

LASER HEATING AND EVAPORATION OF A LEVITATED WATER DROP

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Summary Single water drops with initial diameter of approximately 1-mm are acoustically levitated and subject to laser radiation from a 1070 nm cw laser with mean irradiance of 530 W/cm². Effects of the radiation on the drop are measured using high speed video, and a beam profiler measures the corresponding effects of the drop on the laser beam. Turbulent convection within the drop is visible from the video, unlike what has been seen in prior laser heating experiments using smaller drops. Phase change begins immediately upon initiation of the laser strike, with no obvious sensible heating period. The drop evaporation rate is measured, and shows good agreement with a simple 1-D laser heating model.

INTRODUCTION

The U.S. Navy is actively developing both offensive and defensive technologies related to the use of lasers in warfare. For the Navy, the complexity of a maritime environment poses particular challenges for laser propagation due to high probabilities of liquid water in the form of fog, rain, or sea spray along the beam path. Several previous studies have examined laser heating effects on water droplets with diameters less than 100 microns [1], but less is known about laser interactions with larger drops with diameters upwards of 1-mm. At this size, geometric optics may be used to describe the beam propagation through the drop, and convection within the drop is expected to play a much more important role. Current interest in this problem lies in both predicting the laser's effect on the drop, including the evaporation rate and the fate of the subsequent water vapor, and in understanding the drop's effect on the transmission of the laser beam.

EXPERIMENT

To quantify the effects of a high energy NIR laser on a water drop, a series of experiments were conducted using acoustic levitation to isolate single water drops from solid boundaries, preserving a near-spherical drop shape and allowing a free path for the laser. Levitation was achieved using a tec5TM acoustic levitator, which creates a standing wave between a fixed transducer and an adjustable reflector. Using the acoustic pressure at the nodes, the levitator is capable of stably supporting drops up to approximately 2.4-mm in diameter [2].

The water samples used in the present data are tap water, with an absorptivity of 14.1 m⁻¹ at 1070-nm measured using a Jasco NIR spectrometer. The light source is an IPG continuous wave fiber laser with a wavelength of 1070-nm, power of 105 W, and a beam diameter of approximately 5-mm. Drop imaging is achieved using a Hamamatsu ORCA Flash2.8 CMOS scientific camera with a Navatar macro lens. The Hamamatsu is equipped with an IR filter to protect the instrument, and extra ambient lighting is supplied through either a pair of 500W halogen bulbs or a pair of 500W equivalent LED spotlights. After passing through the drop interrogation region, the laser beam passes through an optical wedge and a series of ND filters before the beam is profiled using a Spiricon beam profiler with 1600 x 1200 pixels at full resolution. A schematic of the experimental setup is shown in Fig. 1 below, and a sample drop image is shown in Fig. 2.

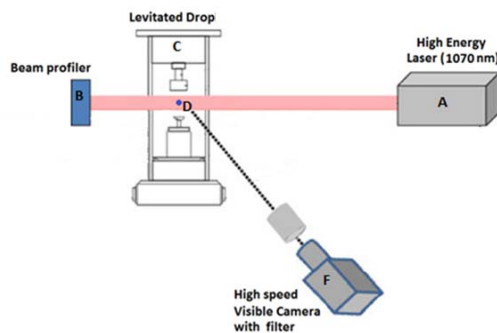


Fig. 1 – Experiment schematic

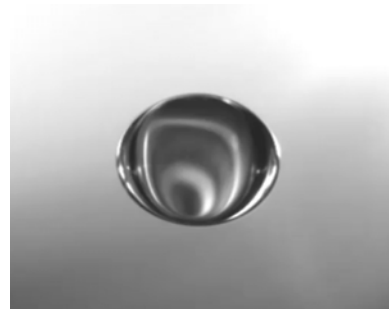


Fig. 2 – Nearly-spherical drop in levitator

The experiments shown here consist of drops with an initial size of approximately 1-mm, centered on the laser beam, which is operating at full power of 105-W. The levitator causes some distortion of the drop, making the horizontal diameter slightly larger than the vertical diameter. The range of major to minor drop diameter for these experiments is typically $H/D \approx 1.05$, and this value tends towards 1.00 as the drop evaporates and shrinks. Experimental runs typically last 40-sec or more, assuming the drop is not lost from the levitator. When placing the drop in the levitator, care is taken to reduce the probability of introducing trapped gases inside the drop, which result in instability of the drop during irradiation.

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RESULTS

A few interesting qualitative results have been found from observing the drop evaporation. First, strong convective processes within the drop are visible during and after irradiation. Small vapor bubbles within the drop arrange along vortex lines, and can be seen circulating in an apparently turbulent manner. The speed of this circulation has not been quantified, but the dissipation of kinetic energy within the drop after the end of the laser strike is also observable. This is in contrast to laser heating of aerosols, which is characterized by either a slow diffusive heating regime dominated by thermal diffusion, or a fast, explosive regime controlled by the pressure wave from fluid that has exceeded the superheat limit. A second observation is that when the ellipticity of the sphere is particularly large (due to tuning or “over-tightening” of the levitator’s reflector) vapor bubbles can be seen escaping from the top of the drop as would be expected with nucleate boiling. This has not been observed with more spherical drops.

Unexpectedly, vaporization appears to begin immediately after the beginning of the laser strike, with no clear sensible heating phase. Because the drops are initially at room temperature, some delay in the onset of phase change (determined from the rate of change of the drop size) was expected. The irradiance of the laser, with a mean value of approximately 530 W/cm^2 , is unlikely to provide enough energy for any part of the drop to reach the superheat limit in the first few seconds of exposure, or for the drop as a whole to reach saturation within the same timeframe. Along with the observation of vigorous mixing within the drop, this is therefore a somewhat surprising finding.

From the video data of the irradiated drop, major and minor drop diameters were calculated throughout the process to produce a time history of drop volume. Figure 3 below shows the results from eight different runs, each lasting 40-s or more. The run-to-run repeatability is good, suggesting that changes in absorptivity from one liquid sample to the next are small. The outliers in the data are due to instability of the drop within the levitator. Occasionally during a laser strike, likely due to the formation and release of a vapor bubble, the drop will shake or oscillate around the acoustic node for a second or two before stability is re-established. Because these movements are very fast, the drop images can appear blurry and measurement accuracy of drop size is temporarily reduced. The decay in drop size vs time is not exponential, so it is characterized with a half-life value found to be 18.3-s for the laser at full power. This number agrees with a half-life of 20-s calculated from a simple 1-D numerical model that assumes uniform irradiance, an initially saturated drop, and approximates the drop as a thin film normal to the incoming laser (see Fig. 4).

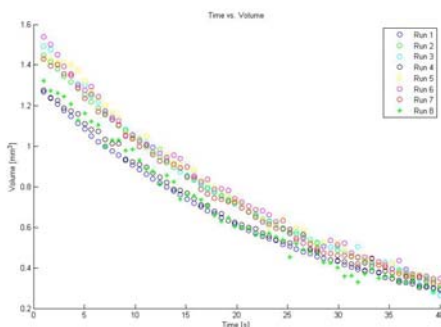


Fig. 3 – Drop volume vs time for eight water samples

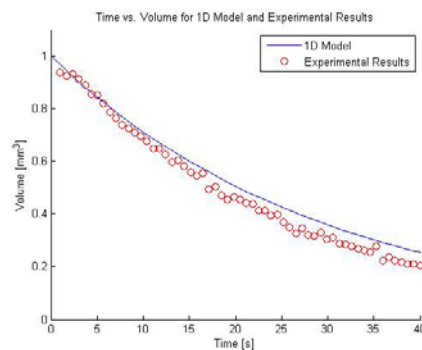


Fig. 4 – Comparison of data and 1-D model

CONCLUSIONS

Acoustic levitation is a promising method for the study of laser heating of spherical water drops. Results show good sample-to-sample repeatability, and agreement with a simple 1-D model. Effects of drop size and irradiance on convection within the drop require further study, as does the effect of the drop (and the escaped water vapor) on the beam profile.

ACKNOWLEDGEMENTS

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References

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- [2] “Basics About Ultrasonic Levitation.” In *Ultrasonic Levitator Manual*, tec5 – Technology for Spectroscopy, 2014.