Untersuchungen zur Rolle von ’fast jet’ und Kollaps-Stoßwelle bei Kavitationserosion

Investigation on the role of the ’fast jet’ and the collpase shockwave on cavitation erosion

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Introduction

The main phenomena considered for the erosive power of collapsing cavitation bubbles are the liquid jet and the emitted shockwaves. However, details of the processes leading to material damage still need further clarification. For experimental investigations, single, laser pulse generated bubbles close to a solid wall have been employed since decades. Such a bubble expands to a maximum radius $R_{\max}$ and then collapses violently, driven by the ambient pressure. It produces a liquid jet directed towards the solid wall when the initial distance between the wall and the bubble, D_{init}, is about 10 times $R_{\max}$ or less. The bubble would attain a maximum radius of $R_{\max,\text{unbound}} \neq R_{\max}$ in an unbounded liquid for the same energy. When being close to an object or boundary, $R_{\max}$ will differ from $R_{\max,\text{unbound}}$ due to the flow restrictions by the object. Therefore, a unique normalisation parameter

$$D^* = D_{\text{init}}/R_{\max,\text{unbound}} \tag{1}$$

was defined in [5]. Historically, the range of $D^* \in [0.3, \approx 10]$ was investigated where jet velocities in the order of 100 m/s develop (see e.g. [8]). However, only recently it was found by numerical simulations in axis symmetry that in the range $D^* < 0.2$ another jet formation mechanism takes place that drives a jet with velocities in the order of 1000 m/s [6, 7], the *fast jet*. Simulations in full 3D confirmed the numerical stability of the phenomenon and a direct comparison of the full 3D simulations to experimental results confirmed the existence of the fast jet [3, 4].

In this work the major results of [3, 4] are shown and elaborated on the question whether this newly found jet phenomenon is a candidate for erosion. The results presented here mainly deal with a bubble of $R_{\max,\text{unbound}} \approx 500\,\mu\text{m}$. The question whether the fast jet is a stable phenomenon concerning the initial bubble shape is answered in the manuscript by C. Lechner et al. with the title “Jet formation of non-spherical bubbles close to solid boundaries” in this conference proceedings (note the different notation, $R_{\max,\text{unbound}}$ is called $R_{\max}$ there).

Results

When a bubble expands and collapses at $D^* = 0.06$ with an $R_{\max,\text{unbound}} \approx 500\,\mu\text{m}$ it attains the shape shown in Fig. 1 during collapse. As described in [7], the main cause for the bubble shape with the respective kinks in the interface roots in the viscous boundary layer that forms during the expansion phase at the solid wall. During bubble collapse, an annular inflow is generated due to *flow focusing*, i.e. the interface parts with the highest curvatures collapse first. The second frame shows an instant shortly before annular jet impact onto the axis of symmetry. The annular inflow is seen in the region where the magnitude of the velocity is about 90 m/s. Due to the overall liquid motion of the collapse, the fast jet is mainly produced in the direction towards the solid wall, when the annular inflow impacts. In the case of Fig. 1, the jet starts with a velocity of 919 m/s in the numerical simulation. However, this speed depends on the numerical grid resolution. A grid convergence study has been performed in axis symmetry in [6], but convergence could not be achieved, since the annular impact is a nearly singular phenomenon. In full 3D a pseudo grid-convergence study has been carried out in [3], as shown in Fig. 2, top frame. The simulation has been calculated until $t = 109.864\,\mu\text{s}$ and restarted with different grid resolutions from there. The maximum jet velocity ranges from about 900 m/s (2 µm resolution) to 1000 m/s (1.8 µm resolution). The jet is accelerated to the maximum velocity within a time interval of about 20 ns. The bottom frames of Fig. 2 show the interface and liquid velocity of the full 3D bubble during jet impact onto the solid wall.

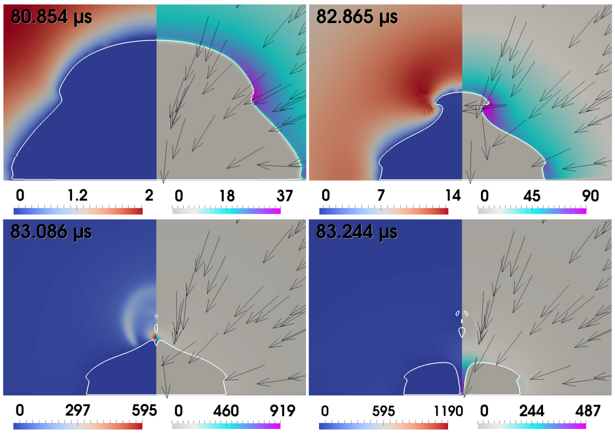

Figure 1: Four frames of an axisymmetric simulation of a cavitation bubble at $D^* = 0.06$. Left side: pressure (bar), right side: velocity of the liquid (m/s). Frames taken from [3], Fig. 5.9

In order to determine, whether the fast jet is a real phe-

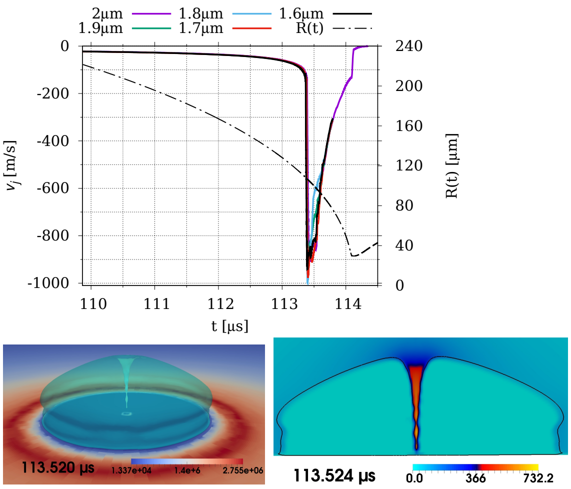

Figure 2: Top: Pseudo grid-convergence study in full 3D starting about 3.5 µs before jet formation. bottom left: Bubble shape with fast jet in full 3D. Bottom right: Cross section through the bubble on the left with denoted liquid velocity.

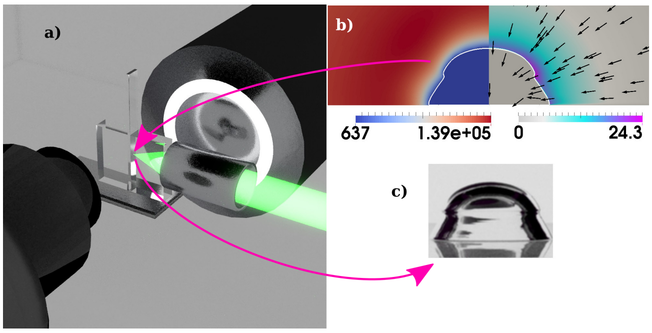

Figure 3: a) virtualized setup with objective, cuvette, flash and bubble (taken from [3, 4]) b) simulation of the bubble c) ray traced simulation

nomenon, an experiment was designed using an Imacon 468 Mfps high-speed camera and a laser seeded bubble in a cuvette. However, due to the refraction of light at the highly curved bubble interface, a method was developed to decipher what happens inside the bubble. Fig. 3 shows the sketch of the principle of the method published in [3, 4]. The experiment has been set up virtually in a ray tracing software [1]. The interface of the bubble that has been obtained from the simulation is inserted into the virtual setup. In this way, an image can be rendered that looks quite as if it was taken from the experiment. The experimental image then can be compared to the ray-tracing image and the physics can be inferred when there is a match.

Fig. 6 shows the sequence of a bubble generated at the solid wall. The odd rows show the experimental results, the even rows show the ray-traced images from the full 3D simulation. Since the camera produces 8 images per measurement and the measurements were repeatable, results of 7 measurements appear in the image, in order to extrapolate and interpolate the dynamics obtained by a single measurement only. The respective measurement number is denoted in brackets above the frame, as well as the time after triggering the camera. The trigger delay with respect to the plasma generation by the laser varied between the measurements. Exposure time of the experimental frames is 150 ns, except for the first frame with the plasma, which has an exposure time of 500 ns and is enhanced in contrast. From the fit with the numerical simulation it can be deduced that an exposure time of 150 ns still leads to blurring of the image during fast jet motion, because of significant changes in the shape during this interval. The proof that there is a fast jet in the experiment is seen in the magnification (bottom two rows in Fig. 6). The bubble is indeed pierced by a black shadow through the middle.

To judge the erosion potential of the phenomenon, axisymmetric simulations have been performed for several D^*, while monitoring the pressure in the symmetry point at the solid wall [3]. In Fig. 4 the average pressure during jet impact and the peak pressure during the whole cycle of collapse and rebound is shown as a function of D^*. The maximum, quasi-static yield stress that metals and metallic materials endure is about 600 MPa. The average pressure due to the fast jet impacting on the solid wall is still below that threshold. However, 250 MPa are reached, which might be sufficient to erode soft alloys. The peak pressure, on the other hand exceeds 3 500 MPa at $D^* = 0.1$. The reason is the focusing of the torus collapse shockwave. Both numbers are not precise in terms of grid-convergence, however they can be considered as a trend.

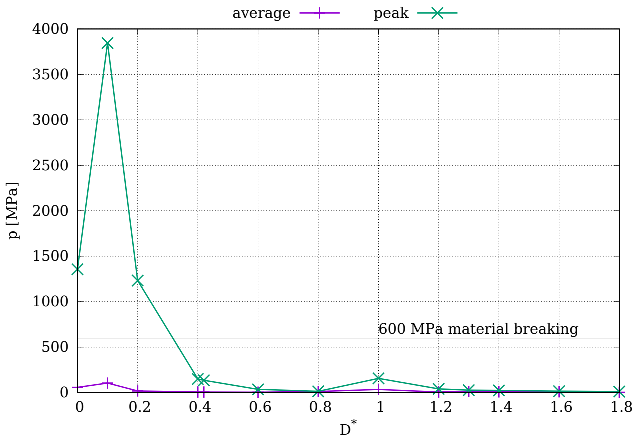

Figure 4: Simulated average pressure and peak pressure in the symmetry point below the bubble at the solid wall [3]

The correlation between shockwave focusing and peak pressure can be understood by comparing the bubble sequence with the pressure over time, shown in Fig. 5. The impact of the fast jet has already passed at $t = 111.6$ µs. The collapse of the remaining torus bubble produces a shockwave that is focused in the center at $t = 111.65$ µs.

Conclusion and discussion

For single cavitation bubbles a fast jet with velocities of about 1000 m/s was found [6, 7]. In the course of [3] it could be shown that it exists also in full-3D simulations and in reality as well. It can be stated that the pre-

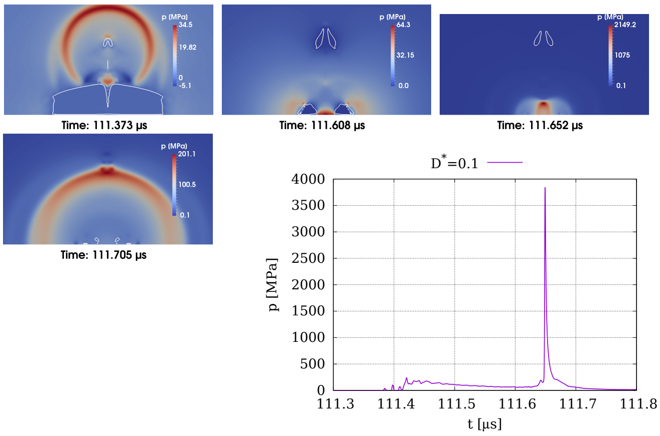

Figure 5: Simulated sequence of bubble dynamics ($D^* = 0.1$) compared to the pressure in the symmetry point at the solid wall below the bubble [3]

cise velocity up to now could not be determined neither numerically, nor experimentally. However, the following holds:

- The formation of fast jets has been predicted and described by numerical simulations in axial symmetry and in full 3D
- The formation of fast jets has been confirmed experimentally
- The jet velocity is one order of magnitude higher than the jet velocities found so far (see e.g. Philipp and Lauterborn [8] (measurements), Brujan et al. [2] (measurements), Supponen et al. [9] (Boundary Element simulation))
- The jet seems to accelerate within approximately 100 ns to the maximum velocity

According to Fig. 5 this fast jet produces pressures of 200 MPa for about 200 ns (in the case of $D^* = 0.1$ and the given resolution). This can be the cause for damaging or deforming metals. The peak pressure of several gigapascals produced by the subsequent focusing of the shockwave might be the major candidate for erosion.

Acknowledgements

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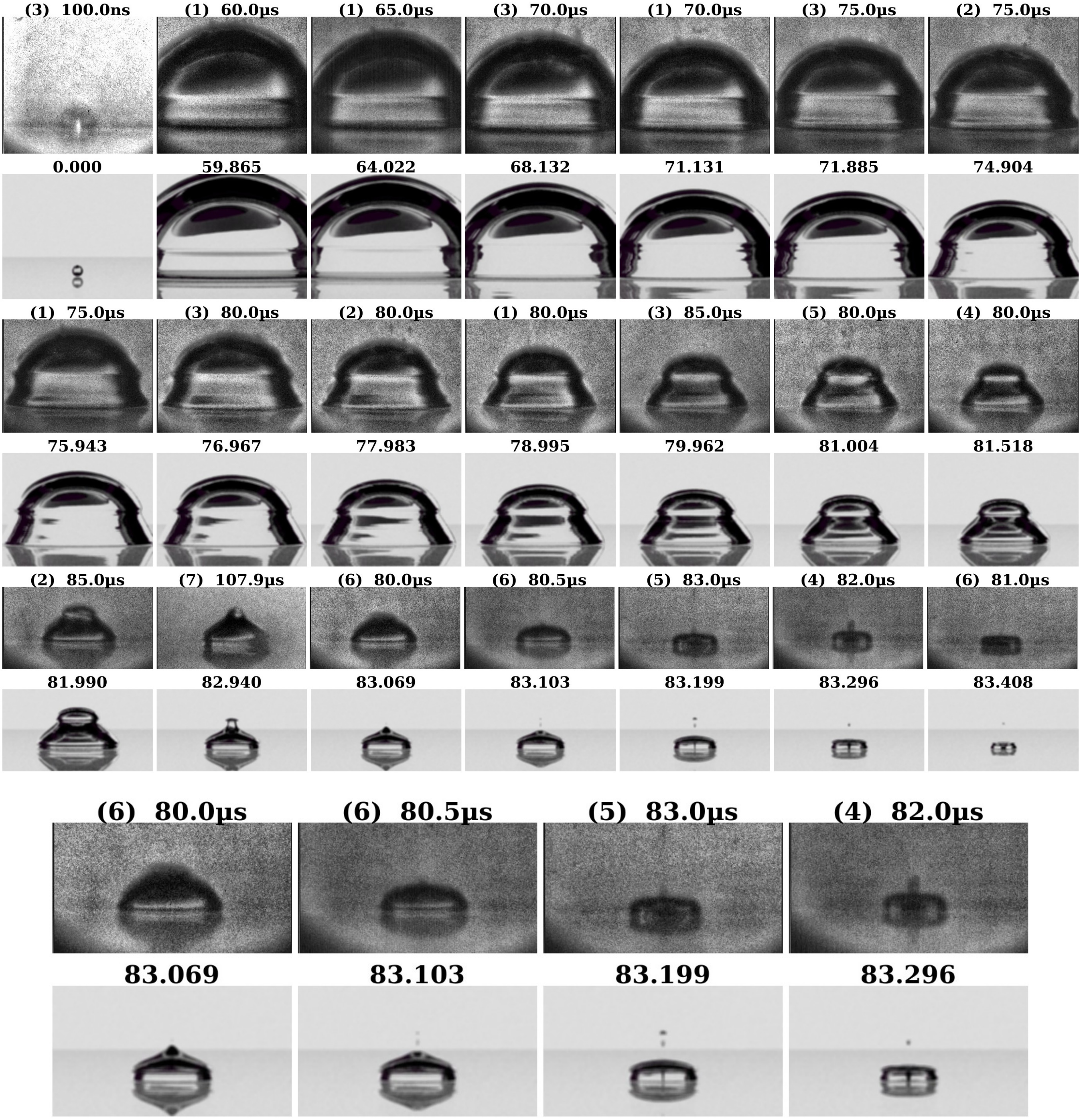

Figure 6: Experiment (odd rows) and ray-traced images from the simulation (even rows, simulation shown also in Fig. 2) of a bubble generated on the solid wall. Image taken from [3]. The last 4 frames are magnified in the bottom two rows. Frame width = 664.5 µm