Laser-Induced Bubbles in Glycerol-Water Mixtures

Allison R. McCarn, Erin M. Englert, and Gary A. Williams
Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA

Abstract

In order to study the effect of viscosity on bubbles in a cavitating fluid, the properties of laser-induced bubbles and the resulting luminescence pulses are examined for various glycerol-water mixtures over 1-8 bars of pressure. Bubbles are generated by a Nd:YAG laser, with the bubble radius monitored by a laser-beam photodiode system and the luminescence structure measured by fast photomultiplier. Observable luminescence disappears at 75% volume glycerol solution, and luminescence is found to be more common at higher pressures and lower glycerol concentrations. The bubbles are seen to oscillate more in the glycerol mixtures than in water, and the maximum radius of the bubble appears to decrease with concentration.

I.   Introduction

The mechanism by which laser-induced bubbles in a fluid collapse and generate a luminescence pulse is still not entirely understood. The general theory on how this occurs involves the vaporization of the fluid to create a bubble, with a subsequent adiabatic collapse which heats up the interior of the bubble to ~ 10,000K, ionizing the gas in the interior. At the minimum radius, an acoustic shockwave is thought to be emitted, along with the characteristic luminescence pulse from the free electrons I n the ionized gas.

Most of the research in the field of laser-induced luminescence has involved luminescence in water [1] and salt solutions [4]. In order to better understand the conditions required for luminescence to occur, we decided to study how the viscosity of the fluid used for cavitation affects the luminescence. To this end, we used glycerol-water mixtures. Glycerol and water are miscible, so the viscosity of the solution could be easily varied simply by varying the concentration of glycerol in the mixture. The concentrations studied were 0, 16, 25, 33, 50, 60, 75, and 100 % volume glycerol at pressures ranging from 1 to 8 bars. We studied the nature and frequency of luminescence, as well as the dynamics of bubbles created in solutions of increasing viscosity.

II. Apparatus

Two setups were used in the taking of the data. In both, bubbles were generated in an airtight, stainless steel cell formed from a cubical block with sides of 68mm. Three of the four side holes were fitted with 2.5 cm diameter, millimeter thick, quartz windows, which were affixed with epoxy to mounting flanges and sealed to the cell with rubber O-rings. The fourth side hole was fixed similarly, but with a stainless steel wall instead of a window. The bottom hole is fixed in the same way with a 30 mm diameter lens with a focal length of 35 mm. The top of the cell is attached to a copper tube that allows the cell to be pressurized. The tube runs to a high purity dry nitrogen gas tank which is monitored by a Bourdon pressure gauge and is used to pressurize the cell up to 8 bars.

The laser used to form the bubbles in both setups is a Nd:YAG laser which sends out a 6 ns pulse when the Q-switch is triggered, at 1064 nm wavelength. The laser is deflected into the cell by a mirror below it and focused by the lens on the bottom side into the center of the cell.

In the first setup, pictured in figure 1, fast photomultipliers were set up on two of the three windows, and a slower photomultiplier was set up on the third window. The slower one was used to measure the collapse time, which was displayed on an HP oscilloscope, and the two faster ones were hooked to an Agilent 54820 oscilloscope and recorded the luminescence pulse. One photomultiplier was fitted with an optical density 2 filter, which transmits 1% of incident light, and later with an optical density 0.1 filter, which transmits 79% of incident light. The other was fitted with a low-pass filter.
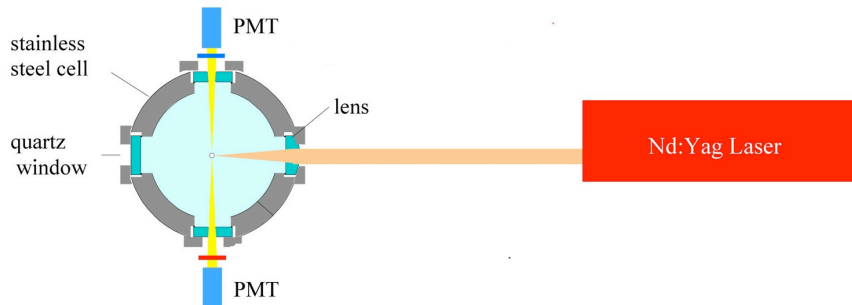

Figure 1: diagram of first setup

In the second setup, pictured in figure 2, an infrared laser was directed into the back window of the cell, through the region where the bubble was generated, and out of the front window into a lens that focused the laser onto an amplified photodiode. The photodiode read the radius of the bubble directly from the amount of laser light blocked from the photodiode as the bubble was formed. A fast photomultiplier was set up on the remaining window, and recorded the luminescence pulse in detail.
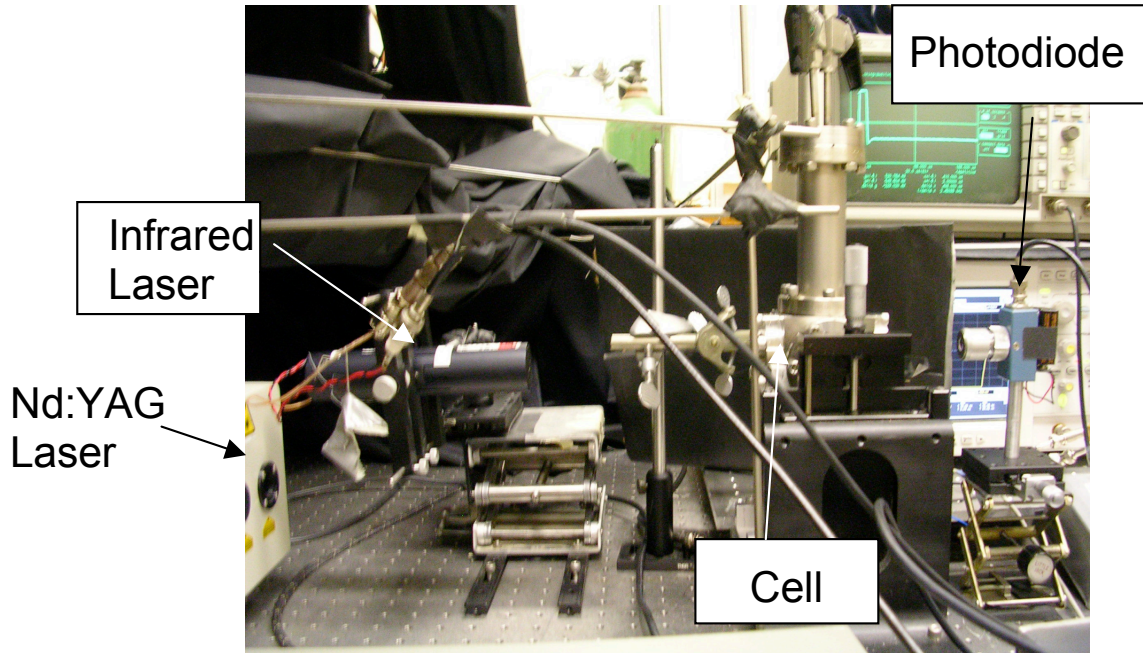
Figure 2: Photograph of second setup

The fluid inside of the cell was a mixture of triple-distilled water and glycerol with a purity of 99.9%. Bubbles were formed by increasing the power of the Nd:YAG laser slowly until the ionization pulse was just visible inside the cell. The bubbles were formed by vaporizing impurities in the solution, so there was some variation in the size of the bubbles, even in a single solution at a fixed pressure. The maximum radius of the bubbles was found from the recorded collapse time by using Rayleigh's formula for spherical bubbles [3],

$$R_m = 0.55\, T_c \sqrt{(p - p_v)/\rho}$$

where p is the pressure of the solution, p_v is the vapor pressure of the solution, ρ is the density of the solution, and T_c is the recorded collapse time. The bubbles created in this experiment are considered to be spherical because they are created in the center of the cell, reasonably far from boundaries, and because the laser pulses that create the bubbles are far shorter than the bubble collapse time.

II.   Results

Figure 3 shows the change in viscosity as a function of percent weight of glycerol. All of the measurements taken in the experiment were in percent volume, so the concentrations of all of the solutions used have been located accurately on the curve. The viscosity increases more per percent at higher concentrations of glycerol.
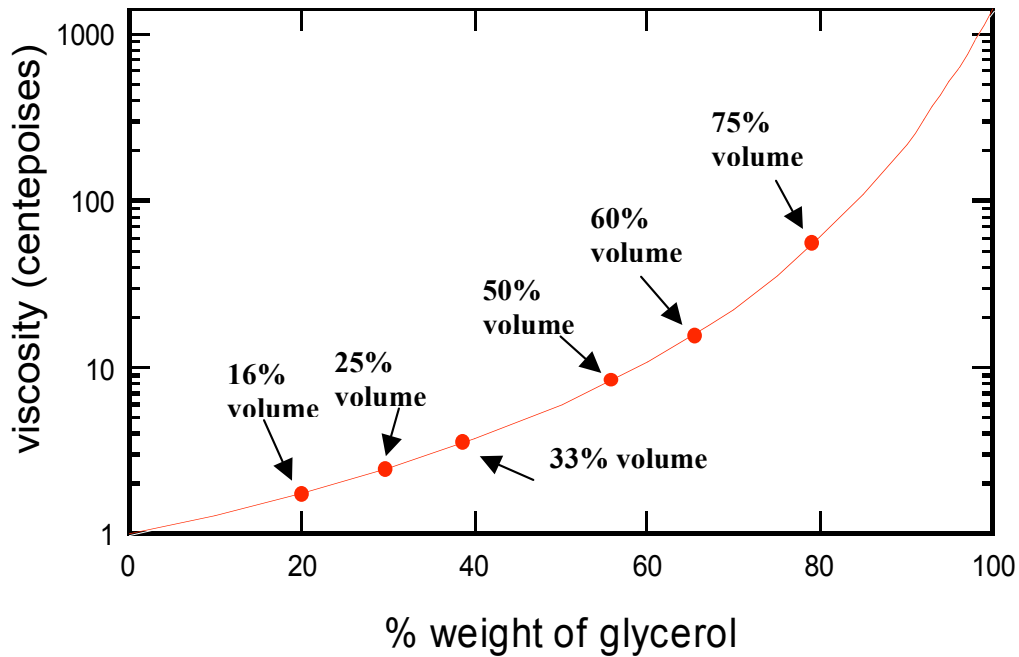
Figure 3: Viscosity of glycerol-water mixture as a function of the % weight of glycerol [2]

The highest concentration listed on the graph is 75% volume, since it was found that there ceases to be observable luminescence at 75% volume glycerol solutions. Non-luminescent bubbles, however, have still been recorded from 75% up to 100% glycerol. It is possible that luminescence could be occurring at 75% volume and higher, but if it is, it is too faint for fast photomultipliers to detect.
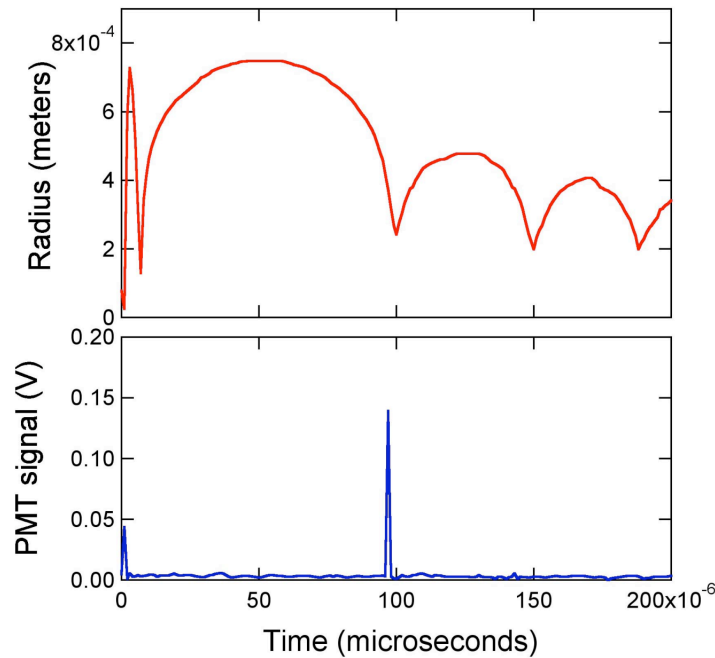

Fig. 4 Bubble radius versus time (upper) in a 16% solution, and photomultiplier signal showing the luminescence pulse at the first bubble collapse point.

Figure 4 shows the formation of a bubble in a 16% solution with two bars of external pressure applied. The laser pulse at t = 0 vaporizes the liquid and creates an expanding bubble that reaches a maximum radius of 0.75 mm and then begins to collapse. As it collapses the gas inside heats adiabatically, and at the minimum radius a fast luminescence flash is emitted. Figure 5 shows the luminescence pulse on an expanded time scale, indicating the full width at half maximum of the pulse, which is one of the parameters measured in this experiment, for different concentrations and pressures.
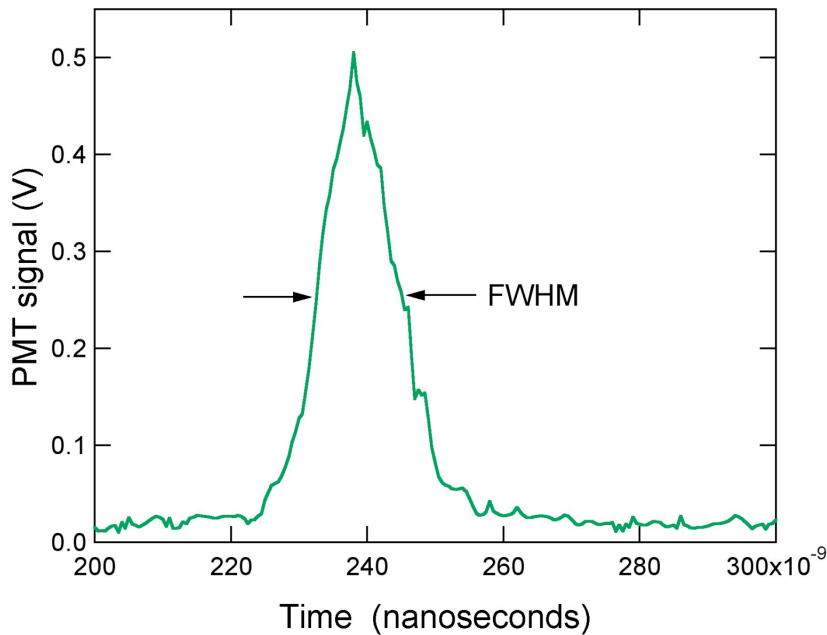

Fig. 5 Expanded view of the luminescence pulse from Fig. 4

Luminescence appeared to be more common at both lower concentrations of glycerol and higher pressures. This is perhaps due to the slowing effect of the viscosity on the collapse of the bubble. As concentration is increased, the slower collapse makes it increasingly less likely for the temperature inside of the bubble to become high enough at the minimum radius to result in a luminescence. At higher pressure, this may be due to the fact that pressure tends to speed up the bubble's growth and collapse, increasing adiabatic heating, leading to higher temperatures.

The slowing of the collapse of the bubble due to viscosity also affects the later oscillations of the bubble. Figure 6a shows the radius vs. time graph of a typical bubble in a glycerol-water mixture. This particular R(t) graph is from a mixture with 16% volume glycerol at two bars. Comparing it to figure 6b, an R(t) graph from a bubble created in water at the same pressure, it appears that the bubble in water has much less oscillation. When the bubble collapses more slowly, less energy in the form of sound is radiated out at the collapse, so the rebound of the bubble is more elastic, and it continues to oscillate for much longer than the bubble in water.
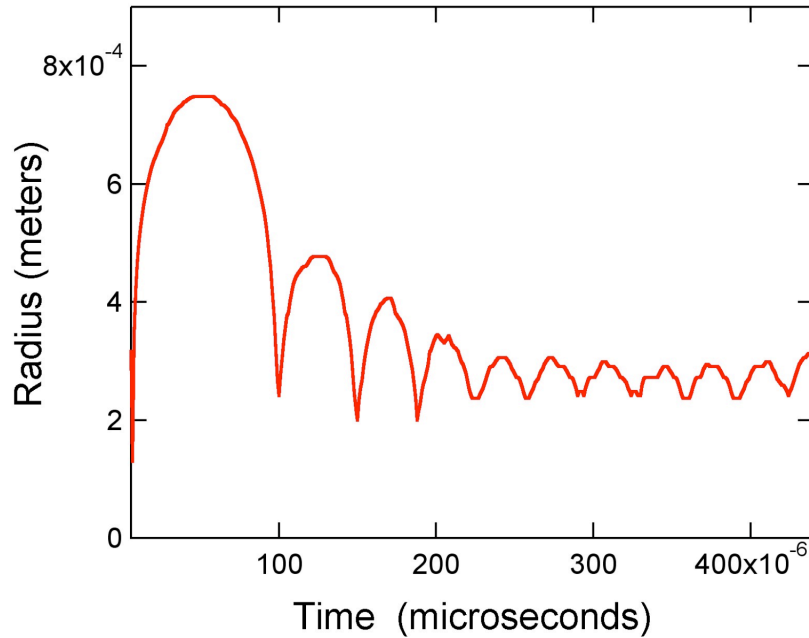
Figure 6a: R(t) graph of a bubble in 16% glycerol mixture at 2 bars pressure.
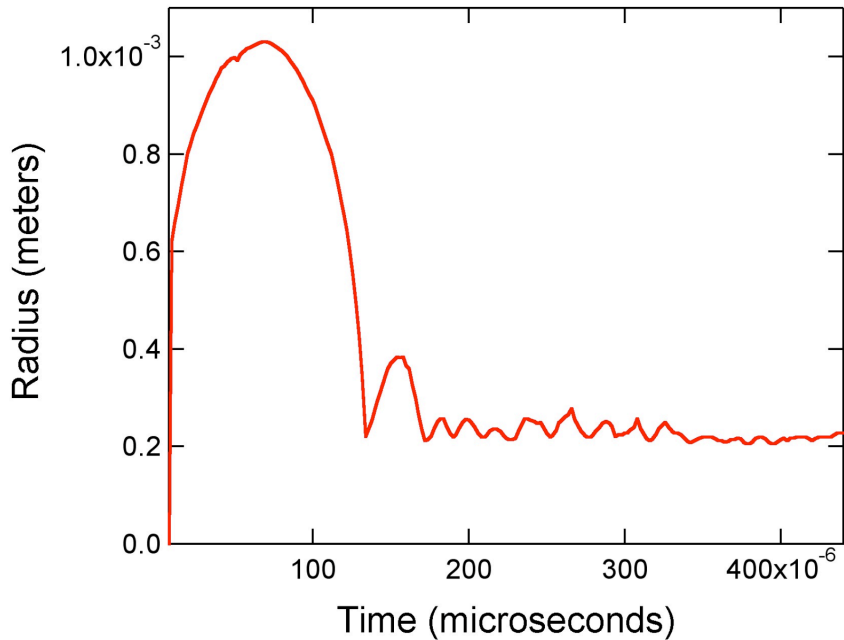

Figure 6b: R(t) graph of a bubble in water at 2 bars pressure.

In Figure 7, it is shown that there is a dependence on concentration for the maximum radius, as well. The maximum radius of the bubbles appears to decrease slightly with increasing concentration. This could be another result of viscosity on the bubble dynamics. As mentioned earlier, the exterior force of pressure decreases the time of the growth and collapse of a bubble. This process decreases the maximum radius. The viscosity of the fluid would also exert a radial force opposite to the direction of attempted

motion in the fluid, shortening the growth time of the bubble. Therefore, the observation of smaller bubbles could be due in part to an increase of viscosity.
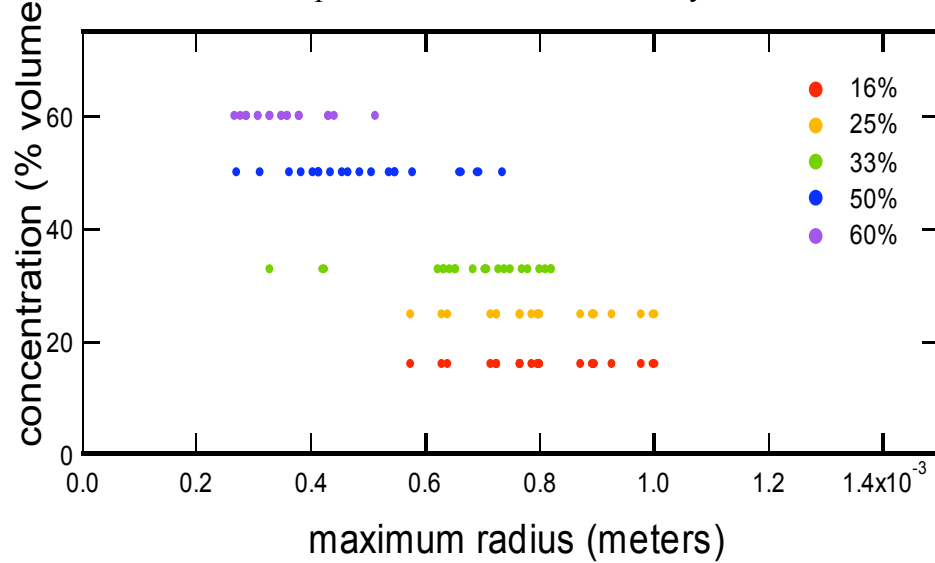

Figure 7: Concentration of glycerol vs. maximum radius.

In Figure 8, the pulse width is shown to be a linear function of maximum radius for a glycerol solution, with the slope increasing with increasing pressure. This is the same result as found for water in previous work [1], and appears to hold true for glycerol. Figure 9 shows that there is no clear correlation between concentration and pulse width. However, the pulse widths for solutions containing 16-60% glycerol appear to be greater than water. We currently have no explanation for this observation.
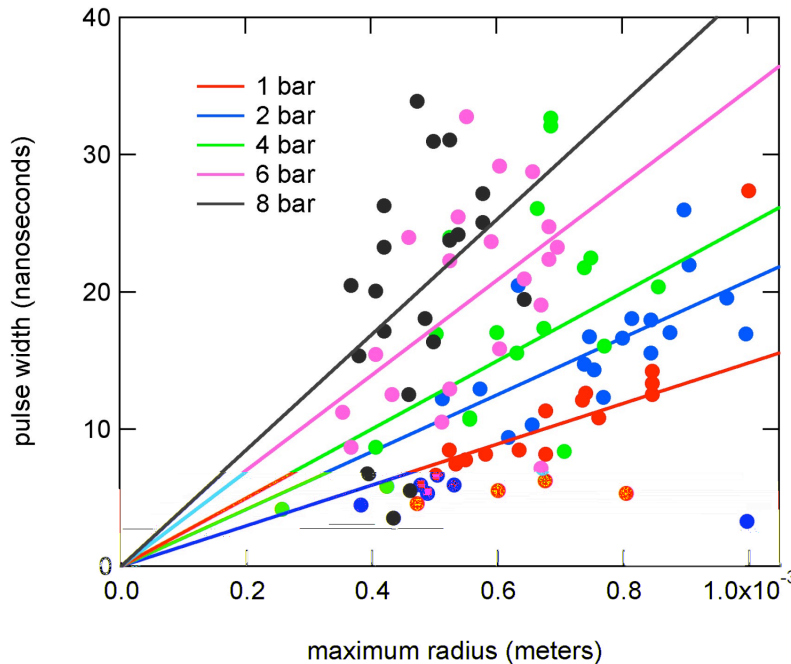

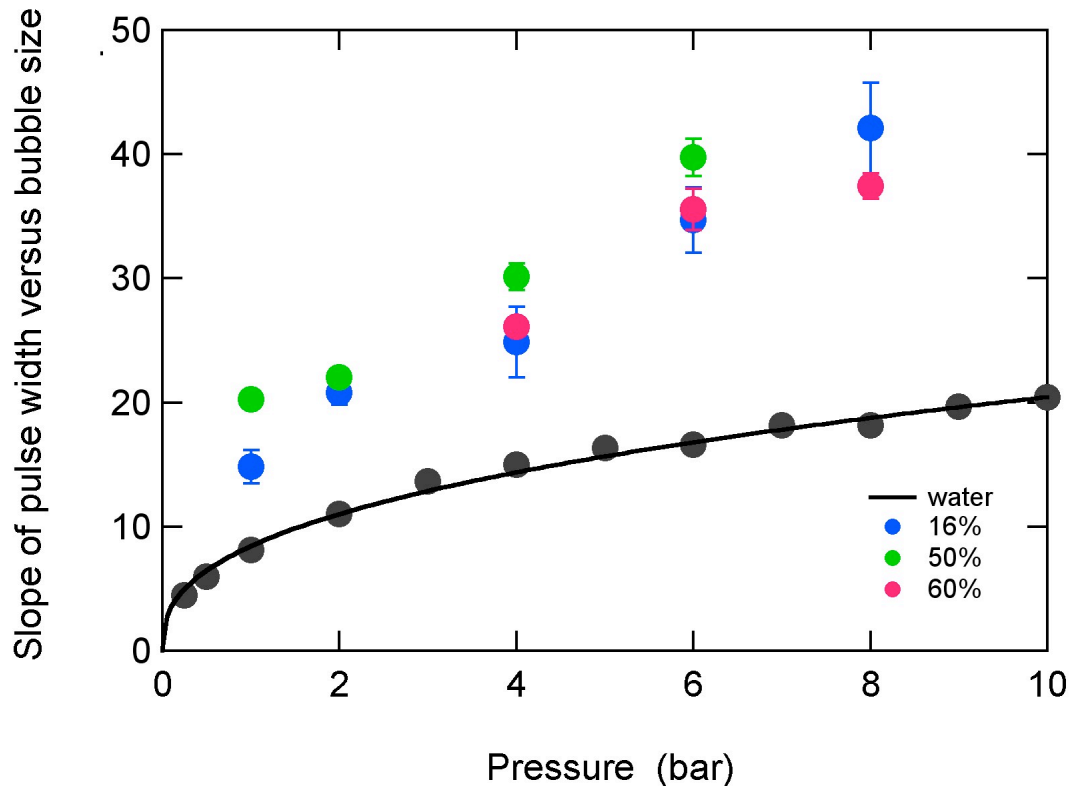Figure 8: Pulse width as a function of maximum radius for various pressures of 16% glycerol solution

Figure 9: Plot of pulse width/maximum radius versus pressure.

There were also differences from water results in the low concentration mixtures concerning the structure of the light pulses emitted. In water, it was noted in a previous paper [1] that double luminescence, where a bubble splits on its collapse and the resulting bubbles give off light pulses nanoseconds apart (Figure 8), only became common around 10 bars of pressure, though they were observed occasionally at lower pressures. In the case of glycerol-water mixtures, double luminescence was very frequent, especially at low concentrations of glycerol (16-25% volume), at pressures as low as 4 bars. It is not clear why this would happen.
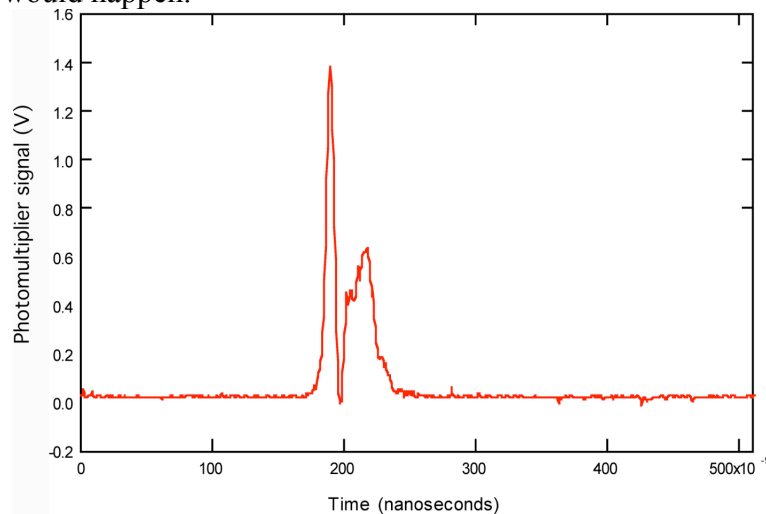

Figure 8: A double luminescence pulse at 16% and 6 bars pressure

III. Conclusions

We have measured the effects on bubble dynamics and luminescence properties of increasing the viscosity of the cavitating fluid in laser-induced luminescence. We have found that increasing the viscosity slows the collapse of the bubbles, resulting in less frequent luminescence and more radial oscillations. Luminescence appears to cease entirely at 75% volume glycerol. Increasing viscosity also decreases the maximum radius of the bubbles, but does not appear to have a clear correlation with the pulse width, at least for solutions of 16-60% glycerol. However, those solutions do appear to have longer pulse widths than water in general. There also appears to be a large number of double and multiple luminescences at lower glycerol concentration at pressures as low as 4 bars. The effects of viscosity on luminescence and cavitation are not completely understood, so we hope that this data will be useful in the future for theorists studying laser-induced luminescence in fluids of differing viscosity.

IV. Acknowledgements

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