Surface ignition on a heated horizontal flat plate

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Abstract

One major source of machinery fires and accidents may be attributable to the leakage of flammable fluids onto hot surfaces and its subsequent ignition. The mechanism by which a fuel may be ignited is not always apparent especially in the presence of a hot surface. Different flow mechanisms created by the hot surface may make the ability of a fuel to ignite more, or less, certain. The present work examines how a better understanding of the flow field over hot horizontal surfaces affects ignition. Although Schlieren and Laser sheet techniques are not new, they provide an opportunity to examine the convective flow field above a plate before and during fuel impingement. These techniques coupled with the more standard approaches of temperature and velocity measurements could provide a 'Standard' that would, in some cases, be more appropriate than just the Auto-Ignition Temperature *and* Hot Surface Ignition Temperature *that are presently used.*

Therefore, this research is concerned with the development of an approach that may be used to examine and provide further knowledge of this type of ignition process.

Introduction

One of the most devastating events that may occur in an aircraft is that of a fire, whether it is from an electrical malfunction, heating appliance, fuel rich environment or by deliberate means, the consequence remains the same. Mitigation of the possible causes of aircraft fires is a prerequisite and this is even more so in the areas of fuel storage and of the delivery of the fuel to the engines. Even to-date, our knowledge of fire behaviour caused by leaking fuel, whether it is at normal or at an elevated temperature, into specific areas, such as, engine nacelles, bleed air ducts and dry bays, is limited. One particular area of interest is that of the ignition and sustainability of a fire due to leakage of a flammable fluid onto a hot surface, an area that is also known to be a major source of machinery fires and accidents.

An important application of hot surface ignition studies extends to situations where flame re-ignition occurs in spite of initial containment by fire suppressants. A typical scenario would be in an aircraft engine nacelle where the occurrence of a fire is in the form of turbulent diffusion flames due to leakage of jet fuel or hydraulic fluid. In such cases, cessation of the fire may be carried out by spraying a critical amount of an extinguishing agent. While there are a number of such agents available, a problem has been observed in the form of flame re-ignition, which is often caused by the vaporization of the pool of leaked flammable fluid on, or near, a metal surface that is typically maintained at an elevated temperature. Thus, ignition might occur from contact of the fuel air mixture with the hot surface.

Safety concerns regarding the leakage of flammable fluids onto hot surfaces have provided strict guidelines of the allowable temperature limits for such fluids and these are based on a number of fuel parameters such as the auto-ignition temperature (AIT), and the minimum hot surface ignition temperature (HSIT). However, accidental fires have still occurred even when either/or both ignition temperatures have been below that of the hot surface. Such ignition is, in part, governed by the convective heat transfer from the hot surface to the wetted area and is a complex phenomenon governed by various factors such as fuel flow rate, evaporation modes, and the equivalence ratio.

Although the occurrence of natural convection flow around heated surfaces has been studied extensively, they have been mainly concerned with relatively low temperatures (< 200^0C) and for the case of horizontal flat plates, from the heat generated on the underside of the plate configuration. The problem of elevated temperatures from the top surface of such plates has received less attention. The flow field over a heated flat plate is regarded as a result of indirect natural convection, where a boundary layer flow is initially established as a result of a pressure gradient that is induced by a density gradient, which is in turn is induced by the temperature gradients above the heated plate, Schlichting [1979], Rotem & Claassen [1969], Higuera & Linan [1993], Traugott [1975]. Instabilities in the boundary layer then cause separation from the surface and the fluid convects upwards, Pera & Gebhart [1973].

The aim of this work is to establish how, in the first instance, a fuel behaves in the presence of a heated surface and then to examine the fluid dynamic parameters influencing ignition and fire sustainability for different fuels. By providing a systematic approach to this problem of study it is hoped that an improved understanding may be developed for improved fire mitigation.

This experimental investigation of the hot surface ignition process is being undertaken using qualitative and quantitative mapping of the convective flowfield above a heated flat plate (with and without a vaporizing fuel). A number of different techniques are being utilized to model the hydrodynamic aspects of the turbulent flowfield above this surface, namely,

a) Temperature measurements using thermocouples,
b) A Schlieren technique for quantitative measurements,
c) A Laser sheet methodology for both quantitative and qualitative measurements.

This will be achieved by developing an experimental set-up that models a hot surface in a controlled manner. This surface may be set at various plate temperatures (200^0 – 600^0C), and by using the above techniques the resulting flowfield and temperature profiles above the surface will be examined. In addition, the effect of different fuel flow rates and size of fuel jet impinging onto the hot surface is also being studied.

Experimental Facilities & Procedures

The main element of this set-up is that of a single horizontal circular flat plate that is constructed from a 20 cm diameter (316) stainless steel disk, Figure 1, Bennett, [2003]. The plate is capable of being heated to surface temperatures of 473^0 – 973^0 K (200^0 – 700^0C) by a CALROD heating coil embedded within the plate assembly. A series of 40 gauge K-type Chrome-Alumel thermocouples are embedded into the side of the plate to monitor the temperature throughout the plate, where it was found that the variability of the temperature at any radial position was less than 1%, and that the temperature difference between the center and the perimeter was approximately 5%. A simple gutter arrangement was also constructed around the circular plate to contain any excess fuel spillage.

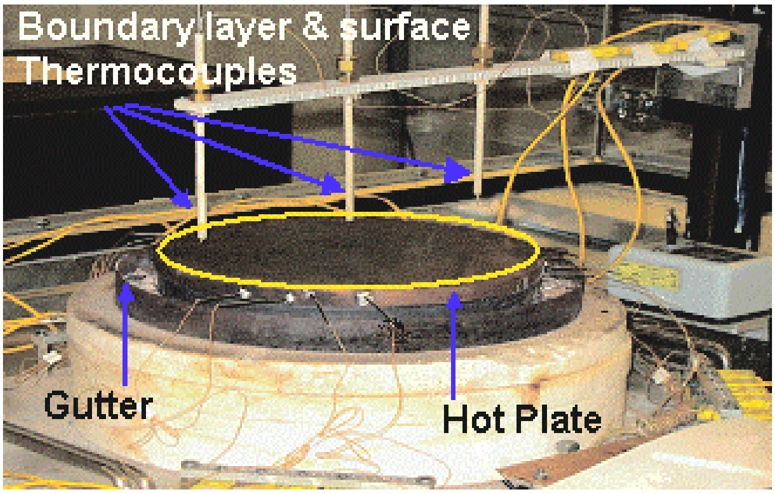


Figure 1. Hot plate Assembly

Temperature measurements

Temperature measurements above the plate surface were performed by three K-type thermocouples mounted on a vertical traverse as shown figure 1. The bead diameter of the thermocouples was of the order of 0.2 mm and their thermal response times were of the order of 500 ms. The thermocouples were connected to an AMUX data acquisition system and displayed on a LabView program on a computer.

Image analysis

Two methods of image analysis of the thermal flow above the heated plate were performed. The first method, that of a Schlieren technique, provided an overall qualitative aspect of the flow structure, whereas the second method, that of laser sheet analysis allowed for both a qualitative and a quantitative approach to the flow structure.

Schlieren technique

A classic Z-type Schlieren configuration was constructed by allowing white light from a 5 mm diameter source placed at the focal point (2.438 m) of a 305 mm diameter parabolic mirror (M_1) to produce a collimated beam, figure 2. This beam was then allowed to pass over the surface of the hot plate (the test section) and onto a second parabolic mirror (M_2) of 349 mm diameter. The reflected light from this second mirror was focused at its focal point (2.946 m) and onto a knife-edge. This knife-edge cuts off any unwanted refracted rays and only allows the reflected rays to be imaged onto a 3 – CCD Panasonic WVF250B series NTSC colour video camera. The subsequent images were then displayed on a Panasonic CT-1331Y colour monitor and recorded for later use on a Panasonic AG – 7750 SVHS recorder.

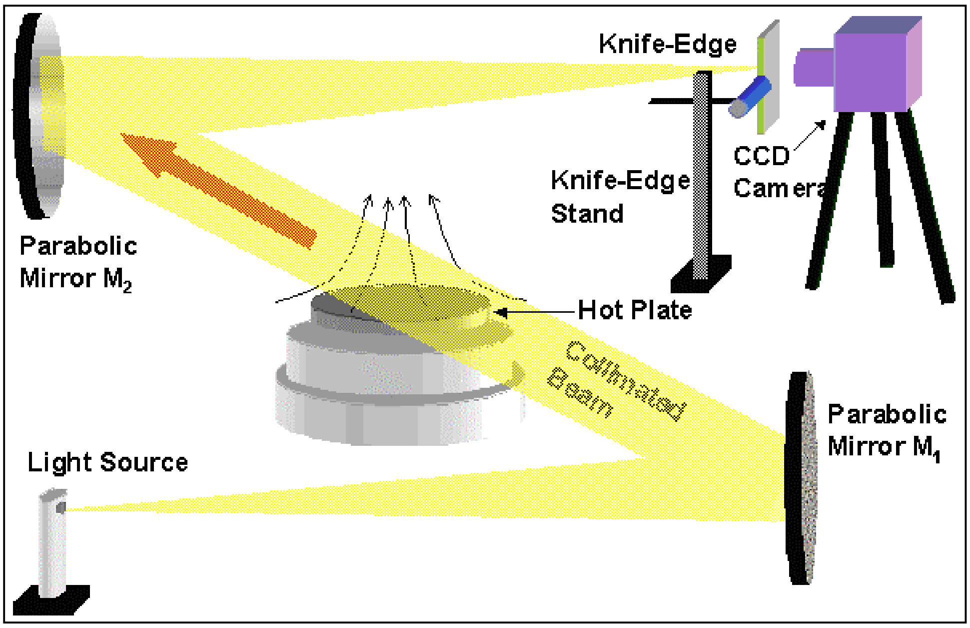


Figure 2. Set up of Z – type Schlieren system

Laser sheet technique

The Laser light sheet was constructed from the 1 mm diameter beam of an Argon Ion Laser with a wavelength of 350 –1100 nm. Although the Laser had a 4-Watt power capability, typical power requirements for this technique only required approximately 300 mW. The beam was guided using two front surfaced planar mirrors (M_1 & M_2) onto either a cylindrical lens, or onto one of the faces of a rotating (eight facet) mirror assembly rotating at a speed of 2358 rpm, figure 3. Either of these methods is capable of producing a continuous sheet of laser light. The plume from the hot plate was observable from vaporizing a petroleum product that was initially spread onto its surface. Since the laser light sheet is of the order of only 1 mm thick it has the capability of detecting the vaporized particles (by Mie scattering) in the vertical plane, thereby allowing the plume to be recorded on the camera system described above. The images were also acquired into a computer through an Adaptec VideOH USB device, and captured using associated software.

Unlike the Schlieren methodology, the laser sheet technique also allowed the flow through a horizontal slice of the flow to be visualized. This was achieved by simply rotating the cylindrical lens through 90^0 and allowing the light beam to expand in the horizontal plane.

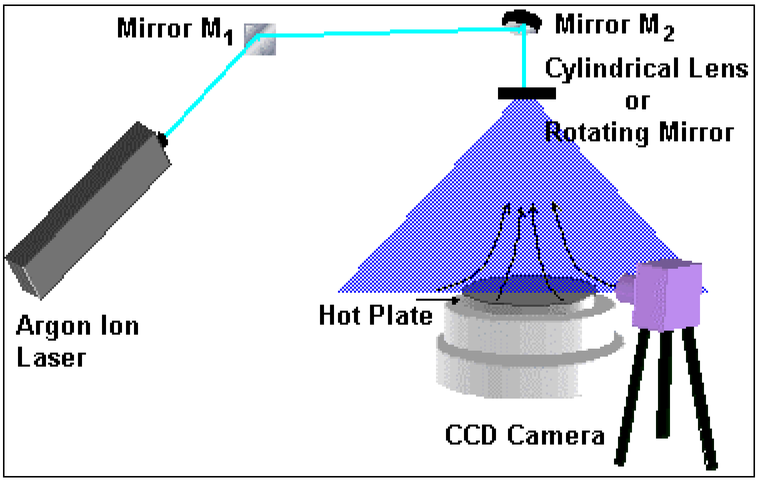


Figure 3. Laser light sheet arrangement

Results & Discussions

In the first instance, measurements of the temperature profile above the flat plate at its center were taken for six different plate temperatures of 250^0, 300^0, 350^0, 400^0, 450^0 and 500^0C. Figure 4 shows how the temperature falls off with vertical height for a plate temperature of 500^0C, along with a numerically determined profile obtained from a computational fluid mechanic turbulence model that is also being currently developed as a parallel study.

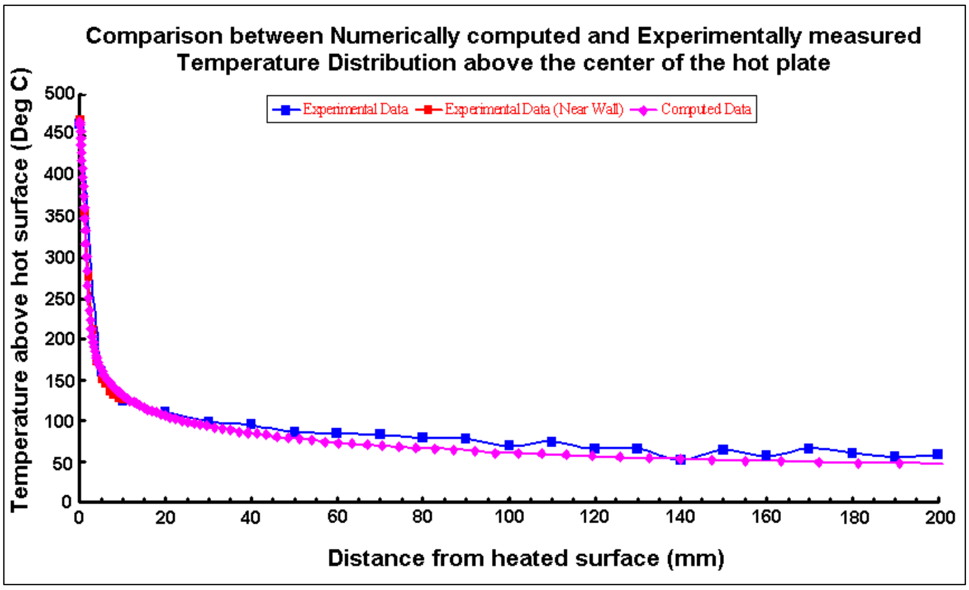


Figure 4. Typical temperature profile above the center of the hot plate surface

It may be observed from this figure that there are perhaps two distinct regions that may be considered. First, there is a region close to the surface in which the temperature falls off very rapidly, which is within approximately the first 10 mm, and then a second region (>10 mm) in which the temperature falls of more gradually. Within the initial region the flow is developing along the plate surface in a radial direction towards the center of the plate, whereupon the flow collides and forms the turbulent plume, figure 5.

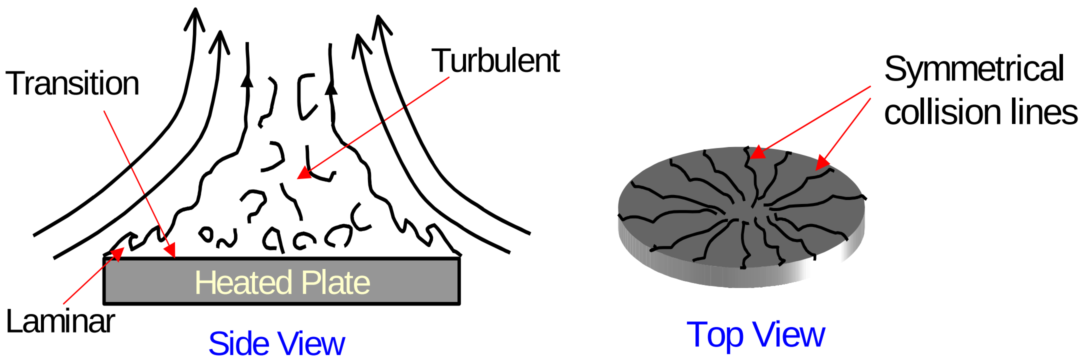


Figure 5. Diagrammatic representation of the convective flow over a hot flat plate

In this case, the temperature of the rising air reduces the local density bringing about a small horizontal pressure difference on the plate surface between the center and the perimeter of the plate. This difference in pressure is sufficient to create a small boundary layer to develop, starting at the perimeter edge and increasing in thickness toward the plate center, in the radial direction. This boundary layer will begin laminar and become turbulent once collisions of the radial flow occur. This horizontal flow mechanism takes place within the thin high temperature gradient that is observed in figure 4.

This may be further illustrated with the Schlieren system. In this case, any changes in the local refractive index of the fluid above the heated surface, brought about by changes in the local density/thermal values will provide an integrated effect of the light path through this convective flow field. Although this will produce a highly three-dimensional image of this flow it does show the extent of the flow field in the radial sense as well as how the flow changes with height above the plate, figure 6.

Figure 6. Schlieren Image of the flow field over a heated circular flat plate

From the analysis of these type of images for the range of surface temperatures investigated (200^0 – 600^0C) it was observed that the turbulence level in the flow increased as the temperature increased. In addition, the external air entrainment profile could be clearly identified, as was the location of the inception point of the vortices that were being generated at the plate surface and their subsequent destruction. This location appeared to increase in height with increase in plate temperature, as might be expected. This mechanism would therefore infer that these vortical structures, which are formed at the surface, are buoyant masses of air that can transport a large amount of heat compared to the external fluid, have a greater energy and are able to dissipate this at a greater distance from the plate surface for higher plate temperatures.

The production of the thermals above a heated plate is known to be related to the instabilities of the vortical structures and may be observed using the laser sheet methodology described above. In this case, the plate has been covered with a thin film of a petroleum product and the ensuing vapours are visualized using a thin laser sheet, figure 7.

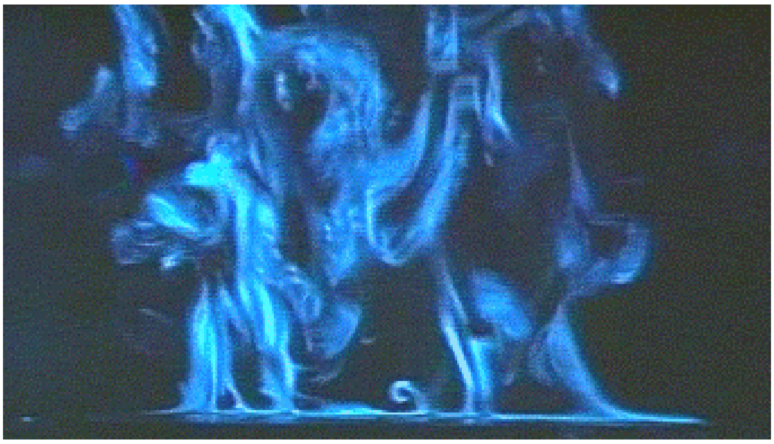


Figure 7. Growth of vortical structures from the surface of a heated flat plate

These laser sheet images provide an instantaneous snapshot of the structure of these vortices as they are formed for each plate temperature. From these images it may be observed that as the plate temperature is increased, so to do the size and shape of the thermals. The consequence of this is that as these mushroom vortices increase in size, then it is likely that they will play a large part in the evaporation and ignition process.

This may be further emphasized from an analysis of velocity estimates obtained from these laser sheet images. This was achieved by digitizing an image and estimating the velocity of a specific structure using a Langragian particle tracking approach. That is, a distinct structure was selected and its position determined for successive frames. Since the frame rate of the camera was known (1/30 s) the velocity of the structure could be estimated, and a typical velocity profile for plate temperatures of 250 ^{0} C and 350^{0}C is plotted against non-dimensional distance above the plate in figure 8.

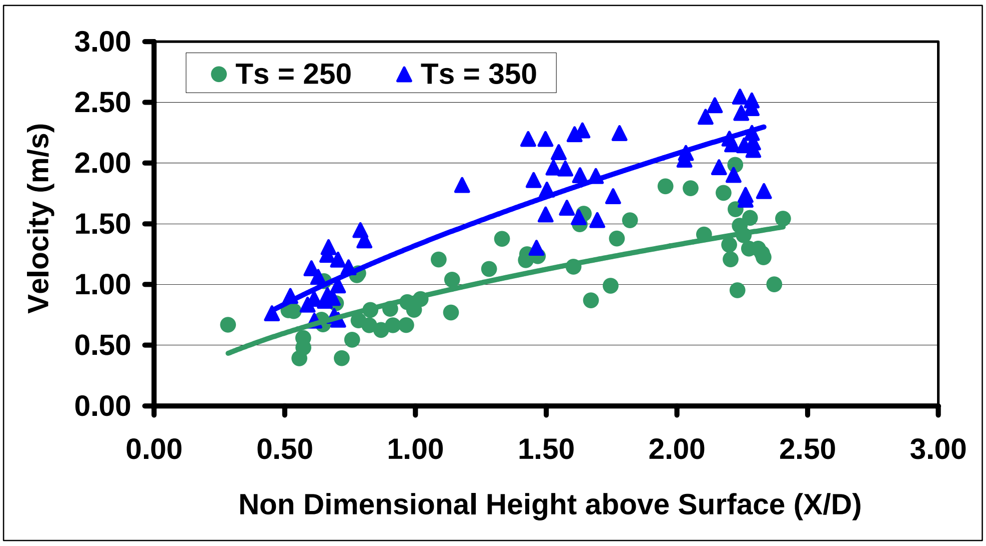


Figure 8. Velocity distributions above a heated flat plate at 350^{0} C

It may be observed that, in this case, the scatter in the velocity estimates increases as the height and temperature increases, and is due to the increase in the turbulent fluctuations within the flow field. Furthermore, there is an acceleration of the flow with height. This is also true as the plate temperature is increased.

With the light sheet rotated through 90^0 such that it was now parallel to the plate surface, visualization of the developing fluid motion may be perceived. In this case, the resulting Mie-scattering of the light from the particles vaporized from the petroleum product was taken at two particular locations above the plate, one within the boundary layer (at approximately 4 mm above the surface) and the other at approximately 100 mm above the hot surface. For this particular study the plate temperature has been set at 250^0 C.

An instantaneous image of the structure of the internal motion within the boundary layer at 4 mm height is presented in figure 9. The most prominent feature of this image is of the cell-like structure of the fluid motion and these appear to be either of 5 or 6 sided in construction. These cells are similar to the Benard cellular structures seen in closed cavity type flows. Furthermore, it may be observed that there are, indeed, radial collision lines emanating from the edge of the plate towards the center and appear to be attached to the apex of a forming cellular structure. Although these radial fluid elements are not necessarily symmetrical (as shown schematically in figure 5) they will be carrying vorticity that will assist in the forming of the 'mushroom' type vortices that form and break away from the hot surface as observed in the earlier vertical slice through the heated plume, figure 7. It is anticipated that the very nature of these small mushroom vortices will assist in the evaporation of an impinging fuel and may assist in the ignition process, but this has yet to be confirmed.

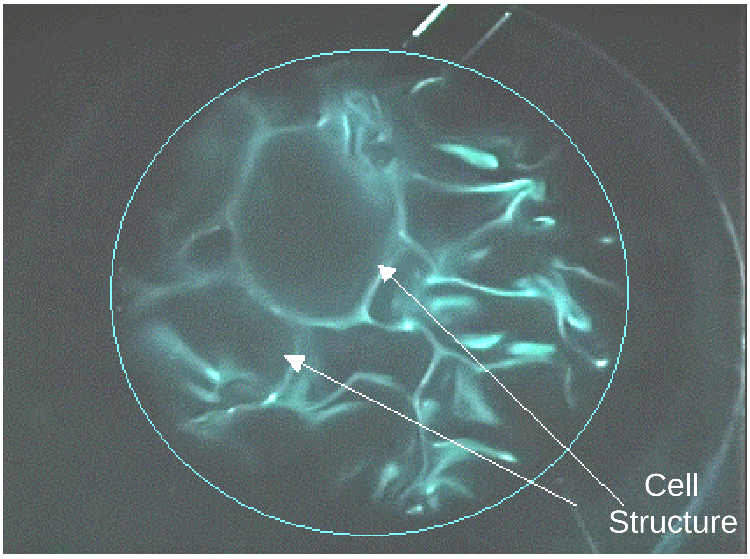


Figure 9. Cellular structure of the flow field within the boundary layer

With the light sheet set at approximately 100 mm above the plate surface, a completely different flow regime is apparent, figure 10. The cellular structure is no longer evident and the image is one of a rapidly changing scene where small, but significant, globules of Mie-scattered light may be observed. These globules are, in fact, the centers of the rising vortices that were in evidence in figure 7, and the scattered thin veils of light are likely to be the break-up of outer edges of these vortical structures. Again, it is not evident which of these flow mechanisms will assist in the evaporation/ignition process.

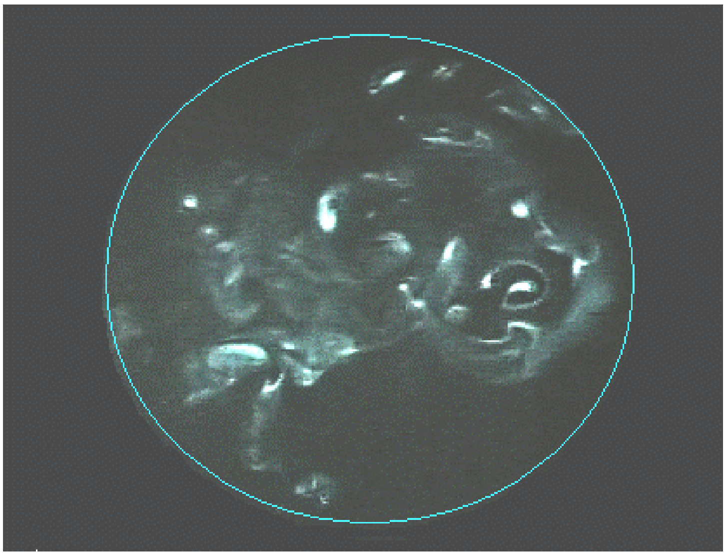


Figure 10. Vortex cores as visualized at 100 mm above hot plate surface

These flow fields may also be correlated to that of the temperature profile if the profile is plotted in non-dimensional form, with the local temperature divided by the plate temperature and the height at which the temperature is measured by the plate diameter, figure 11. Here, two distinct regions are discernable, one related to the near field, that is, close to the plate surface in which the plumes are evolving in a cellular fashion, and that of the far field, in which the vortical motions are breaking down and the velocity is increasing.

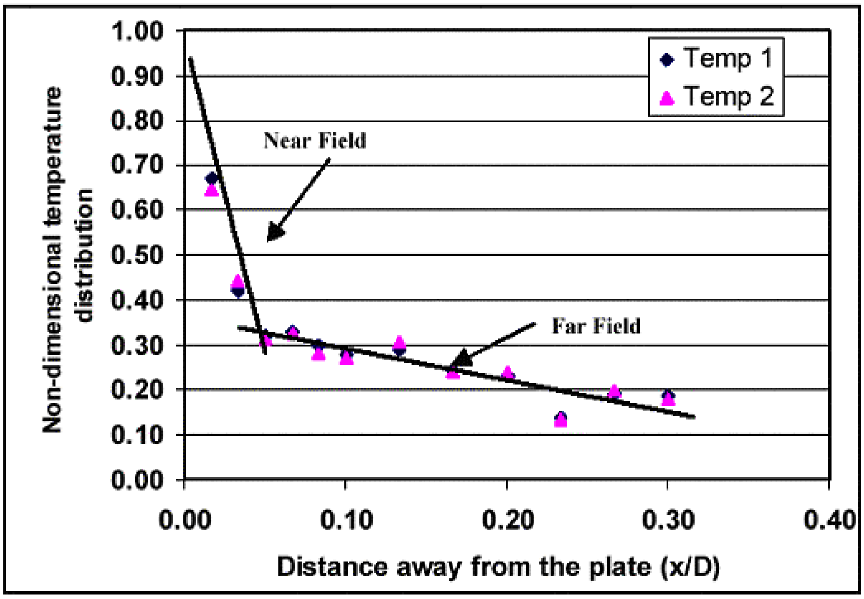


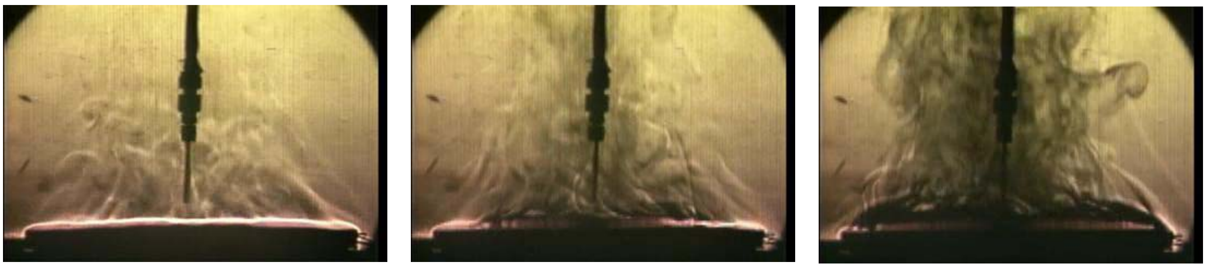
Figure 11. Non-dimensional temperature profile above a heated flat plate

Preliminary Ignition studies

In order to further develop this experimental technique a preliminary study has been initiated to assist in establishing the criteria at which fuel may evaporate and ignite. The fuel chosen for this preliminary study was Kerosene that has an AIT of 210^0 C and a HSIT of 650^0 C. In this study the Kerosene was introduced onto the center of the hot plate through a nozzle with the plate set at different temperatures between 350^0C and 550^0C, in steps of 50^0C. Visualization of the evaporation and ignition sequence was taken using the Schleiren system as described above.

Study with a 1.75 mm Diameter Nozzle

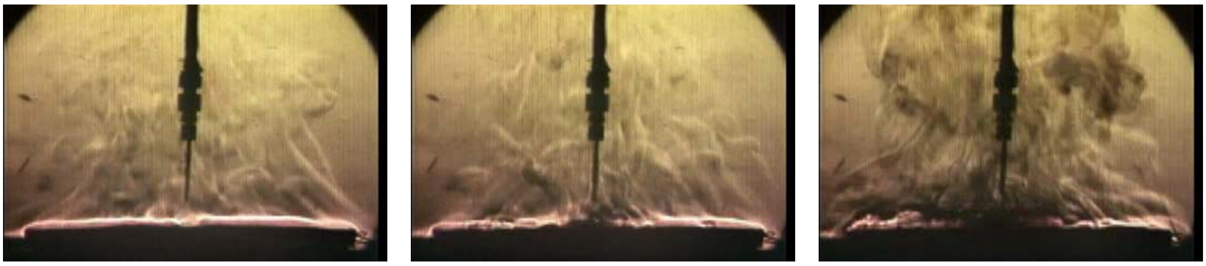
With the plate temperature set at 350^0C, fuel was introduced through a 60 mm long, 1.75 mm diameter stainless steel nozzle set at a location of 20 mm above the hot plate, figure 12(a). The temperature of the fuel was 24^0 C, and in all cases was delivered at a flow rate of 50 ml/min. It may be observed in this figure 12(a) that prior to introducing the fuel the boundary layer is very prominent (as shown by the white area adjacent to the plate surface). Once the fuel is introduced, figure 12(b), the fuel starts to evaporate from the center of the plate, producing pool boiling of the fuel and is shown as a more intense density change. With further fuel delivery, the Kerosene spreads out radially across the plate and into the catchment gutter, figure 12(c), increasing the evaporation as depicted by the darkening image of the flow, but without ignition.



(a) (b) (c)

Figure 12. Evaporative behaviour of fuel on heated surface at 350^0 C

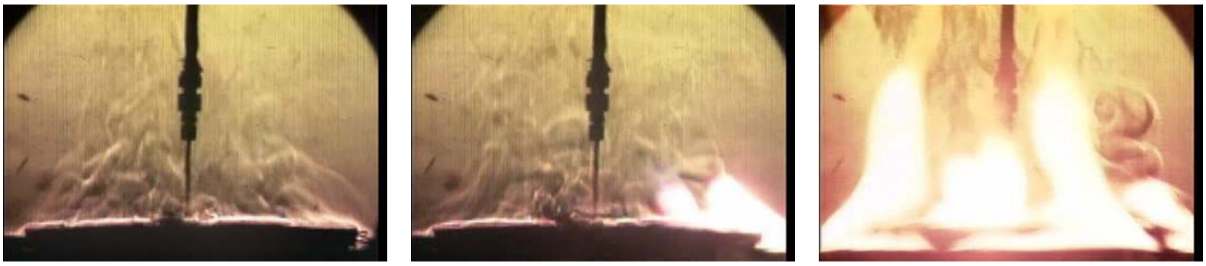
The same behaviour was clearly visible when the plate temperature was set at 400^0C, figure 13. Even at this elevated temperature the fuel did not ignite but it was observed that the flow was more energetic than the previous plate temperature, producing a clearer image due to the increased evaporation, as shown in figure 13 (b) and 13(c) where the plumes are less dense. In addition, there is evidence of film boiling as the fuel stream forms droplets and runs radially towards the gutter, figure 13(b). Furthermore, it is evident that the fuel temperature also plays an important role in the ignition behaviour since the plate temperature is, initially, above that of the AIT of Kerosene and should have produced ignition. The introduction of the fuel has momentarily reduced the surface temperature of the plate, thereby lowering its heat transfer capability to the fuel. This is being investigated further.



(a) (b) (c)

Figure 13. Evaporative behaviour of fuel on heated surface at 400^0 C

Increasing the plate temperature a further 50^0C to 450^0C produced the first ignition of this fuel, figure 14. The first image figure 14(a) shows the introduction of the fuel onto the hot plate, whereupon film boiling occurred again with droplets running off to the edge of the plate. In this case the fuel appeared to ignite close to the edge of the plate and in the gutter, figure 14(b), and very quickly spread over the entire plate surface, figure 14(c).



(a) (b) (c)

Figure 14. Evaporative behaviour of fuel on heated surface at 450^0 C

With the plate set at 500^0C, the fuel was again introduced at the plate center. Here the fuel migrated towards the edge of the plate producing film boiling across most of the plate, figure 15(a). Once the fuel had begun to reach the gutter, the evaporation loss appeared to have been sufficient to cause ignition of the fuel, since it ignited close to the center of the plate, figure 15(b). This fire was sustainable and spread to the fuel in the gutter, figure 15(c).

(a) (b) (c)

Figure 15. Evaporative behaviour of fuel on heated surface at 500^0 C

Study with a 2.78 mm Diameter Nozzle

As an example of the ignition process of this fuel when delivered via a larger diameter nozzle, the following figure 16 shows fuel being introduced through a 60 mm long, 2.78 mm diameter stainless steel nozzle. The first image, figure 16(a), shows the fuel producing film boiling on a plate set at 500^0C. Once again, the fuel ignites close to the plate center once sufficient fuel has appeared to have been evaporated during the film boiling stage, figure 16(b), with the complete plate being quickly engulfed, including the fuel in the catchment gutter, figure 16(c).

(a) (b) (c)

Figure 16. Evaporative behaviour of fuel on heated surface at 500^0 C

Summary

A hot plate fuel ignition setup is being developed to provide insight into how fuels may ignite when in contact with a heated surface. Although this investigation is in its preliminary stages the techniques that are currently being employed, that of Schlieren and Laser sheet methodologies, have provided evidence of various fluid flow mechanisms. In particular it has been demonstrated that

(a) the turbulence level in the plume increases as the plate temperature increases
(b) the location of the inception point of the vortices that are generated at the plate surface, and their subsequent destruction, may be determined
(c) this inception point appears to increase in height with increase in plate temperature
(d) as the plate temperature is increased, so to do the size and shape of the thermals
(e) as these mushroom vortices increase in size, then it is likely that they will play a large part in the evaporation and ignition process
(f) 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
(g) 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
(h) there is evidence of the centers of the rising vortices as well as their break-up
(i) at certain surface temperatures, pool boiling of the fluid is initiated

(j) at higher temperatures, film boiling occurs, and
(k) the extent of this film boiling appears to lead to ignition and flame propagation.

Further work is continuing in developing this experimental approach to take into account different fuels and their temperatures, repeatability tests, improvements to the optics, three-dimensional velocity measurements, and the development of a CFD model to assist in the explanation of some of the fluid mechanic and thermal properties of this complex flow mechanism.

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