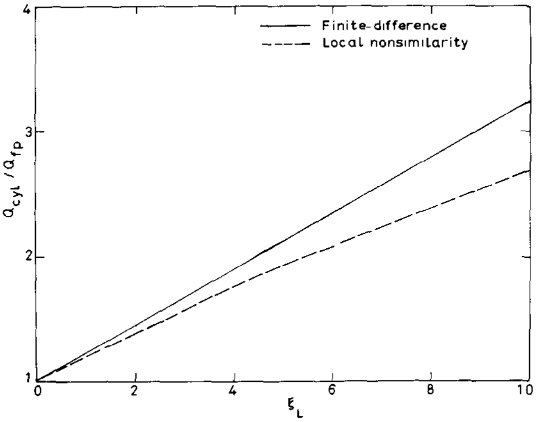

FIG. 1. Comparison of total heat-transfer ratio Q_{cyl}/Q_{fp}.

appreciably. Therefore, the local nonsimilarity method is not suitable for those nonsimilar problems where the nonsimilar terms are not small. However, the perturbation method with the Shanks transformation can successfully be used to tackle nonsimilar problems with relatively fair degree of accuracy.

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Int. J. Heat Mass Transfer. Vol. 28, No. 11, pp. 2174 2176, 1985
Printed in Great Britain
0017-9310/85 $3.00 + 0.00

Pressure/temperature ignition limits of fuel droplet vaporizing over a hot plate

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(*Received* 25 *February* 1985 *and in final form* 17 *June* 1985)

1. INTRODUCTION

IN VARIOUS forms of liquid-fuelled combustors part of the injected fuel may impinge on the hot walls of the combustion chamber either intentionally or by design. A particularly innovative example is the recent development of the open chamber, stratified charge engines in which the fuel is directly injected into a hollowed space in the piston head. It is suggested that this design facilitates ignition of the fuel spray through its interaction with the hot surface, and thereby results in the observed improvement in the engine performance in terms of combustion efficiency and pollutant emissions.

The scientific problem of interest here is the ignition of a fuel droplet over a hot plate. In order to appreciate the complexity and richness of the phenomena of interest, let us first consider the basic process of droplet gasification over a hot plate, which is commonly known as the Leidenfrost phenomenon [1, 2]. Figure 1, obtained in the course of present study, shows the droplet evaporation time τ of a dodecane droplet as a function of the plate temperature T_w for three chamber pressures; the initial droplet diameter is about 2 mm. It is seen that the lifetime curve consists of three segments, namely a low-temperature regime during which the droplet is in full contact with the surface and τ decreases rapidly with increasing T_w, a transition regime during which the droplet begins to push itself off the plate with increasing vapor pressure and τ increases with T_w, and a third regime during which the droplet is fully levitated by its vapor pressure and τ again decreases with T_w, albeit slowly. The minimum and maximum points are respectively known as the nucleate boiling point and the Leidenfrost point.

Figure 1 further shows that with increasing pressure the vaporization time curves are shifted in the direction of higher

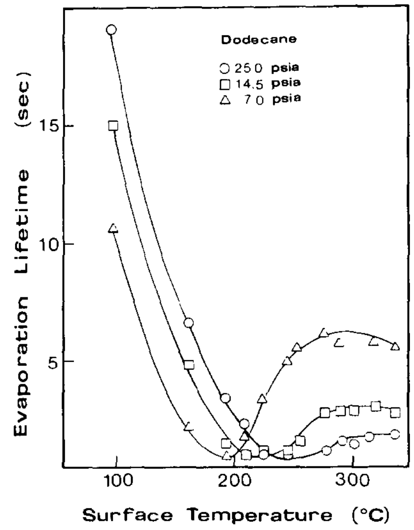

FIG. 1. Effect of ambient pressure and plate temperature on droplet evaporation lifetime.

surface temperature [3, 4] because of the increased boiling point. Indeed, Hiroyasu *et al.* [4] showed that τ correlates well with the difference between the plate temperature and droplet saturation temperature, which increases with the system pressure. It is also found [5, 6] that the droplet ignition delay time follows the same trend as that of the evaporation lifetime except that it does not change much with $T_{\rm w}$ once the droplet is completely levitated off the hot surface.

The present study extends the earlier works on ignition delay by mapping the limiting conditions under which the droplet fails to achieve ignition during its lifetime. Thus the ignition limit so defined should indicate the extreme values of the system parameters for which the concept of droplet ignition by a hot plate is viable. In the present investigation, we have defined these ignition limits in terms of the plate temperature $T_{\rm w}$ and the chamber pressure p, which are important system parameters because they not only characterize the basic Leidenfrost curve, but also sensitively influence the intensities of chemical reactions and fuel/oxidizer buoyant mixing. In addition, we have also studied pure as well as multicomponent fuels in order to assess the effects of fuel volatility.

The experimental methodology is discussed in the next section, which is followed by presentation of the results.

2. EXPERIMENTAL METHODOLOGY

The cylindrical combustion chamber, 12.7 cm I.D. × 15.2 cm, is designed for a maximum pressure of 10 atm. The hot plate is a thin stainless-steel disc (7.62 cm in diameter and 1.33 cm thick) with a spherical indentation in the center of the upper surface so that the freely moving droplet is confined within the indentation.

The plate is slowly heated by a heating coil which is concentrically arranged below the plate to provide uniform heating. The surface temperature is determined from linear extrapolation of two measurements made by chromel–alumel thermocouples placed 0.127 and 0.381 cm below the lowest point of the indentation. Due to the high thermal conductivity of stainless steel, the temperature of the plate has been found to be almost axially uniform.

After the desired plate temperature and chamber pressure are established, a single droplet is introduced through a high-precision hypodermic needle. To compensate for any slight statistical fluctuations, the initial droplet size is determined by averaging the amount of liquid needed to produce 100 droplets. Furthermore, since the surface tension force decreases with increasing plate temperature and thereby chamber temperature, the initial droplet size d_0 decreases slightly with increasing $T_{\rm w}$. The variation is somewhat linear, from $d_0 \simeq 2.1$ mm at 300°C to $d_0 \simeq 1.85$ mm at 650°C. The variation is small and is not expected to have any significant effect on the experimental results. For example, although the intensity of chemical reaction and thereby the likelihood of ignition is expected [7] to depend on both p and d_0, through the *approximate* grouping (pd_0), we note that over the entire experimental range p varies by over a factor of four while d_0 varies by only about 15%. Thus for subsequent interpretations it is adequate to assume a constant d_0 of 2.0 mm. We do note, however, that for larger variations of d_0 the system ignitability will exhibit a more pronounced dependence on d_0. This aspect is not investigated due to the limited size range over which droplets can be produced in the present study.

Finally, as part of the scavenging process to ensure that the chamber is free from residue contamination, the gas in the chamber is evacuated after each evaporation or combustion event.

3. RESULTS AND DISCUSSIONS

Single-component fuels

Figure 2 shows the minimum chamber pressure required for ignition of pure dodecane droplets as a function of the surface temperature $T_{\rm w}$. Since ignition is a sensitive event, for each $T_{\rm w}$ 100 runs were conducted over the range of limiting pressures. This results in a lower and an upper ignition boundary such that ignition is absolutely not possible below the lower limit, is always possible above the upper limit, and may or may not occur between the limits. Four types of ignition behavior are observed (see sketches in Fig. 2):

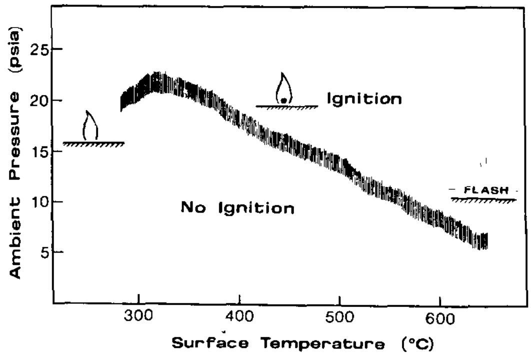

FIG. 2. Pressure/temperature ignition limit of dodecane droplet in air.

(a) In the low temperature regime ($T_{\rm w} \lesssim 290^\circ$C), droplet ignition is not possible for all pressures. However, ignition does occur immediately after the droplet is completely vaporized. The resulting flame is conical in shape, sooty, and sustains for a period of time. We call this the vapor pocket ignition mode. Ignition becomes absolutely not possible when $T_{\rm w}$ becomes sufficiently low, say around 200°C.

(b) In the ascending segment of the intermediate temperature regime ($290^\circ\mathrm{C} \lesssim T_{\rm w} \lesssim 320^\circ$C), droplet ignition is possible if the chamber pressure is sufficiently high. The limit pressure increases with increasing $T_{\rm w}$.

(c) In the descending segment of the intermediate temperature regime ($320^\circ\mathrm{C} \lesssim T_{\rm w} \lesssim 650^\circ$C), the limit pressure decreases with increasing $T_{\rm w}$.

(d) In the high temperature regime ($T_{\rm w} \gtrsim 650^\circ$C) droplet ignition is again not possible for all pressures. After the droplet is completely gasified, a short, quiescent delay exists before a spontaneous flash fills the entire chamber. However, unlike the vapor pocket ignition mode at low temperatures, this combustion event is not sustained over prolonged periods of time. We call this the flash ignition mode.

The above behavior can be explained on the basis of the Leidenfrost curve coupled with considerations of chemical reactivity and fuel/air mixing. Thus, referring to Fig. 1, we see that in regime (a) the droplet vaporization rate is about the highest although the reaction and buoyant mixing rates are low because of the low plate temperature. It is therefore reasonable to expect that the droplet is rapidly vaporized before ignition can occur. However, since ignition is still quite efficient relative to mixing, very little fuel/air mixing has been effected such that ignition and the subsequent combustion occur in the diffusion-flame mode involving a fuel pocket in the ambient air. Consumption of this fuel pocket requires some time, being limited by diffusive transport.

Vaporization in regime (b) is likely controlled by the transition segment of the Leidenfrost curve. Thus with increasing $T_{\rm w}$, for fixed p, the vaporization and thereby reaction rates slow down, implying the need to increase p in order to achieve ignition.

By the same reasoning, vaporization in regime (c) is controlled by the final segment of the Leidenfrost curve, representing the levitated mode of vaporization. Here increasing $T_{\rm w}$, for fixed p, increases the vaporization and thereby the reaction rate. Thus ignition can be achieved with reduced p.

In regime (d), vaporization again becomes sufficiently fast such that the droplet is completely vaporized before ignition is possible. However, unlike the behavior in regime (a), fuel/air mixing in this regime appears to be more efficient than chemical reaction. This is reasonable because with increasing T_w, buoyant mixing is promoted although chemical reactivity is not affected much due to the fact that we are mapping along the boundary of ignitability. Thus, the eventual ignition event resembles that of the thermal explosion of a well-mixed fuel/air combustible, which is consumed spontaneously.

Multicomponent fuels

We next study effects of fuel volatility and blending on the ignition limit. Figure 3 shows the ignition limits for heptane, dodecane and their mixtures. The results on pure fuels reveal the interesting behavior that ignition is more difficult for fuels with higher volatility, which is completely contrary to the ignition of free droplets in hot environments. This can be explained by recognizing that decreasing volatility is qualitatively equivalent to increasing the chamber pressure as far as the changes in the liquid boiling point and thereby the Leidenfrost vaporization behavior are concerned. Indeed, it is well established [1] that with decreasing volatility the Leidenfrost curve is shifted to higher T_w while the absolute values of the evaporation lifetime beyond the nucleate boiling point are also reduced. These behaviors are qualitatively similar to the curves of Fig. 1 for increasing pressure. Since reduced lifetime implies faster vaporization rate and thereby enhanced ignitability, a lower pressure is sufficient to ignite, say, dodecane as compared with heptane, as presently observed.

The results on fuel blending show a monotonic shift in the limit curves as the mixture concentrations are varied, which is reasonable. The shifts do seem to weigh more towards the less volatile component.

4. CONCLUDING REMARKS

In the present investigation we have experimentally determined the limiting values of the plate temperature and chamber pressure below which droplet ignition by the hot plate cannot be achieved. The results show that ignition is strongly influenced by the basic Leidenfrost droplet vaporization behavior, which is non-monotonic with respect to the plate temperature. Thus increasing the plate temperature may or may not facilitate ignition, while decreasing fuel volatility leads to enhanced ignition. It is further shown that the droplet fails to achieve ignition when the plate temperature is either sufficiently low or sufficiently high, with the ensuing ignition being diffusion controlled in the low temperature regime but resembling thermal explosion in the high temperature regime.

The main limitation of the present study is that the sizes of the droplets are substantially larger than those in realistic fuel sprays. Thus, the results reported herein should be viewed as being qualitative instead of quantitative. Further experiments involving smaller droplets are desirable.

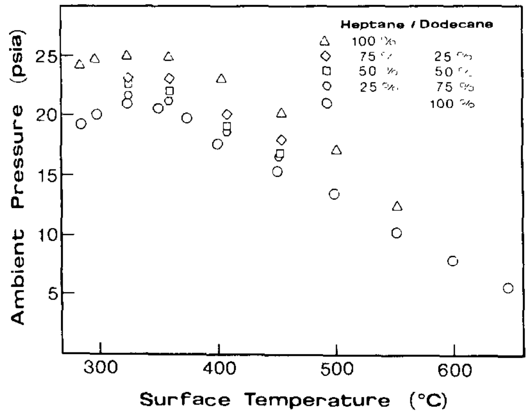

FIG. 3. Pressure/temperature ignition limit of pure and multicomponent fuel droplets in air.

Acknowledgements—This research was supported by the Army Research Office under the technical management of Dr David Mann.

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