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CIRCULATION AND COALESCENCE WITHIN A VAPORIZING EMULSIFIED FUEL DROPLET*

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The internal processes which occur during vaporization of an emulsified fuel droplet, are not well understood. Consequently, modeling effects[1,2] have been based upon speculative arguments regarding the participation of the dispersed component (water) during vaporization. The existence of enhanced vaporization (i.e. vapor explosion behavior) has been clearly demonstrated by Lasheras, et al.[3] using a technique of injecting free droplets into the combustion product stream of a flat flame burner. Although this method avoids the interference effects introduced by isolating a droplet on a suspended filament, it is difficult to study in detail the internal structure of the droplet during vaporization.

The present study uses an approach which is somewhat in the spirit of the Princeton work, whereby the droplet is supported by a vapor film between the droplet and a polished hot surface (Liendenfrost phenomena). A description of the experimental setup can be found in a companion paper.[4] Instead of backlighting with a gas laser, overlighting with the laser was used to avoid the reflection which otherwise obscure the internal observations. The emulsified fuel studied was hexadecane with 30% dispersed water and 2% surfactant. Hot plate temperature were typically 500°C, well above the Liendenfrost temperature for pure hexadecane and pure water.

Study of a vaporizing droplet was accomplished using high speed photography. Figure 1 depicts selected frames of a vaporizing droplet approximately 2000μm in diameter. (The framing rate was 5000 fps.) It is seen that during vaporization, rapid internal circulation cause coalescence of the dispersed water droplets. Convective velocities are seen to be 0.2 to 0.5 m/sec. During circulation, these droplet move directly along the fuel surface and, surprisingly, are not preferentially distilled from the droplet. A continual coalescence of the water occurs until the water is collected into a single lump. At this time, the

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convection is reduced and the water falls to the base of the droplet, (which provides an explanation for the apparent clearing of the initial milky appearance seen in earlier studies).[5] The last three frames depict the internal structure prior to homogeneous nucleation. Estimates of the water content at this time consistently suggest that nearly all the water has remained within the droplet.

Coalescence of the dispersed phase has been previously reported in an earlier study by F. Dryer.[6] It was suggested that the presence of the supporting filament caused this phenomena. Obviously, a different mechanism is responsible for the motion observed in the present study. Several possible mechanism are identified and the predicted velocity fields compared with observed internal convection velocities.

First, buoyancy effects induced by the hot surface are estimated. An upper bound of internal natural convection velocities is found by application of Bernoulli's equation. (Viscous effect which resist the motion are ignored.) For a temperature difference of 25°C between the top and bottom of droplet the induced velocities are calculated to be 0.01 m/sec. For 250°C temperature difference the velocities increase to 0.05 m/sec. It thus appears that internal natural convection effects are too weak to account for the observed rapid circulation.

Another mechanism is the effect of surface shear induced by the external vaporization film below the droplet. The gas film was characterized using a theoretical model similar to Gottfried, Lee, and Bell.[7] Shown in figures 2 and 3 are distribution of gas velocity and shear below a levitated droplet. Film thickness, δ_l, ha~~ve~~s been previously measured to be 0.001 to 0.005 cm.[8] With this distribution of surface shear it is possible to estimate the surface force which is necessary to induce a Hill's vortex. Consistent with the work of Prakash and Sirignano[9] it was found that induced liquid velocities are an order of magnitude lower than gas velocity. For a hexadecane droplet of radius 1000 m maximum gas velocities below the droplet are predicted to be 0.3 m/sec and, thus, the liquid velocities are approximately 0.05 m/sec.

Another possible mechanism of the internal motion is the effect of surface tension gradient at the interfaces between the immiscible components. These gradients are due to temperature differences within the droplet and the effect of the surface active component.[10] Owing to a lack of data for interfacial surface tension for hexadecane/water/surfactant a true estimate of induced velocities can not be made at this time. An induced velocity for a spherical droplet with a surface variation of surface tension $\Delta\sigma'$ and liquid viscosity of μ_ℓ can be estimated to be $v = 0(\Delta\sigma'/\mu_\ell)$. For a pure water droplet with a 1% variation of surface tension over its surface the induced translation velocity is ~ 1.0 m/sec. (This corresponds to a temperature variation of 3°C.) Typical measurements of temperature variations are of the order of 5°C.[8] It thus appears, that the driving mechanism for the internal circulation is due to variation of surface tension.

The implication of the internal circulation observed in these experiments is that any vaporizing droplet with asymmetric heating (i.e., distorted flame envelope) would be expected to have surface-tension gradient induced behavior.

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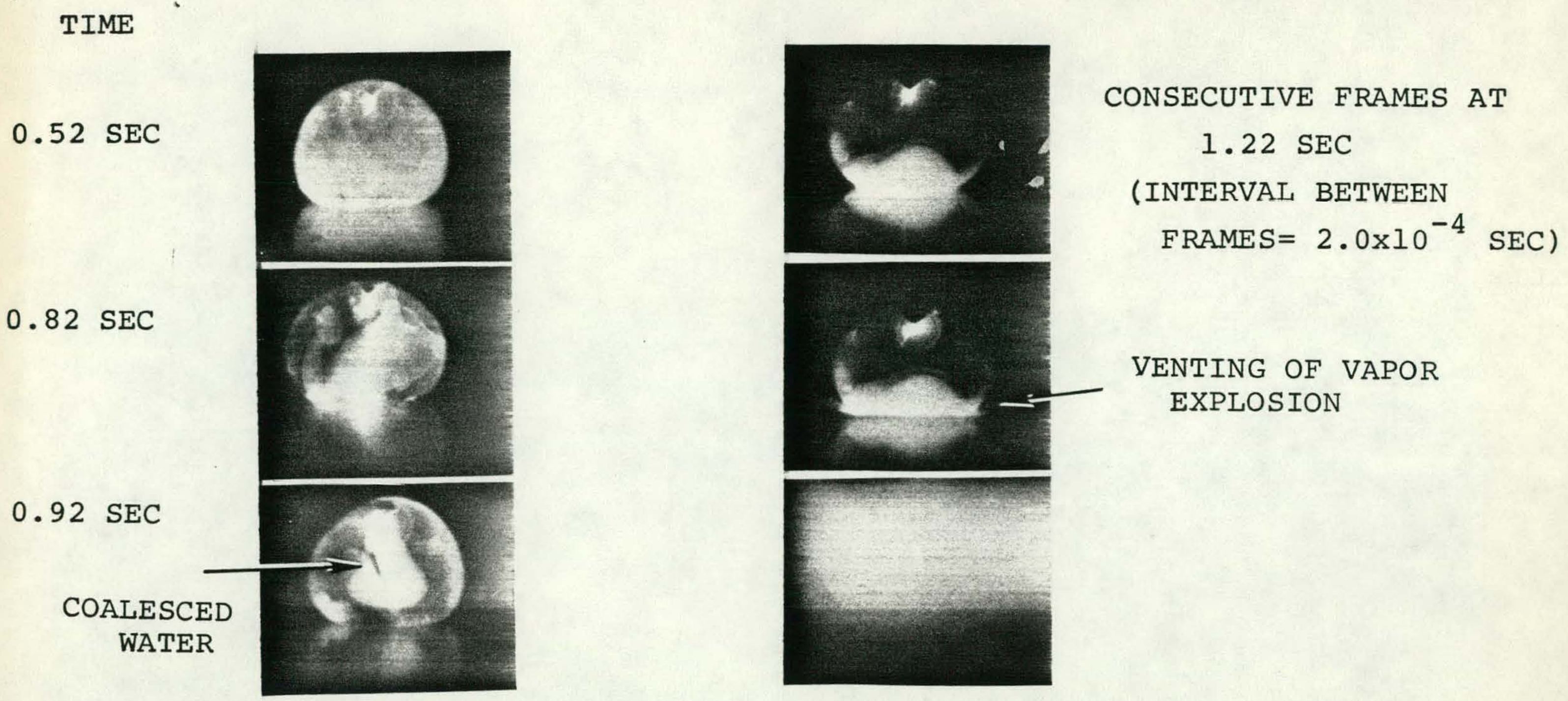

Fig 1. Selected frames during vaporization of a 2000 μm droplet of hexadecane/30% water/2% surfactant.

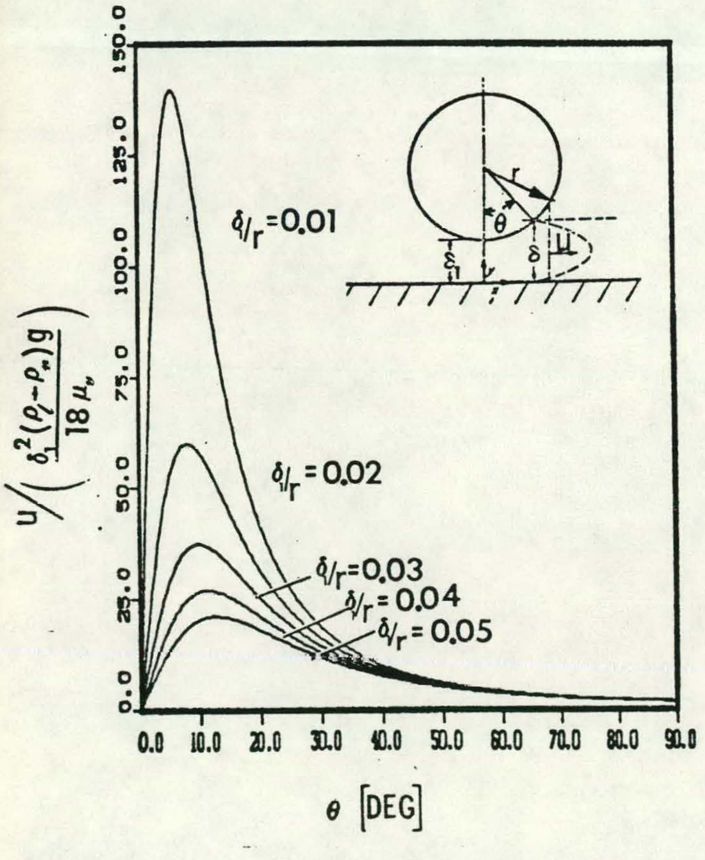

Fig. 2. Distribution of gas velocity below the droplet. The variables ρ , μ are density and viscosity and g is the gravitational constant. (Subscripts v, l refer to vapor and liquid quantities)

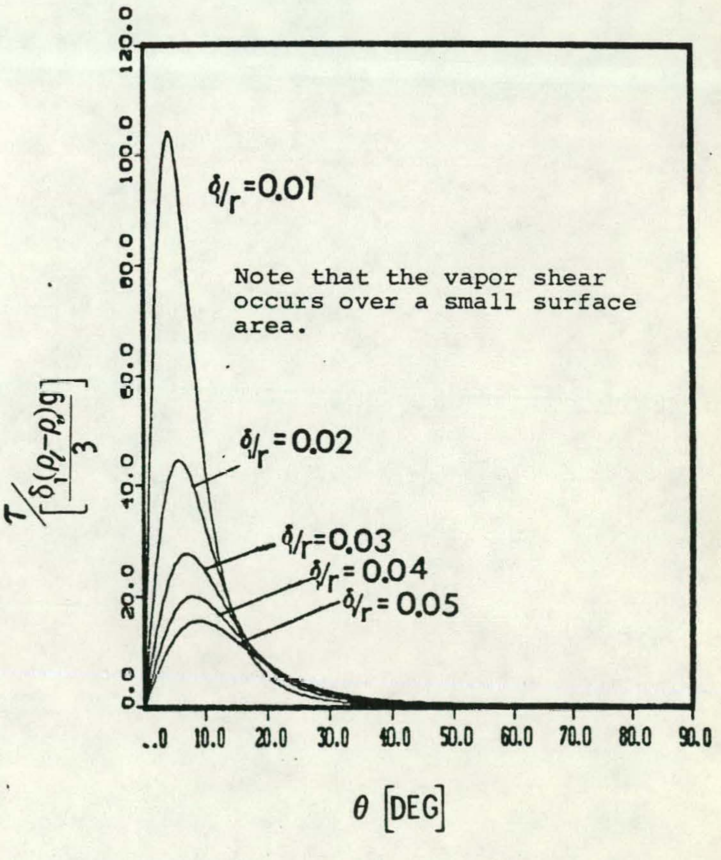

Fig. 3 Distibution of induced shear on the bottom surface of the droplet