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Holographic studies of the vapor explosion of vaporizing water-in-fuel emulsion droplets

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Abstract

Holographic studies have been performed which examine the fragmentation process during vapor explosion of a water-in-fuel (hexadecane/water) emulsion droplet. Holograms were taken at 700 to 1000 microseconds after the vapor explosion. Photographs of the reconstructed holograms reveal a wide range of fragment droplet sizes created during the explosion process. Fragment droplet diameters range from below 10 microns to over 100 microns. It is estimated that between ten thousand and a million fragment droplets can result from this extremely violent vapor explosion process. This enhanced atomization is thus expected to have a pronounced effect on vaporization processes which are present during combustion of emulsified fuels.

Introduction

Water has long been observed to have a beneficial effect on combustion of liquid fuels but a complete understanding of the mechanisms by which this enhancement occurs is just beginning to emerge. Water-in-fuel emulsions are being used or considered for use in many combustion applications where particulate pollution is a problem because of the potential of decreased particulate emissions and enhanced combustion. Although a number of studies have been carried out to determine the physical processes involved in the combustion of emulsified fuels, primarily phenomenological explanations have resulted. The present experiments are part of a larger program designed to quantify the phenomena which have been observed and understand the enhancement process.

The first enlightening experiments were performed by Ivanov, et al.[1] of the Soviet Union in the late 1950's. They showed that water/oil emulsion droplets burned disruptively when suspended on a quartz fiber (called a sting) and ignited. This disruptive burning process was called a "microexplosion." In 1976, Dryer and coworkers[2,3] performed similar experiments at Princeton University and from their observations suggested that the water in the oil matrix was superheating. Near the limit of superheat, the water homogeneously nucleates rapidly to produce a vapor-phase explosion. The limit of superheat for water is approximately 260°C so their concept was that paraffinic fuels with a boiling point above this, when emulsified with water, should lead to a vapor explosion while those with boiling points below would not vapor explode. This means that hexadecane (boiling point 287°C) emulsions should vapor explode while tetradecane (252°C) emulsions should not. However, their early observations of burning emulsion droplets suspended on a quartz sting indicated dodecane (216°C) emulsions microexploded. They felt the sting was probably a source of nucleation sites that led to premature water nucleation. In order to eliminate the sting nucleation problems, free droplet studies were necessary.

Recently, studies by Lasheras, Dryer, et al.[4,5] have been carried out in which free emulsion droplets were injected into the hot combustion products streaming out of a flat flame burner. Vapor explosions were observed using droplets of hexadecane/water and tetradecane/water emulsions but not in dodecane/water emulsions. These results correlated very nicely to a theoretical prediction by Avedesian[6,7] which predicted tetradecane/water emulsions should be on the edge of failure to undergo vapor explosion because the fuel boiling point is very close to the superheat limit for the system.

The above mentioned studies have been primarily phenomenological with respect to the processes occurring during the vapor explosion because of the difficulties in photographing a free droplet. Two recent studies by Sheffield, Baer and Denison[8,9] using emulsion droplets levitated above a hot plate have shown that a number of very interesting processes take place during the heatup and vapor explosion process. Surface tension induced circulation occurs inside the droplet and the small water droplets coalesce to form larger water globules during the heatup process. Then the large globules settle to the bottom of the droplet just prior to the vapor explosion. The explosion process was clearly shown to be very violent, producing fragment velocities ranging from 30 to 90 meters per second. However, instrumentation was not adequate to resolve fragment sizes in these experiments.

The holography experiments described in this paper were carried out for the purpose of visualizing the explosion fragments to determine the extent of the fragmentation process. Droplet fragments from less than 10 to over 100 microns in diameter have been clearly identified at times 700 to 1000 microseconds after the vapor explosion starts. These experiments will be discussed in detail in terms of the experimental setup, experimental observations, and their correlations with previous results.

Experimental Setup

A water-in-fuel emulsion consists of a heterogeneous mixture with the fuel as the matrix, water as the dispersed phase, and a surfactant which is used to stabilize the material. In this study, the fuel was n-hexadecane ($C_{16}H_{34}$). The surfactant was a mixture of Span 80 and Tween 80[10] to give an HLB number of about 5.5 which results in a fuel soluble surfactant and produces a relatively stable water-in-fuel emulsion. Emulsions were made by mixing 29% water, 69% n-hexadecane, and 2% surfactant (by volume) in a domestic blender for several minutes. The resulting emulsion has a milky color with the dispersed water drops a few microns in diameter.

The free droplet experiment adopted in the present study uses the Leidenfrost phenomenon[11] to levitate a droplet above a heated surface. This experiment consists of placing an ~2 mm diameter droplet of emulsion on a heated metal surface using a small syringe to form the drop. The plate temperature is maintained above the Leidenfrost temperature of the fuel so that fuel evaporation causes the droplet to levitate about 10 to 50 microns above the plate[12]. A slight 50 mm diameter spherical indentation in the highly polished plate stabilizes the droplet in one area during its heatup period so that it can be easily photographed. The heated plate was maintained at temperature by using a laboratory hot plate.

For these particular experiments, the plate was replaced by a stainless steel substrate machined to the shape of a truncated cone 25 mm diameter at the base and 12 mm diameter at the top, which was highly polished with a spherical indentation in it. This substrate was placed on a laboratory hot plate and maintained at a temperature of about 500°C. An insulation sheet 25 mm thick with a cutout to accommodate the cone shaped substrate was placed over the hot plate during each experiment to eliminate any hologram noise which might be generated by a large amount of natural convection induced turbulence in the 30 cm hot plate region surrounding the exploding droplet. The holocamera, Model HTC-5000 built by Spectron Development Laboratories, has a pulsed ruby laser light source which is switched by a Pockels cell to give a 10 to 20 nanosecond pulse between 700 and 1200 microseconds after the holocamera is triggered. The low end of this delay is controlled by the amount of time it takes the flash lamp to pump the ruby rod to a sufficiently energetic state that a reliable laser pulse can be obtained when the laser pulse is allowed to escape by triggering the Pockels cell. A schematic of the experimental setup is shown in Figure 1. Notice that the holography system consists of a reference beam which travels approximately the same distance as the information beam. The information beam passes through the explosion regime and then interfers with the reference beam on the film plane and exposes the glass holographic plate producing the hologram. Two lenses which are not shown on the figure were inserted in the information beam at the proper places to position the image of the droplet explosion behind the holographic plate to simplify the reconstruction. By properly choosing these lenses, magnification of the explosion was obtained in some of the experiments.

Triggering of the holocamera was accomplished by passing a helium-neon laser beam close to the side of the droplet and into a photo detector setup that was designed to send out a trigger signal when the beam was interrupted. Since the beam was near the bottom of the droplet, it was interrupted when the vapor explosion produced the early jetting to the side. A trigger signal then went to the holocamera. Between a setable delay of 700 to 1000 microseconds after the holocamera was triggered, the Pockels cell was triggered, providing the laser pulse required to produce the hologram. Since the laser pulse width was limited to 10 to 20 nanoseconds, a stop action hologram of the explosion process was produced. Resolution of the holograms was a few microns with this configuration so fragment droplets of a few microns were detectable.

Reconstruction of the explosion images was accomplished by expanding a helium-neon laser beam and orienting the developed holographic plate in the expanded beam so that the three dimensional image was formed off at an angle from the main beam as shown in Figure 2. Pictures were then taken of the image using macrophotography techniques to provide the desired magnification. An Olympus OM-2 camera was used to take the pictures.

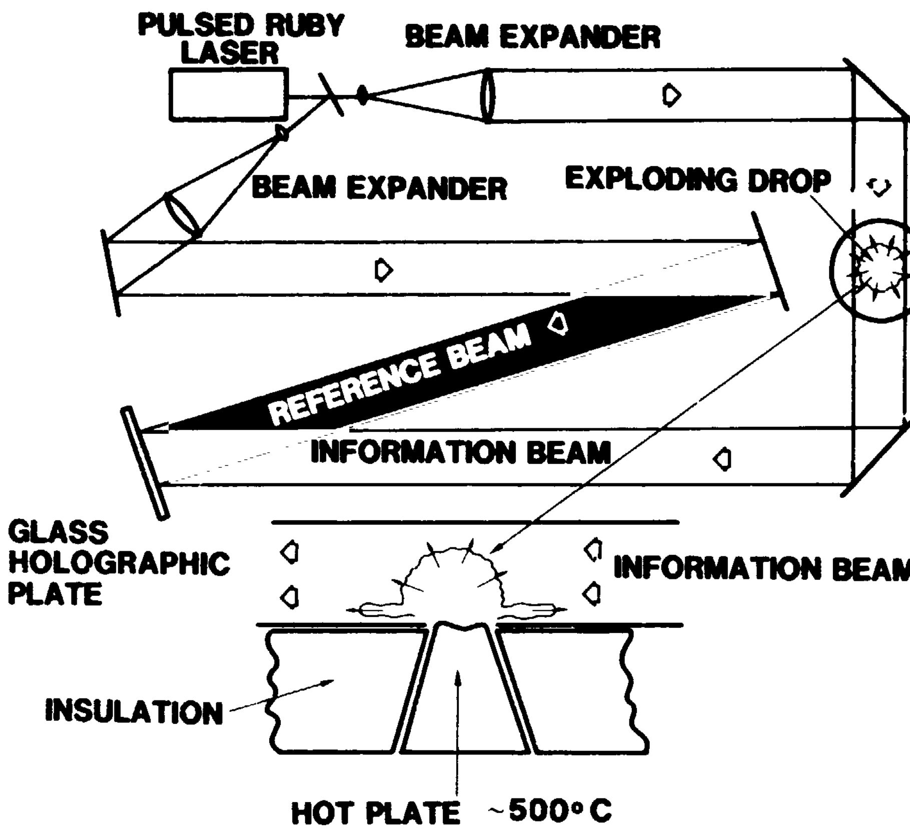

Figure 1. Exploding droplet holography experimental setup.

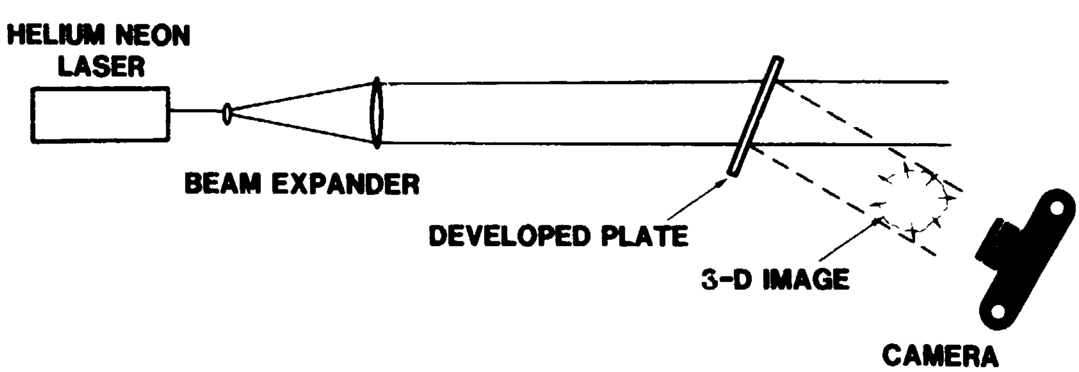

Figure 2. Holographic image reconstruction setup.

Results and Discussion

Over 30 holograms of exploding droplets were taken during this study. Some explosions were obviously less violent than others probably due to premature heterogeneous nucleation of the water before it reached the superheat limit. Three representative holograms were picked for close study and several photographs of the reconstructed images were made. In Figures 3, 4, and 5, respectively, fragmentation is shown 700, 875, and 1000 microseconds after the holocamera was triggered. It was possible to make only one hologram of each droplet explosion so these figures represent three different explosions with the accompanying differences between them one might expect.

Figure 3 clearly shows the nature of the fragmentation process with a jet visible near the plate, moving out parallel to the plate. Other parts of the droplet liquid are in the form of ligaments in the process of breaking up to form droplets. The lower left enlargement shows a ligament that has nearly completed the breakup process. The next two enlargements, moving clockwise around the center picture, show a common area; only the position of the camera focus has been changed to show the three dimensionality of the hologram image. Some droplets which are in focus in one enlargement are out of focus in the other. The enlargement in the top-right corner was made in an area that appears to have only a few droplets in the center picture but the enlargement shows a large number are actually present. The same is true for the lower-right enlargement. From the scale it is clear that the ligaments and a few droplets are larger than 100 microns in size, but a large number are substantially smaller.

Figure 4 shows a droplet explosion 875 microseconds after the holocamera was triggered. Although this explosion looks considerably different from the one shown in the previous figure, many droplets with a wide range of sizes are discernable. No ligaments appear in this explosion, however. The jet on the left side is visible but the one on the right seems to have already disappeared, perhaps, as a result of the explosion venting more to the right side than the left during the early part of the process. This phenomenon has been observed in high speed framing camera pictures in earlier testing.

Figure 5 shows a droplet explosion 1000 microseconds after the holocamera triggered. Again the remains of the jets are visible near the plate. The lower-left enlargement contains part of the jet, but droplets are not clearly discernable in this area of the picture, so they are apparently on the order of the resolution of the hologram, around 1 to 5 microns. Other drops in the center picture and the enlargements range from about 10 to 100 microns in size. Most of the ligaments appear to have already broken up because there are only a few small ones present throughout the picture. The top-left enlargement shows an area where very few droplets are discernable in the central picture, but many drops are clearly observable in the enlargement, some in the 10 micron range. Again this figure shows, in a graphic way, the tremendous fragmentation that results from the vapor explosion.

Although this experimental setup represents a somewhat non-physical situation as far as simulating a combustion environment is concerned, it does provide a needed visualization of the explosion process. The jetting near the substrate is due to the asymmetric confinement and heating provided by the substrate. It is felt, however, that the explosion upward is quite representative of what one might expect in a combustion environment. The small droplets formed in the jets by the rapid venting provide an interesting comparison to those formed in the less violent upward explosion.

Droplets formed in the jet are on the order of a few microns which means they could vaporize in a few hundred microseconds[13] unless the atmosphere around them was saturated with fuel vapor as is probably the case at the late times of the holograms. This correlates nicely with high speed framing camera pictures which show the jets disappearing. For comparison purposes a sequence taken at 40,000 frames per second has been included as Figure 6. It shows the jet disappearing in frame 5, about 200 microseconds after the explosion starts. In this sequence, the side jets are moving out at about 90 m/s and the droplet is exploding upward at between 30 and 70 m/s. The droplets visible in the holograms, which are much later in time than the film sequence, have moved about 30 mm in 1000 microseconds (average velocity of 30 m/s). As expected, the droplets are slowing down due to drag as they move out. It is estimated that the drop velocity should be reduced to the surrounding gas velocity in 10 to 20 mm of travel[13] so the true droplet velocity is probably slower than the calculated average velocity at these late times. Based on this, one would expect the diameter of the sphere of influence of the explosion to be about 30 to 60 mm or about 15 to 30 original droplet diameters in these experiments.

Pictures of the holograms in Figures 3 through 5 clearly show that a large number of fragment droplets are formed. No attempt has been made to carefully count all the drops in each picture because this only represents a small slice of the whole explosion volume. If one assumes a 2 mm droplet is reduced to a monodisperse group of 50 micron diameter fragments, one drop would produce over 50,000 fragment droplets. If the fragment diameter

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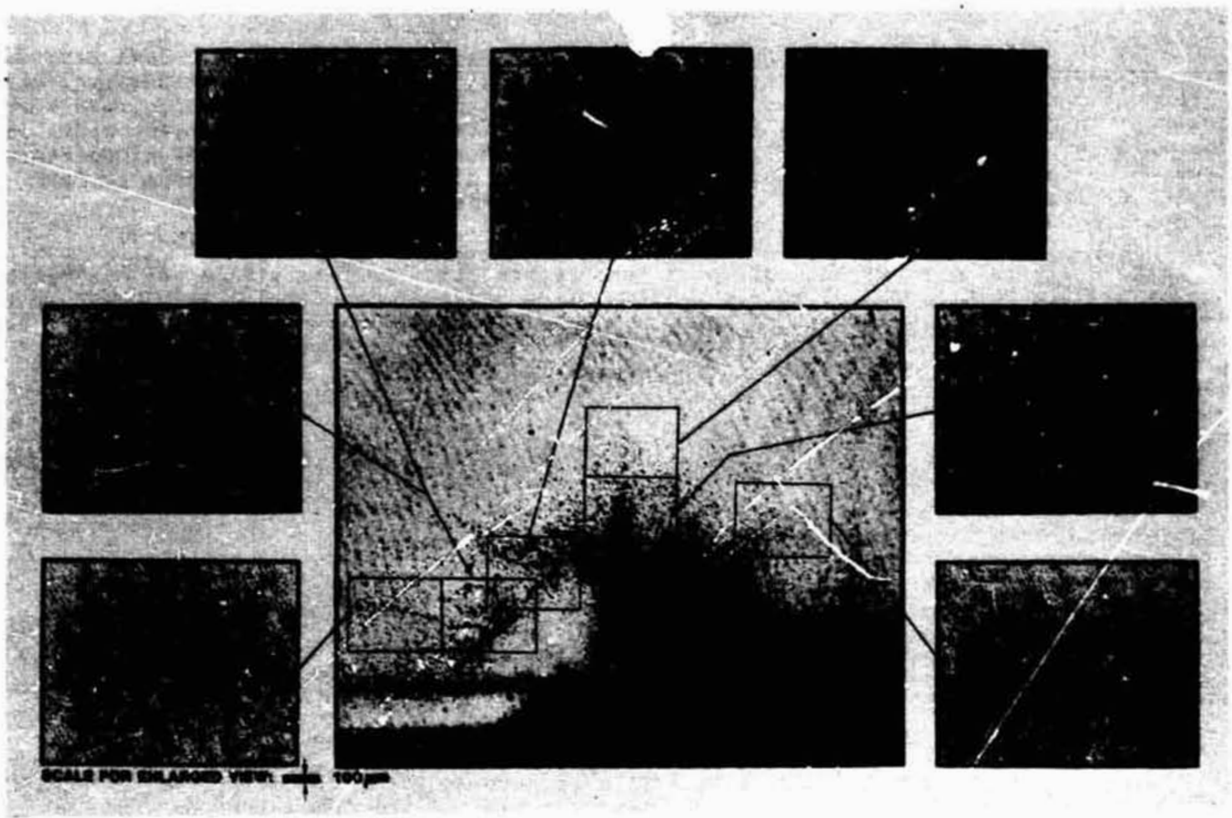

Figure 3. Picture of image of droplet explosion 700 microseconds after holocamera was triggered.

Figure 4. Picture of image of droplet explosion 875 microseconds after holocamera was triggered.

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was 30 microns, one drop would produce 300,000 fragment droplets. In this case we have a distribution of sizes from too small to measure in the jets (probably a few microns in diameter) to over a hundred microns. An average size is probably between 30 and 50 microns which indicates there are on the order of tens of thousands to hundreds of thousands of fragments from one drop exploding. An estimate of the number of drops visible in one picture led to about 4000 drops. Since this is only a slice of the whole volume, one would expect to have 10 to 100 times this many in the entire explosion, again leading to the same estimate as above. We have estimated that the lower and upper limits on numbers of fragments formed are ten thousand and a million, respectively.

Figure 5. Picture of image of droplet explosion 1000 microseconds after holocamera was triggered.

Conclusions

Time resolved holography has been shown to be an extremely useful experimental technique to study the vapor explosion of a vaporizing water-in-fuel emulsion droplet. It has led to some very graphic pictures of the droplet fragmentation which results from the explosion. Fragment sizes from less than 10 to larger than 100 microns are visible with the average probably in the 30 to 50 micron range. In the early time holograms (700 microseconds), ligaments that are breaking up are visible, while at the later times (1000 microseconds) the ligament breakup is nearly complete. Estimates based on the average size and the number of drops visible in the pictures of the holograms indicate that lower and upper limits for the numbers of fragments are ten thousand and a million. The typical number is probably between 50,000 and 300,000, indicating the very violent nature of the vapor explosion.

The distances that the fragments have traveled after the explosion lead to an average velocity of 30 m/s compared to between 30 and 70 m/s when the explosion first starts, indicating a drag induced reduction in velocity. The sphere of influence of the explosion is estimated to be about 15 to 30 original droplet diameters.

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Figure 6. High speed framing camera sequence of a droplet explosion. Droplet was backlighted with an expanded laser beam. Frames are 50 microseconds apart.

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