LIF temperature measurements on cavitation bubble collapse

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Introduction

Single laser-induced bubbles in water are investigated with a focus on thermal effects. Upon collapse the temperature and pressure inside the bubble can attain extremely high values. This may lead to short light pulses being emitted by the collapsing bubble. The temperature inside the bubble is also important to chemical reactions (sonochemistry). Furthermore, heat conduction contributes to the damping of the bubble oscillation. However, experimental data on the liquid temperature close to a collapsing bubble is not available in the literature. We present an experiment for temperature measurements using the laser-induced fluorescence (LIF) method.

Fundamentals

An oscillating bubble in a liquid typically shows a slow growth phase followed by a rapid collapse [1]. Due to the strong collapse high temperatures are reached inside the bubble which will lead to heat transport from the bubble to the liquid. An approximate ODE model of a bubble in a sound field including heat transport is given in [2]. The authors find an increase in liquid temperature at the bubble wall of more than 10 K. The thickness of the thermal boundary layer can be estimated by assuming that it is infinitely thin in the beginning. After $t = 60\,\mu\text{s}$ the thickness of the thermal boundary layer in water will be $\sqrt{\alpha t} \approx 3\,\mu\text{m}$, where $\alpha = 1.46 \cdot 10^{-7}\,\text{m}^2\,\text{s}^{-1}$ is the thermal diffusivity of water. Thus, we need an experiment which is capable of detecting a temperature change of a few K inside a boundary layer which is a few µm thick.

The emission spectra of certain fluorescent dyes show a strong temperature dependence which can be exploited to measure the temperature in dye solutions. The emission intensity also depends on several other parameters (e. g. excitation intensity, dye concentration, pH, excitation wavelength). Their influence should be ruled out in the experiment. Fluctuations in the excitation intensity can be compensated by using a second dye. The ratio of the intensities of the two dyes Rhodamine B and Sulforhodamine 101

$$\frac{I_{\text{RhodB}}(x,y)}{I_{\text{SR101}}(x,y)} \propto T(x,y) \qquad (1)$$

also shows an increased temperature sensitivity when compared to a single dye. For details about the LIF method see [3] and [4].

Experimental setup

The two indicated fluorescent dyes are used in the experiment which is shown schematically in Fig. 1. Figure 2 shows the emission spectra for a solution of both dyes in deionized water. A bubble is produced by focusing a nanosecond laser pulse (Spectra Physics Quanta Ray PIV 400, $\lambda = 1064\,\text{nm}$, pulse length: 8 ns) into the cuvette filled with the solution (Rhodamine B: $1 \cdot 10^{-6}\,\text{mol/l}$, Sulforhodamine 101: $2 \cdot 10^{-6}\,\text{mol/l}$). A second laser pulse (Litron nano, $\lambda = 532\,\text{nm}$, pulse length: 4 ns) is used to form a light sheet which excites the two dyes. The fluorescent light is collected by a long-distance microscope (Infinity K2), separated with a dichroic beamsplitter, and then recorded using two cameras (PCO SensiCam qe) with bandpass filters attached. The colored wavelength regions in Fig. 2 correspond to the transmission bands of the filters (green: Rhodamine B, red: Sulforho-

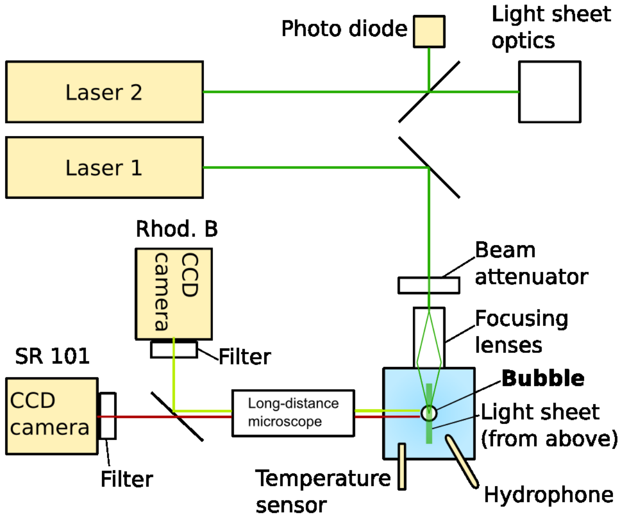

Figure 1: Experimental setup for LIF temperature measurements on laser-induced bubbles.

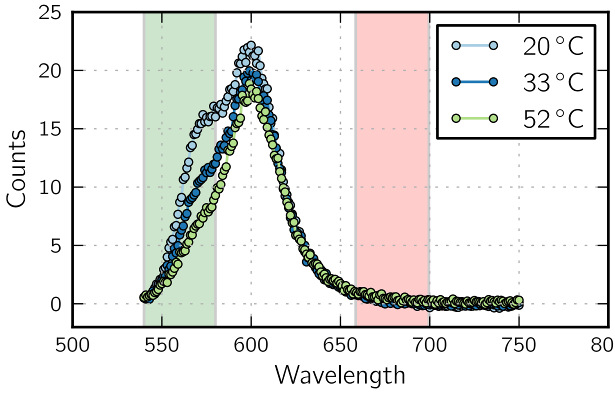

Figure 2: Emission spectra of a mixture of Rhodamine B and Sulforhodamine 101 in DI water at various temperatures.

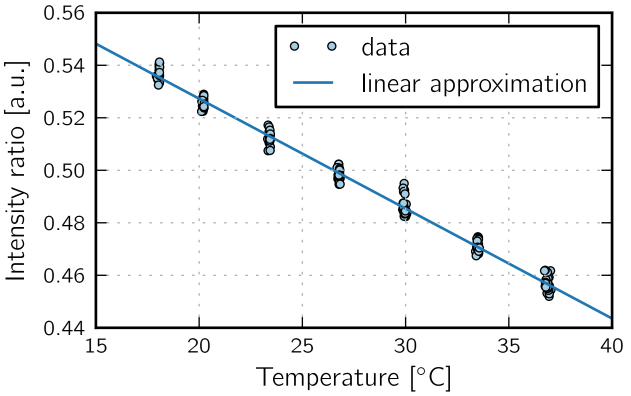

Figure 3: Calibration of Rhodamine B and Sulforhodamine 101 in DI water.

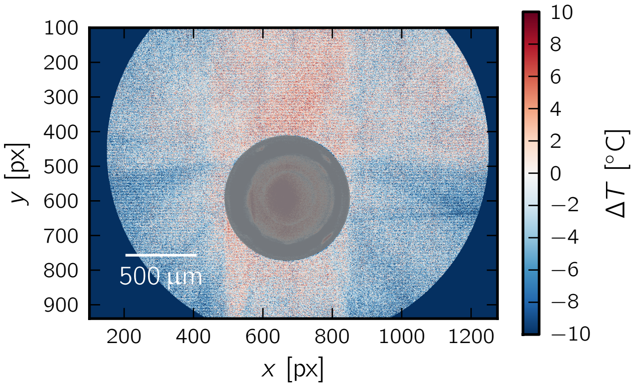

Figure 4: LIF image of a collapsing laser bubble at time $t_0 + 145\,\mu\mathrm{s}$. Collapse time: $77.5\,\mu\mathrm{s}$. The bubble is produced by a laser pulse at $t = t_0$.

damine 101). The ambient temperature of the solution is measured with a Pt100 sensor. The shock waves emitted upon generation and collapse of the bubble are recorded with a needle hydrophone.

One image of every laser-induced bubble is recorded with each of the two cameras. The delay time between bubble generation and camera exposure can be precisely adjusted to obtain images at various instants of the bubble oscillation. A dark image is subtracted from all the images taken with the two cameras, and the intensity ratio of the two fluorescent dyes is computed according to Eq. (1) for all the pixels in the images.

In order to calibrate the fluorescence intensity to the temperature the dye solution is heated using a thermostat and the temperature is measured with a Pt100 sensor. Images of the fluorescent light are taken with the two cameras at various temperatures.

Results

The calibration curve (Fig. 3) shows a linear decrease in the fluorescence intensity ratio with increasing temperature. The linear approximation yields a temperature sensitivity of $-0.004/{}^\circ\mathrm{C}$. In Fig. 4 an example of a LIF measurement result is shown for a laser-induced bubble ($R_{\max} = 459\,\mu\mathrm{m}$). The temperature change with respect to the ambient liquid temperature is shown as computed from the LIF data. The field of view is limited due to vignetting. Therefore a circular mask is used to mask the outer regions of the image. Due to reflection and refraction of light on the bubble surface there are some artifacts in the LIF image. Only the region above the bubble ($100 < y < 411$) contains meaningful temperature data. A cross-section through the bubble is shown in Fig. 5, where the grey area denotes the bubble. Apart from fluctuations in the range of ±8 °C the temperature is constant up to the bubble wall.

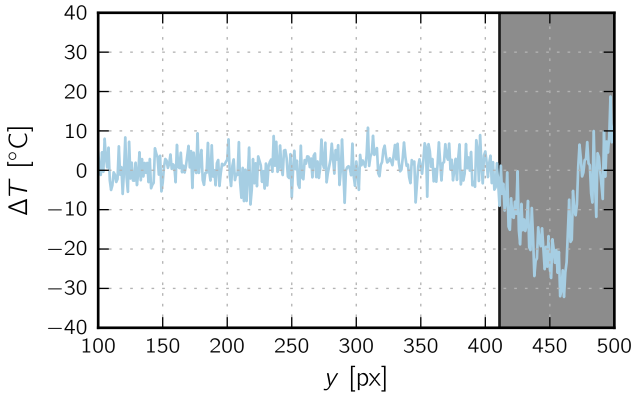

Figure 5: Cross-section along the line $x = 668$ of Fig. 4.

Conclusions

The calibration shows a linear dependence of the fluorescence intensity ratio on the temperature. Fluctuations in the pulse energy of the excitation laser are compensated by using a second dye. However, the camera noise has an impact on the measurement data because the fluorescent light is very weak. In the case of single laser-induced bubbles no significant temperature changes larger than the noise level are observed. The amount of heat transported from the bubble to the liquid seems to be very small. The resolution of $2.5\,\mu\mathrm{m}$ per pixel is on the order of the boundary layer thickness. A higher magnification is required to fully resolve the thermal boundary layer. In the near future we will carry out LIF measurements on a single bubble in a sound field. In this case temperature changes are probably visible more clearly.

References

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