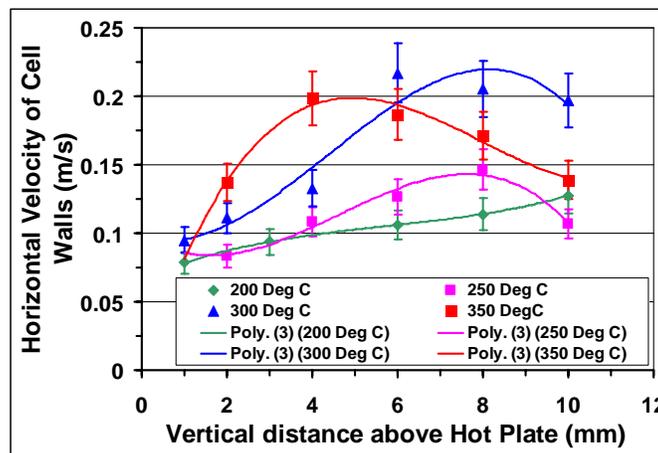


Figure 10: Horizontal velocity of the cell walls with distance above the surface for different temperatures

These horizontal velocities are much lower in magnitude than their vertical counterparts as shown in figure 7, and were obtained with an error of about 10% in the measurement of their location.

Fuel Ignition study

An experimental study has also been initiated to assist in establishing the criteria at which a fuel may evaporate and ignite. The fuel chosen for this preliminary study was Kerosene that has a published Auto Ignition Temperature (AIT) of 210°C and a Hot Surface Ignition Temperature (HSIT) of 650°C . In this study the Kerosene was introduced through a 60 mm long, 1.75 mm diameter nozzle onto the center of the plate with the plate set at different temperatures between 300°C and 500°C , in steps of 50°C . Visualization of the evaporation and ignition sequence was taken using the above Schlieren system. This system is capable of observing at least two different boiling regimes, pool boiling and film boiling of the Kerosene, and this is demonstrated in the following figure 11 and figure 12. In figure 11 the plate temperature is 350°C with fuel being introduced at a rate of 50 ml/min through the nozzle and there appears to be some evidence of pool boiling of the fuel just after initial fuel onset, figure 11(i). Since the temperature of the fuel is at the ambient temperature of 22°C , the plate is initially cooled locally, and the fuel flows radially outwards and is captured by the gutter arrangement around the perimeter of the plate assembly, figure 11(ii). However, at this surface temperature of 350°C , the fuel is unable to ignite and only increases its evaporation rate as it continues to boil producing a dense plume of unburnt Kerosene, figure 11(iii).

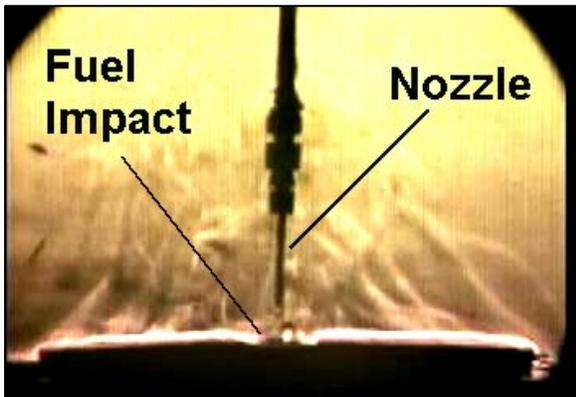
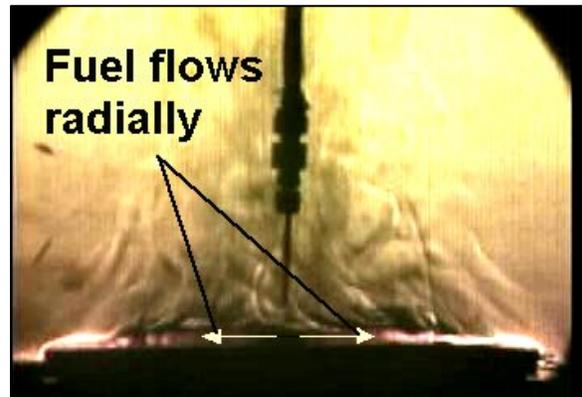
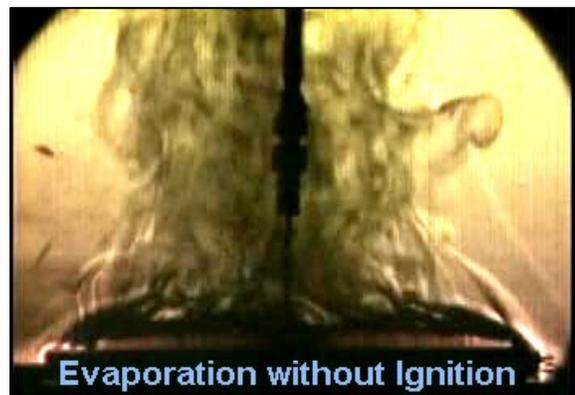


Figure 11: (i) Initial introduction of fuel onto 350°C hot plate



(ii) Excess fuel flows radially outwards along the hot plate



(iii) Fuel is unable to ignite and causes dense black smoke over the hot plate

With an increase in surface temperature to 500⁰ C, the whole sequence takes on a different flow character. Initially, the fuel appears to produce pool boiling, figure 12(i), and this very quickly turns to film boiling as the fuel flows radially out towards the perimeter, figure 12(ii). This film boiling creates very high evaporation rates and ignition is initiated on the surface that quickly consumes the entire plate and gutter assembly, figure 12(iii).

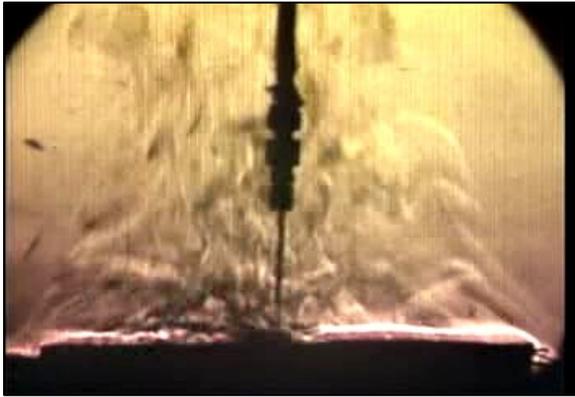


Figure 12: (i) Initially, fuel flows radially outwards on a 500⁰ C hot plate



(ii) Ignition of fuel on the surface of the hot plate



(iii) Fire engulfs the entire plate surface

CONCLUSIONS

A hot surface fuel ignition experimental apparatus has been developed to provide insight into how fuels may ignite when in contact with a heated surface. Visualization techniques are currently being employed, that of Schlieren and Laser sheet methodologies, to assist in providing evidence of the various fluid flow mechanisms that occur. In particular it has been demonstrated that

- (a) as the plate temperature is increased, so to do the size and shape of the thermals (vortices),
- (b) as these mushroom vortices increase in size, then it is likely that they will play a large part in the mixing of outside air with the fuel,
- (c) radial collision lines emanate from the edge of the plate towards the center and appear to be attached to the apex of a forming cellular structure,
- (d) the most prominent feature of the flow near the plate surface is the cell-like structure of the fluid motion that appear to be either of 5 or 6 sided in construction,
- (e) at certain surface temperatures, pool boiling of the fluid is initiated,
- (f) at higher surface higher temperatures, film boiling occurs, and
- (g) the extent of this film boiling appears to lead to ignition and flame propagation.

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