Investigation of thermal effects during single bubble collapse using laser-induced fluorescence and high speed videography

Hendrik Söhnholz[1], Thomas Kurz
Drittes Physikalisches Institut, Universität Göttingen, 37077 Göttingen, Deutschland
[1] *Email: hendrik.soehnholz@phys.uni-goettingen.de*

Introduction

Thermal effects during the oscillation of single bubbles in water are investigated experimentally. We are interested in heat transport across the bubble wall during single bubble collapse. Therefore, the temperature in the water close to a single bubble is measured using laser-induced fluorescence (LIF). These measurements are carried out on laser-induced bubbles as well as on bubbles in a sound field.

The influence of the water temperature on the bubble dynamics is investigated in a separate experiment. Single laser-induced bubbles are observed at various water temperatures, especially above 20 °C. Bubble dynamics changes considerably at elevated water temperatures, mainly due to the increased vapour content.

Fundamentals

Bubble dynamics

A gas/vapour bubble oscillating in water typically shows a slow growth phase followed by a rapid collapse [1]. During collapse the bubble is strongly compressed which leads to high pressures and high temperatures inside. The temperature difference may cause heat transport across the bubble wall. Assuming a collapse time of $t = 60\,\mu\mathrm{s}$ we obtain a thickness of the thermal boundary layer of $\sqrt{\alpha t} \approx 3\,\mu\mathrm{m}$ with $\alpha = 1.46 \cdot 10^{-7}\,\mathrm{m^2\,s^{-1}}$ being the thermal diffusivity of water. One can expect a temperature increase of a few Kelvin inside the boundary layer. When a bubble is excited by an external sound field it can be trapped at a sound pressure antinode. Under certain conditions (gas content, temperature, sound frequency, spherical collapse, ...) the bubble will emit a short flash during each collapse (SBSL). The vapour pressure of water increases significantly with temperature. This leads to bubbles with a high vapour content at elevated temperatures. The dynamics of these bubbles is very different from that of bubbles at low liquid temperatures.

Laser-induced fluorescence (LIF)

The emission spectra of certain fluorescent dyes show a strong temperature dependence which can be exploited to measure the temperature T in dye solutions. The emission spectra also depend on other parameters like concentration, excitation intensity, excitation wavelength, and pH of the solution. These parameters should be fixed during the measurements. Fluctuations in the excitation intensity can be compensated by adding a second,

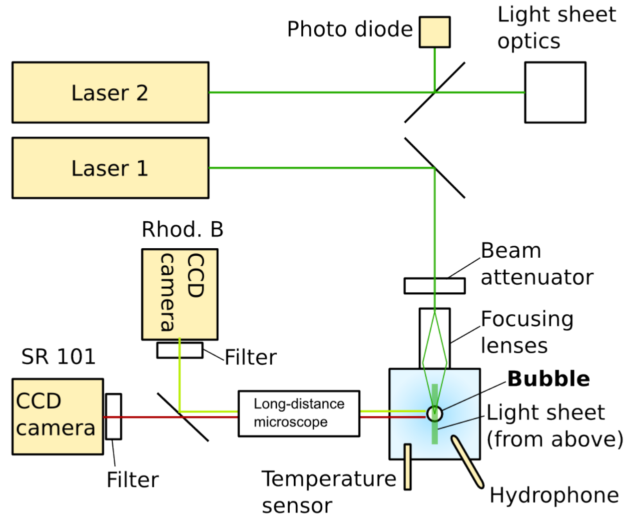

Figure 1: Experimental setup for LIF temperature measurements on laser-induced bubbles.

temperature-independent, dye to the solution. The ratio of the emission intensities of the two dyes Rhodamine B and Sulforhodamine 101,

$$\frac{I_{\mathrm{RhodB}}(x,y)}{I_{\mathrm{SR101}}(x,y)} \propto T(x,y) \quad , \tag{1}$$

shows an increased temperature sensitivity. More information on the LIF method is available in [2] and [3].

Laser-induced fluorescence measurements on laser-induced bubbles

In the experiment which is shown in Fig. 1 the two indicated dyes are dissolved in deionized water. The temperature dependence of Rhodamine B is very strong whereas that of Sulforhodamine 101 is negligible. The emission spectra for a solution of both dyes in deionized water at different temperatures are shown in Fig. 2. A bubble is produced by focusing a laser pulse (Spectra Physics Quanta Ray PIV 400, $\lambda = 1064\,\mathrm{nm}$, pulse length: 8 ns) into the cuvette filled with the dye solution. A second laser pulse (Litron nano, $\lambda = 532\,\mathrm{nm}$, 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: Sulforhodamine 101). The temperature of the solution is

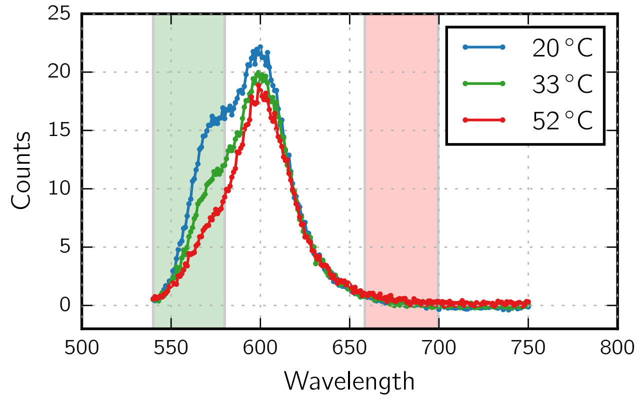

Figure 2: Emission spectra of a mixture of Rhodamine B and Sulforhodamine 101 in DI water at various temperatures.

monitored with a Pt100 sensor. Acoustic emissions from the bubble are recorded with a needle hydrophone.

Laser-induced fluorescence measurements on single bubbles in a sound field

A similar experimental setup is used for LIF measurements on single bubbles in a sound field. A bubble is produced with a syringe and then levitated at the centre of a glass cuvette (50 mm×50 mm×50 mm). A piezo disc glued to the bottom of the cuvette generates a sound field with a frequency of $f \approx 24$ kHz. A single dye, Sulforhodamine 101, is dissolved in deionized water and excited by a pulsed laser light sheet (Litron nano, $\lambda = 532$ nm, pulse length: 4 ns). The fluorescent light is recorded by a camera (PCO SensiCam qe) at a rate of 2 Hz. The bubble collapses many times while oscillating in the sound field as opposed to a freely oscillating laser-induced bubble which undergoes only a few collapses. Moreover, the bubble in the sound field of about 24 kHz is much smaller than the bubbles produced by nanosecond laser pulses. In any case, the light sheet is positioned centrally to the bubble.

Laser-induced bubbles at elevated water temperatures

A special cuvette with temperature control has been constructed for this experiment (Fig. 3). It consists of an inner glass cuvette (40 mm×40 mm×40 mm) and an outer cuvette made of polycarbonate. The inner cuvette is filled with clean deionized water, the outer cuvette is connected to a thermostat containing deionized water. During the measurements hot water flows through the outer cuvette which also heats the water in the inner cuvette. However, there is no flow inside the inner cuvette which would disturb the bubble oscillation. A bubble is produced by focusing a laser pulse (Spectra Physics Quanta Ray PIV 400, $\lambda = 532$ nm, pulse length: 8 ns) into the inner cuvette. The focusing lenses are aligned carefully in order to obtain highly spherical bubbles. High speed videos of the bubble dynamics are recorded with a long-distance microscope (Infinity K2) mounted on a fast camera (Photron SA5). The bubble is illuminated from the

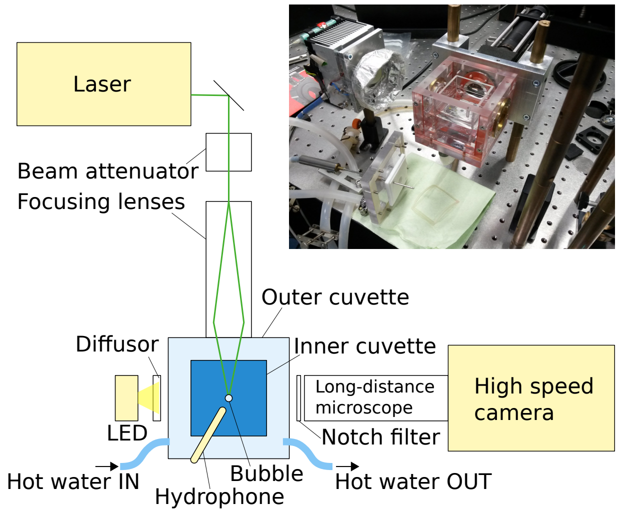

Figure 3: Experimental setup for observing laser-induced bubbles at different water temperatures.

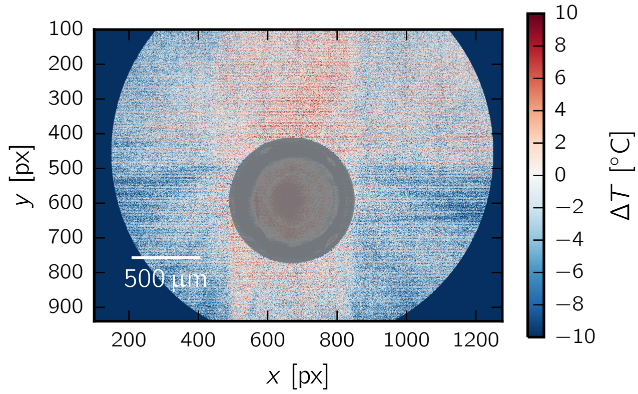

Figure 4: LIF image of a collapsing laser bubble at time $t_0 + 145$ µs. Collapse time: 77.5 µs. The bubble is produced by a laser pulse at $t = t_0$.

back by a bright LED. The laser wavelength is blocked by a notch filter attached to the long-distance microscope. The shock waves emitted by the bubble are measured with a needle hydrophone. Measurements are carried out at various water temperatures ranging from 10 °C to 80 °C. The experimental data are compared to numerical calculations with a modified Gilmore model including water vapour and heat conduction [5]. The model consists of a system of three ordinary differential equations which are solved by the `odeint` solver included in the SciPy library [6].

Results

In order to obtain the temperature from the recorded fluorescence images they need to be processed in a computer. In addition, a calibration of the fluorescence intensity to the temperature is required [4]. Figure 4 shows an example of a LIF measurement result for a laser-induced bubble ($R_{\max} = 459$ µm). The temperature change with respect to the ambient liquid temperature is plotted as computed from the LIF data. Due to vignetting the field

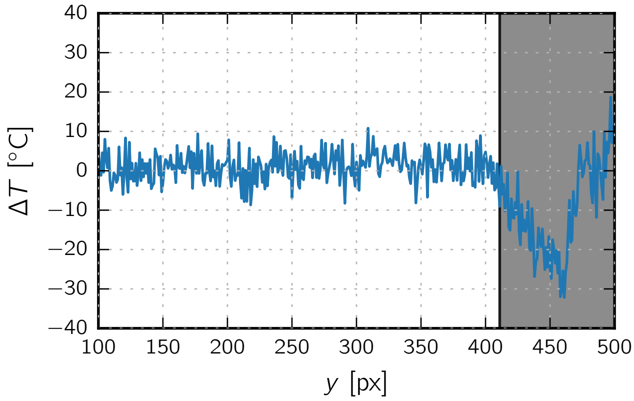

Figure 5: Cross-section along the line $x = 668$ of Fig. 4.

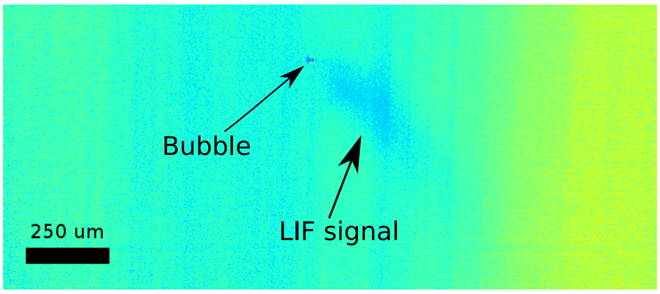

Figure 6: LIF measurement on a single bubble in a sound field ($f = 24.2\,\mathrm{kHz}$).

of view is limited and a circular mask is used to mask the outer regions of the image. Reflection and refraction of light on the bubble surface induce 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.

An example of a LIF measurement on a single bubble in a sound field is shown in Fig. 6. The camera image exhibits a strong signal in the vicinity of the bubble. However, there are multiple causes for a change in fluorescence intensity. During the collapse, OH radicals might have formed which then lead to quenching of the dye. A temperature increase is also one possible reason for the decreased fluorescence intensity. Further experiments are needed to clarify the cause for the change in LIF intensity.

The bubble radius is measured by a Matlab program in all frames of the high speed videos. The resulting radius–time data at four different temperatures are shown in Fig. 7. At elevated water temperatures the collapse is slower and softer, the collapse time is extended, and the rebound is much stronger. This originates from the increased vapour pressure of water at high temperatures. The hydrophone signal does not have a clear temperature dependence. The numerical results show a good agreement to the experimental data up to the second collapse. From then on the bubble radius is overestimated by the

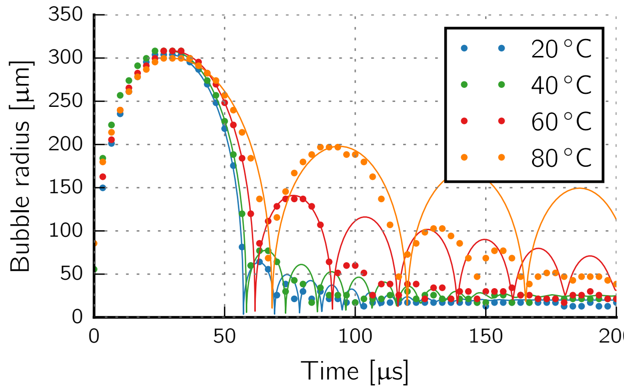

Figure 7: Bubble radius vs. time at four different water temperatures.

model because phase transitions are not included.

Conclusions

The LIF temperature measurements on laser-induced bubbles do not show a thermal boundary layer. Therefore, we conclude that the amount of heat transported from a laser-induced bubble to the surrounding liquid is very low. A laser-induced bubble collapses only a few times and then dissolves in the liquid. We assume that the amount of energy used for shock wave emission is much higher than the energy loss by heat transport. In contrast, a single bubble in a sound field collapses many times and can heat up the liquid over time. The LIF measurements show a strong decrease in fluorescence intensity. The origin of this decrease has to be identified in further experiments. Laser-induced bubbles at elevated temperatures exhibit a softer collapse as well as a much stronger rebound. This may have a bearing on cavitation erosion or ultrasonic cleaning applications. The numerical calculations already conform well to the experimental data. In the next step, phase transitions should be included in the model to get a good agreement even beyond the second collapse.

References

[1] Lauterborn, W. and Kurz, T.: Physics of bubble oscillations. Rep. Prog. Phys. 73 (2010), 106501

[2] Crimaldi, J. P.: Planar laser induced fluorescence in aqueous flows. Exp. Fluids 44 (2008), 851–863

[3] Natrajan, V. K. and Christensen, K. T.: Two-color laser-induced fluorescent thermometry for microfluidic systems. Meas. Sci. Technol. 20 (2009), 015401

[4] Söhnholz, H. and Kurz, T.: LIF temperature measurements on cavitation bubble collapse. DAGA, Oldenburg (2014), 708–709

[5] Eick, I.: Experimentelle und numerische Untersuchungen zur Dynamik sphärischer und asphärischer Kavitationsblasen. Dissertation. Technische Hochschule Darmstadt (1992)

[6] SciPy, URL: `http://scipy.org/`