Effects of a High Energy NIR Laser on Saltwater Drops

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Abstract

As high energy lasers are integrated into ship systems, the effects of the maritime environment on beam propagation must be understood. Laser use on naval vessels or with small watercraft targets presents the possibility that salt water will be thrown into the air by means of sea spray. Research has been conducted on the vaporization of pure water drops, with and without directed radiation, and on effects of lasers on aerosols, but little is known about the effects of lasers on salt water drops. Experiments described here consist of a salt-water drop, levitated in place, and targeted with a directed energy beam in the near-infrared. The interaction was recorded using an infrared camera to measure the surface temperature and size of the drop through a 60 second laser strike as well as a 15 second cool down period. Through these measurements, as well as the power output of the laser beam, the temperature and volume of the drop through the run were determined. Image analysis showed that the salt water drop evaporated and maintained a steady state temperature until reaching some critical volume at which the temperature rose dramatically and the drop boiled. This phenomenon is not observed with freshwater drops. These results will be useful in the context of the naval battlespace as the weapon operators will have to take into consideration how the boiling of sea spray and other salt water drops will affect the effectiveness of the weapon.

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1. Introduction

As the widespread use of high energy lasers in the maritime environment becomes likely, the effects of lasers on large water drops, and of water drops on lasers, must be understood. While much research has been conducted on the natural vaporization of small water droplets through evaporation and boiling at varying temperatures, less is known about larger drops such as rain or sea spray.

The vaporization, or change in state from the solid phase to the gas phase, of a water drop can occur in a few modes. The two relevant modes for this work are nucleate boiling and evaporation (Kotz et. al 2015).

Nucleate boiling occurs below the surface, often at a solid-liquid interface. In the case of directed energy targeting a water drop, boiling would occur near the middle of the drop. Boiling consists of vapor bubbles forming from water molecules that have reached the boiling, or saturation, temperature corresponding to the ambient pressure, releasing from where they were originated and escaping to the environment by moving to the surface of the liquid (Bergman, et. al 2011). Vapor bubbles greatly affect the movement of the liquid at the surface through their transfer from within the liquid to the environment. Vapor bubble growth is dependent upon the excess temperature and the nature of the surface among other variables.

The other method of vaporization, evaporation, occurs at the surface of the liquid at temperatures under the saturation (boiling) temperature. Water drops evaporate because the partial pressure of the water vapor surrounding the drop is lower than the local atmospheric pressure, thus allowing water to diffuse from the liquid at a temperature lower than is required for nucleate boiling (Hollerman 2003). Hollerman explains this pressure difference acts as the driving force for carrying water vapor away from the surface of the drop. “A water drop… floating in air is subject to evaporation and will decrease in size. During a certain (but relatively small) transient time, the drop cools down due to evaporation, until it reaches its wet-bulb temperature” (Hollerman 2003). During the transient time a thin layer of saturated water vapor also forms and surrounds the drop. In the equilibrium case, the temperature of the water drop is lower than the ambient temperature outside the drop, heat flows into the drop and feeds the evaporation. The transient period is miniscule compared to the lifetime of the drop; the transient period makes up between a twentieth and a two-hundredth of the total lifetime of a water drop, normally closer to one two-hundredth.

After the wet-bulb temperature is reached, the transient period ends and is followed by a steady evaporation period (Hollerman 2003). The lifetime of a water drop is inversely proportional to the difference between the saturated water vapor film temperature and the ambient temperature. Rationally, the lifetime of a drop increases with the size of the drop, since it will take longer to evaporate more water at a constant evaporation rate. The evaporation rate can be approximated well by a linear function of drop diameter and the difference between the wet-bulb and dry-bulb temperatures.

For a water drop, heat transfer occurs by conduction as well as convection from hot gases to the drop surfaces from which vapor is transferred by diffusion and convection back into the gas stream (Marshall and Ranz 1952, 173-80). The rate of heat transfer of a drop per unit area is a function of temperature, humidity, and the transport properties of the vapor.

Another experiment, this one performed by Tseng and Viskanta, tested the evaporation rate of water droplets with and without radiation. They determined that “since water is not opaque but semitransparent, absorption of radiation by the droplet is not a surface but a volumetric phenomenon” (Tseng/Viskanta 2006, 236-47). It was found that for wavelengths larger than 2.3 micrometers water absorbs radiation very well, but as the drop decreases in size the absorptivity decreases; therefore absorptivity of radiation decreases through time as the drop evaporate.

The surrounding temperature is much higher than room temperature, so the drop quickly evaporates. The diameter of the drop reduces at a constant rate once the temperature of the surface steadies out. When a droplet receives energy from a directed energy source, it may or may not act similarly because the surface may not hold at a constant temperature.

When a solute, such as sodium chloride, is added to a water drop, a result of a lower temperature difference between wet-bulb and dry-bulb temperatures and pressure difference between atmospheric and saturated vapor pressures are achieved (Marshall and Ranz 1952, 173-80). Marshall and Ranz explain that in addition, as a mixture is evaporated the solutes will tend to concentrate on the surface of the liquid because evaporation occurs at a much faster rate than the solute can diffuse toward the middle of the drop.

There are a few models to simplify the temperature of the liquid inside a droplet. One is the conduction limit model, and another is the infinite conductivity model (Abramzon and Sirignano 1989, 1605-618). The conduction limit model portrays the temperature of the liquid inside the droplet as uniform, though the temperature changes with time. The infinite conductivity model suggests the surface temperature of the droplet is uniform, and the only method of heat transfer within the liquid is through thermal conduction. These models represent the ends of the spectrum of what could be considered reasonable; the actual temperature within the droplet is going to be somewhere between what these two models calculate. The models are useful in that they simplify the problem and allow for the calculation of desired results with parameters that are able to be measured.

Another slightly more complex model for the temperature of the liquid inside a droplet is the extended model. The extended model considers the motion of the liquid inside the droplet to determine the temperature of the liquid within the droplet (Abramzon and Sazhin 2005, 1868-873). This model also considers a volumetric heat source rather than a directed heat source such as a directed energy laser.

2. Methods

An experiment was performed to record the vaporization of saltwater drops. A saltwater drop (35 ppt, or 3.5% salt by mass) was levitated in place using a tec5 ultrasonic levitator, and targeted with an IPG laser with a wavelength of 1068 nanometers and a beam width of 5-mm. The total incident power on the drop varied with drop size, while the irradiation was relatively constant near 800 W/cm^2. The droplet was levitated and formed into an oblate spherical shape, with ellipticity between 0.7 and 0.99. The starting range of drop diameters was between 0.9 - 2.4 mm.

In each experimental run the laser targeted the drop for 60 seconds. An infrared camera recorded the drop surface temperature at a rate of 30 Hz during the laser strike and during a 15 second cool down period. The IR camera also captured drop size, and a separate thermopile measured integrated beam power after passing through the drop. The range of calibrated temperatures for the IR camera setting used was 35°C to 90°C. Past these ranges temperatures have an error of about 2°C, with a high of 98.1°C and a low of 2°C. Figure 1 shows the configuration of the elements of the experiment.

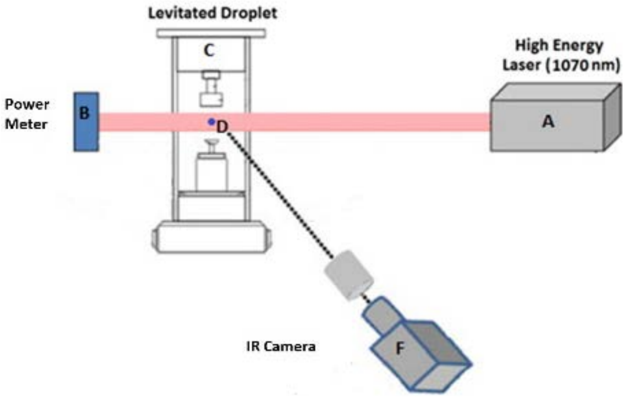

Figure 1: The configuration of the equipment used in the experiment

Matlab was used to analyze individual images in the video of the water drop. The two diameters of the spheroid were estimated using image processing software within Matlab by comparing the number of pixels of a known distance in the image to the number of pixels across the water drop. In addition, the coordinates of the centroid of the spheroid were found using Matlab. Equation 1 was used to find the volume of the drop, where “a” is the equatorial radius and c is the polar radius. Matlab was then used to compare the volume, temperature, and time of each run completed.

$$V = \frac{4}{3}\pi a^2 c \qquad (1)$$

A separate experiment performed was to calibrate the water emissivity used by the infrared camera. To accomplish this, a beaker filled with ice water and a beaker filled with boiling water were imaged by the IR camera. In each case the beakers were brought to a steady state temperature (freezing or boiling), and the camera recorded temperatures from a view of perpendicular to the surface and sweeping down to parallel to the surface. The calibration measurements of the camera showed a constant emissivity for angles within 30° from the perpendicular for the boiling water and 60° from the perpendicular for the freezing water. Temperatures at both ends of the range are accurate to within 2°. Measurement accuracy may extend beyond these limits, however, laboratory fixtures prevented quality calibrations at more extreme angles.

3. Results

Figure 2 shows an image of a water drop through the infrared camera. The drop is initially featureless, as its temperature is approximately the same as the surrounding temperature. Upon initiation of the laser strike, the drop temperature increases by 40-50^{o}C over a short transient period before reaching a quasi-equilibrium temperature. As irradiation of the drop continues, turbulent eddies within the water move hot regions of fluid from the inside of the drop, where absorption is strongest, to the outside of the drop, where evaporation is occurring. Video shows fluctuations in drop surface temperature of 15^{o}C are not uncommon.

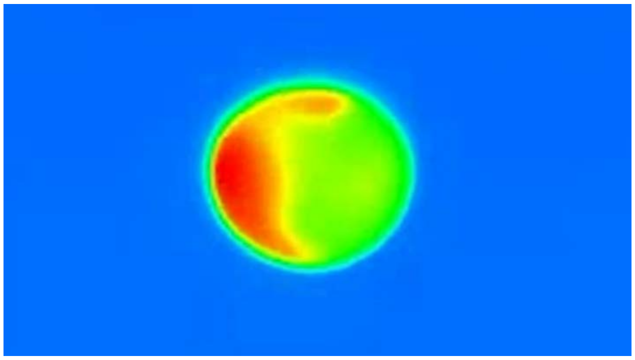

Figure 2: An image of a water droplet in the heating process using the infrared camera

The temperature, volume, and time values were extracted from the image sequences and are shown below. Temperature refers to the maximum temperature observed on the hemisphere of the drop visible by the camera. Volume is extracted using an edge detection algorithm on the visible edge of the drop. Because of the low emissivity of the drop at high angles, volume is slightly underestimated here. Time is taken from the frame rate of the video, recorded at 30Hz, with an arbitrary point chosen for $t = 0$ always before the initiation of the laser strike.

Figure 3 shows the temperature v. time data for a single laser strike event. The temperature begins at a room temperature below 25℃ prior to the laser starting. The laser heats up the drop quickly to a relative steady state value between 50℃ and 60℃ for about 30 seconds. The drops then spikes in temperature to 98.1℃ and maintains a prolonged period of high temperatures as well as a return to near the steady state temperature prior to finally becoming unmeasurable. Some experiments do not maintain a high temperature for such a long period of time.

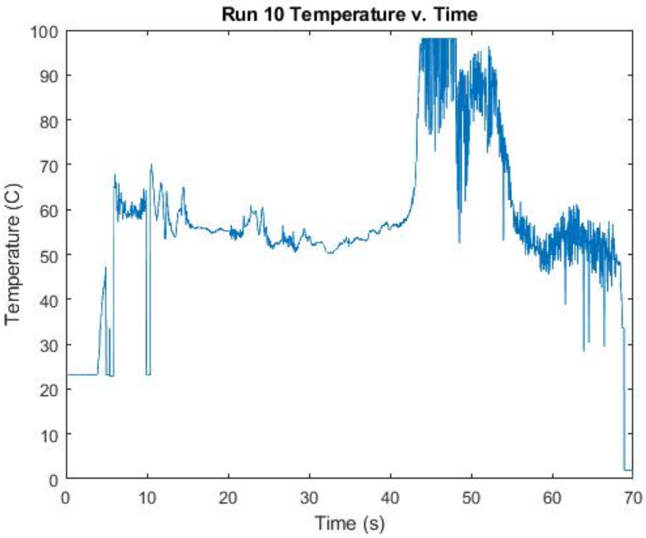

Figure 3: Temperature v. Time data for Run 10

Figure 4 shows the volume v. time data for Run 7. Note that the volume was not correctly measured until about eight seconds into the recording, when the drop temperature changed enough to distinguish the boundaries of the drop from the background. The drop began at a volume of 4.5 mm^3 and decreased exponentially for about 30 seconds until the drop was no longer able to be measured in the recording. The pattern of Fig. 5 is consistent with all volume v. time plots from all runs performed with this experiment. The variables that change with each run are the starting and ending volume.

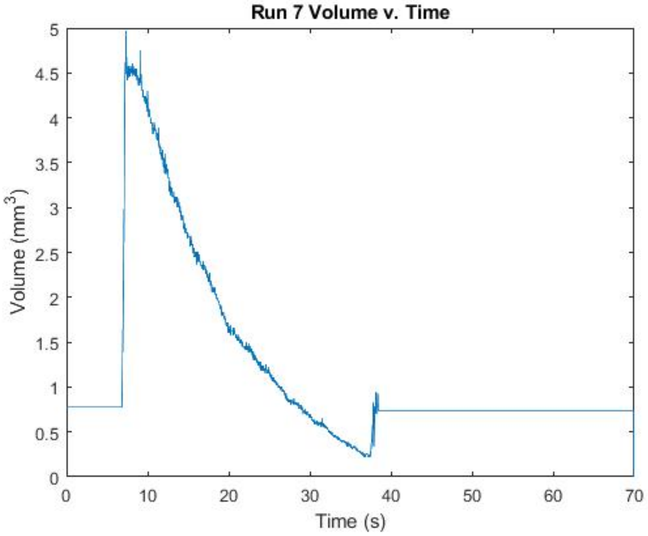

Figure 4: Volume v. Time data for Run 7

Figure 5 shows the volume v. temperature data for the same laser strike as in Fig. 4. There is a vertical line of data points at a high volume, starting at 30℃ and leading toward the average temperature of 55℃. The low temperatures at large volume in the figure correspond to the initial, transient heating of the drop when the laser strike began. The plot is dominated by a horizontal line of points around 55℃, representing a steady temperature over a wide range of volumes. Data points on the right correspond to earlier times, moving to the left (lower volumes and slightly lower temperatures) as the laser strike continued. On the far left there is another vertical line of data points leading from 50℃ to 98.1℃. This represents the spike in temperature observed once the drop reached a critical volume.

4. Discussion

Figure 5 displays a near quasi-equilibrium temperature through most volumes the drop reached through the experiment, caused by a balance of heat leaving through evaporation of water and heat brought into the system by the laser. The slight drop in temperature is expected, as the heat rate from the laser is a volumetric process and scales as D^3, while evaporation from the surface scales with D^2. We anticipate that, as the drop shrinks in size, the incoming heat rate decreases fastest and the required evaporative flux to balance the absorption rate decreases. Because the evaporative flux is proportional to the surface-ambient temperature difference, the quasi-equilibrium temperature also drops.

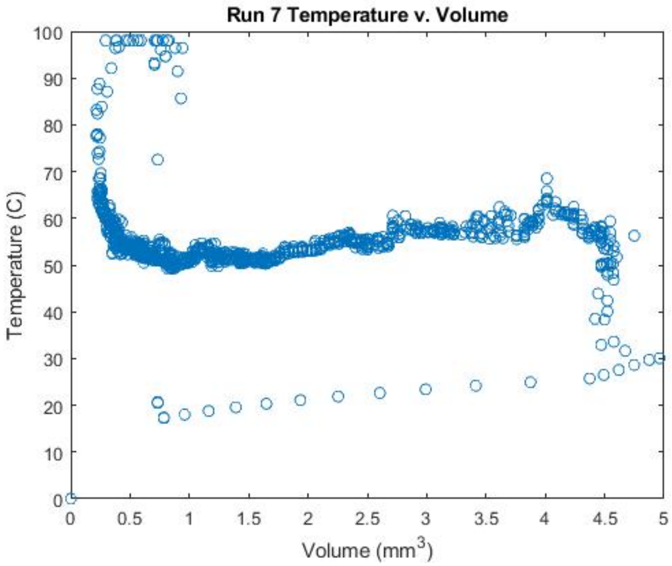

Figure 5: Volume v. Temperature data for Run 7

The vertical line of data points at a volume of 0.2 mm^3 shows the rapid increase in temperature at some critical volume. This critical volume may relate to initial drop volume, irradiance, or other as yet undetermined factors. The spike in temperature increased to the boiling point of water, and the video shows the water oscillating rapidly due to boiling. The drop only remained boiling for a short time in Run 7, but for other runs, such as Run 10, the drop remained boiling for an extended period of time, as shown in Figure 4. The boiling is likely caused by the addition of salt in the drop since this phenomenon does not occur with freshwater drops in the same circumstances. The collection of salt on the surface of the drop prevents enough water from being evaporated to maintain a neutral heat transfer, causing a sharp increase in temperature as the water and salt accumulate heat from the laser. The most likely explanation for the phenomenon is that enough water has evaporated for the salt in the drop to exceed its saturation limit. Salt then comes out of solution, and the crystalline solid has optical properties that are vastly different from salt in solution.

Each temperature v. time plot shows a small dip in temperature at the start of the steady state temperature period and a small rise prior to the end of the steady state temperature period. This drop and rise is likely caused by the movement of water and salinity within the drop. It can be seen in Figure 4 that the rate of change of the volume maintained as an exponential decay until reaching the critical volume. The boiling and rapid oscillation of the drop caused the image processing software to misinterpret the volume of the drop, thus preventing an accurate measurement of drop volume during and after boiling. The variability in behavior after reaching this temperature spike has not been determined. Achieving an average volume v time or temperature v volume plot over all useful runs has not been achieved yet due to the varying starting volumes. The starting volume changes the critical volume, and the small variations in each run make an average of either plot difficult to create. Further analysis will involve incorporating the effects of the measured irradiation during each run, collecting more data to reduce sample size effects, and using numerical simulations to estimate interior drop temperatures.

5. Conclusions

The introduction of laser weaponry and systems in the naval arena creates a need to find how lasers will be affected by and how lasers will affect their environment. In the case of salt water, the water maintains a steady state temperature until reaching some critical volume where the water temperature quickly rises and the drop boils. The initial volume of the drop, and therefore the final salinity of the drop, is the driving force in the critical volume at which the drop boils. As lasers are implemented on ships, the amount of irradiation diverted to boiling sea spray will need to be considered in the practicality of their operation.

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