High-fidelity Numerical Simulations of Collapsing Cavitation Bubbles near a Solid Surface

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1 Executive summary

The inertial collapse of cavitation bubbles is a fascinating flow that involves extreme pressures and temperatures, and is known to be capable of damaging its surroundings. This project focuses on the detailed dynamics of the collapse of a few bubbles, and investigates the mechanisms leading into the cavitation-induced erosion. We perform highly resolved numerical simulations of the collapse of (i) a single bubble, and (ii) multiple bubbles near rigid and compliant objects. For this reason, we have developed a novel numerical model to conduct efficient and accurate simulations by solving the three-dimensional compressible Navier-Stokes equations for a multiphase system. Our simulations yield the detailed non-spherical bubble morphology, as well as the pressure and temperature fields based on the relevant non-dimensional parameters entering the problem. These simulations will be used to model the collapse of bubble clouds, comprehend the damage mechanisms, and potentially mitigate the erosion.

2 Description of research activities and results

2.1 Key challenges

Cavitation appears in a variety of physical disciplines ranging from hydrodynamics to biomedical and energy sciences. Although investigated for decades, this phenomenon has still remained as a mysterious flow. In contrast with boiling, in which liquid vaporizes as the temperature rises, cavitation happens due to local pressure reductions in a liquid, leading to the formation of small-scale vapor bubbles. When subjected to higher pressure regions, these cavitation bubbles implode and generate strong shock waves. The collapse of cavitating bubbles leads to an immense concentration of energy, and, for a portion of a second, can produce transient regions of high pressure and temperature comparable to the Earth's inner core- but with lengthscales a trillion times smaller.

In the vicinity of a neighboring boundary, the collapse of cavitation bubbles becomes asymmetric, which hinders the energy concentration, lowers the produced pressures and temperatures, and leads to the formation of a small-scale high-velocity jet within the collapsing bubble. The impact of this re-entrant jet upon the distal side of the bubble or a solid surface, generates a strong water-hammer shock, and may induce significant structural damage. This erosion is known to be the most important consequence of cavitating flows, and is continually being observed in a broad range of applications, such as turbomachinery, naval structures, biomedical ultrasound, combustion, and neutron scattering.

Investigating this problem is of particular significance in both Physics and Engineering. However, the combination of compressibility effects of high-impedance fluids (e.g. liquids), propagation of shock/rarefaction waves in a multiphase medium, and their interactions with material interfaces and solid boundaries results in a specifically complicated multiscale and multphysics problem. Due to the wide range of temporal and spatial scales of these complex flows, precise measurements are

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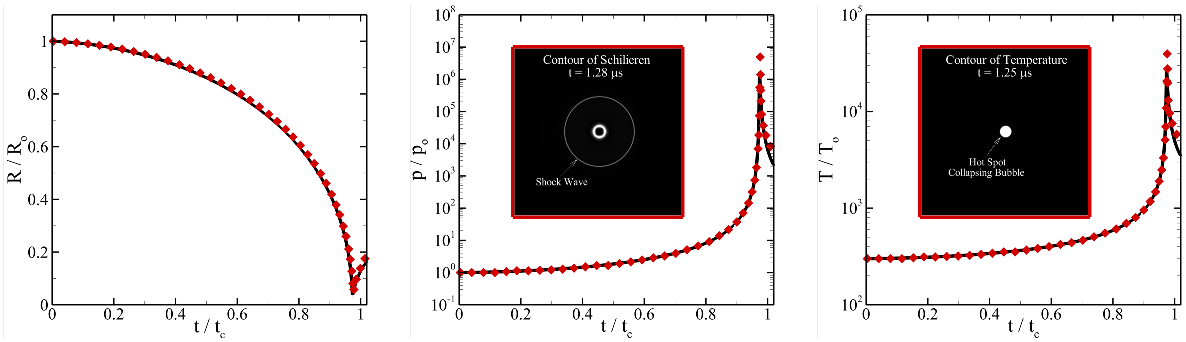

Figure 1: Spherical collapse of an isolated vapor bubble in water. Black solid line: KM solution; red diamonds: numerical simulation.

nearly impossible to obtain experimentally. The available techniques to measure extreme temperatures are highly inaccurate in short time intervals and are incapable of providing detailed explanations. Numerical simulations have therefore emerged as an alternative tool to compensate for this shortcoming. This project leverages high-resolution, three-dimensional simulations of the collapse of a few vapor bubbles near a rigid/compliant boundaries. The results will be used to study the mechanisms causing high pressures and temperatures, and quantify their role in cavitation-induced erosion. Although disruptive effects of cavitation erosion are generally caused by the collapse of bubble clouds containing tens of thousands of bubbles, studying individual bubble dynamics is specifically valuable to explore the detailed physics of the collapse process and the produced pressures and temperatures. This information will help to understand this phenomenon more precisely, and develop a more realistic and comprehensive cloud model.

2.2 Why it matters?

This research will deepen our knowledge and understanding of the non-spherical behavior of the bubbles in cavitating flows. Developing a comprehensive model for bubble clouds including the bubble-bubble interactions and the non-spherical effects of the collapse will result in more precise numerical simulations of the collapse of bubble clusters. This will help to reduce the disruptive effects of cavitation erosion in naval applications and turbomachinery. Reducing cavitation erosion will significantly strengthen the structures exposed to deterioration caused by cavitating flows, extend the lifetime of machineries, and has the potential to save upwards of billions of dollars each year. Moreover, well-known treatments in biomedicine utilize structural damage induced by collapsing bubbles to break apart kidney stones. The same idea has been applied to destroy malignant cells and and soft tissue. However, a negative side effect of these medical advancements is the unwanted damage to neighboring cells and tissues. This project delves further into these matters to provide insight into damage mechanisms to better control them in order to minimize the impairment of healthy cells and tissues.

2.3 Why Blue Waters?

This project utilizes two different in-house codes: our petascale production code for the large-scale simulations (based on MPI), and our next-generation code that enables larger-scale heterogeneous architectures (based on MPI and GPUs). These codes solve the compressible Navier-Stokes equa-

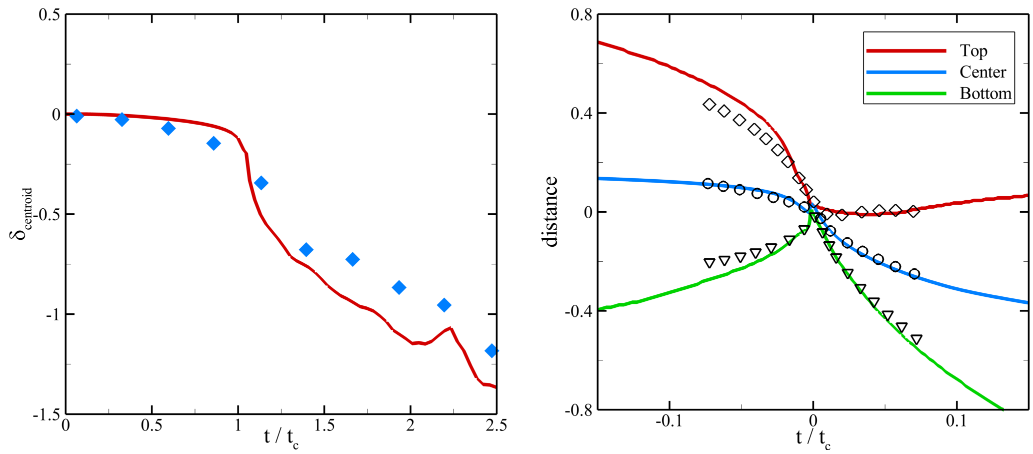

Figure 2: Left: bubble centroid as a function of time; right: time history of the bubble walls and the centroid location around the time of the jet impact. Solid lines: numerical solution; symbols: experiments.

tions for multiple gases and liquids. The foundations of both codes are high-order accurate algorithms, explicit in time and in space, thus naturally lending itself to massive parallelization. To carry out accurate simulations of cavitating flows that effectively resolve the small scale features, extremely high spatial resolution is essential to run even a single simulation over long compute times, which is difficult to achieve on any other NSF computing machines. Given its speed and available computation power, the Blue Waters supercomputer is capable of providing us with this opportunity. This project will help us to gain valuable insights and understanding of these complex flows which was previously not possible.

2.4 Accomplishments

Initially, we validate our simulations against both theory and experiment. For this reason, we simulate the spherical collapse of an isolated vapor bubble in water. In Fig. 1, we plot the normalized averaged bubble radius, and the pressure and temperature at the center of the bubble in time. We further compare our simulation against the Keller-Miksis (KM) model with heat transfer effects. The KM solution is an established model that has been extensively validated against experiments in the literature. Then, we validate our simulations of the collapse of a single vapor bubble near a solid wall with the experiment performed by Vogel *et al.* (1989, published in *J. Fluid Mech.*). Fig. 2 shows a good agreement with the experimental results.

As aforementioned, the focus of the current project is on two specific problems. First, Collapse of a single bubble near solid/soft media: This problem provides insight into the detailed dynamics of the collapse including the non-spherical behavior of the bubble, high-velocity jet formation, propagation of shock waves, and the vortex ring convecting toward the boundary. The simulations provide the flow field pressure and temperature distribution all throughout the collapse that can be used to model cavitation erosion. Fig. 3 shows three frames of the collapse process at three different times (before, right after, and late after the collapse). When the collapse starts, a strong rarefaction wave propagates radially outward, while a shock wave transmits into the bubble. Due to the reflection of the rarefaction from the wall and its interaction with the bubble, the pressure distribution around the bubble becomes asymmetrical, and also a region of high baroclinic vorticity is produced. This non-symmetric pressure distribution further strengthens the dipole vorticity

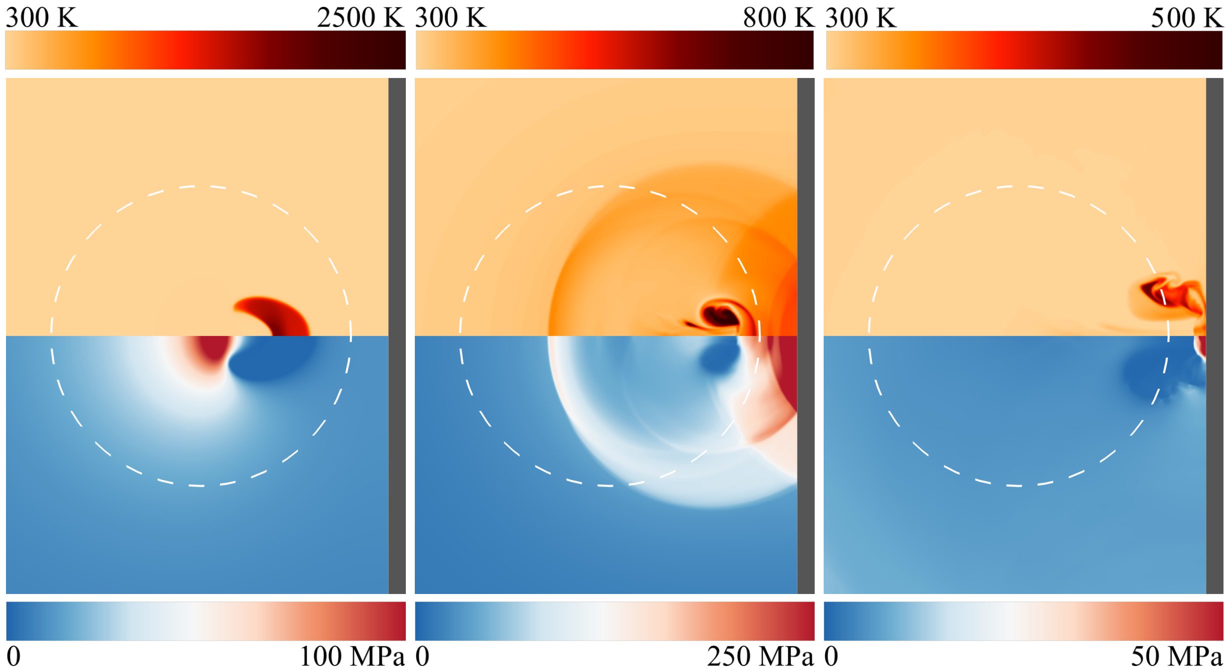

Figure 3: Collapse of a single bubble near a solid wall. 2D slices of temperature (top) and pressure (bottom) fields during the collapse; white dashed line: initial configuration of the bubble.

poking the bubble downstream wall which locally increases the pressure. This leads to the formation of a high-velocity re-entrant "microjet" within the collapsing bubble which is directing toward the solid wall. The compression of the gas bubble and the transmitted shock wave bouncing back and forth within the bubble walls creates high temperatures inside the collapsing bubble (frame 1). The microjet impacting the distal side of the bubble generates a strong outward propagating shock wave. Later on, this shock hits the wall, reflects back, and eventually interacts with the collapsed bubble again (frame 2). These interactions between the shock/rarefaction waves and the distorted collapsed bubble generate high vorticity regions, and give rise to interfacial hydrodynamic instabilities across the material interface of the bubble. Thereafter, the bubble takes the form of a convoluted vortex ring, which is being convected toward the adjacent wall. Although the bubble temperature decreases rapidly after the collapse, it is still a source of high heat swirling very close to the neighboring surface (frame 3). This process produces regions of high pressure and temperature along the wall, which deposit a significant amount of energy into the neighboring surface, leading to structural damage.

Second, Collapse of multiple bubbles near solid/soft media: Although studying single bubble collapse is specifically valuable to explore the flow physics, disruptive effects of cavitation erosion are generally caused by the collapse of bubble clouds containing tens of thousands of bubbles. However, resolving every bubble is computationally prohibitive, such that a model representing the collective behavior of the bubble cloud is necessary. Current such models are rudimentary, as they only account for spherical bubble dynamics. By conducting resolved simulations of individual bubbles, we are investigating the complex interactions within the collapsing bubbles in order to establish a numerical cloud model that includes the bubble-bubble interactions and the non-spherical effects of the collapse. Here, we simulate collapse of a bubble pair near a solid wall in order to investigate

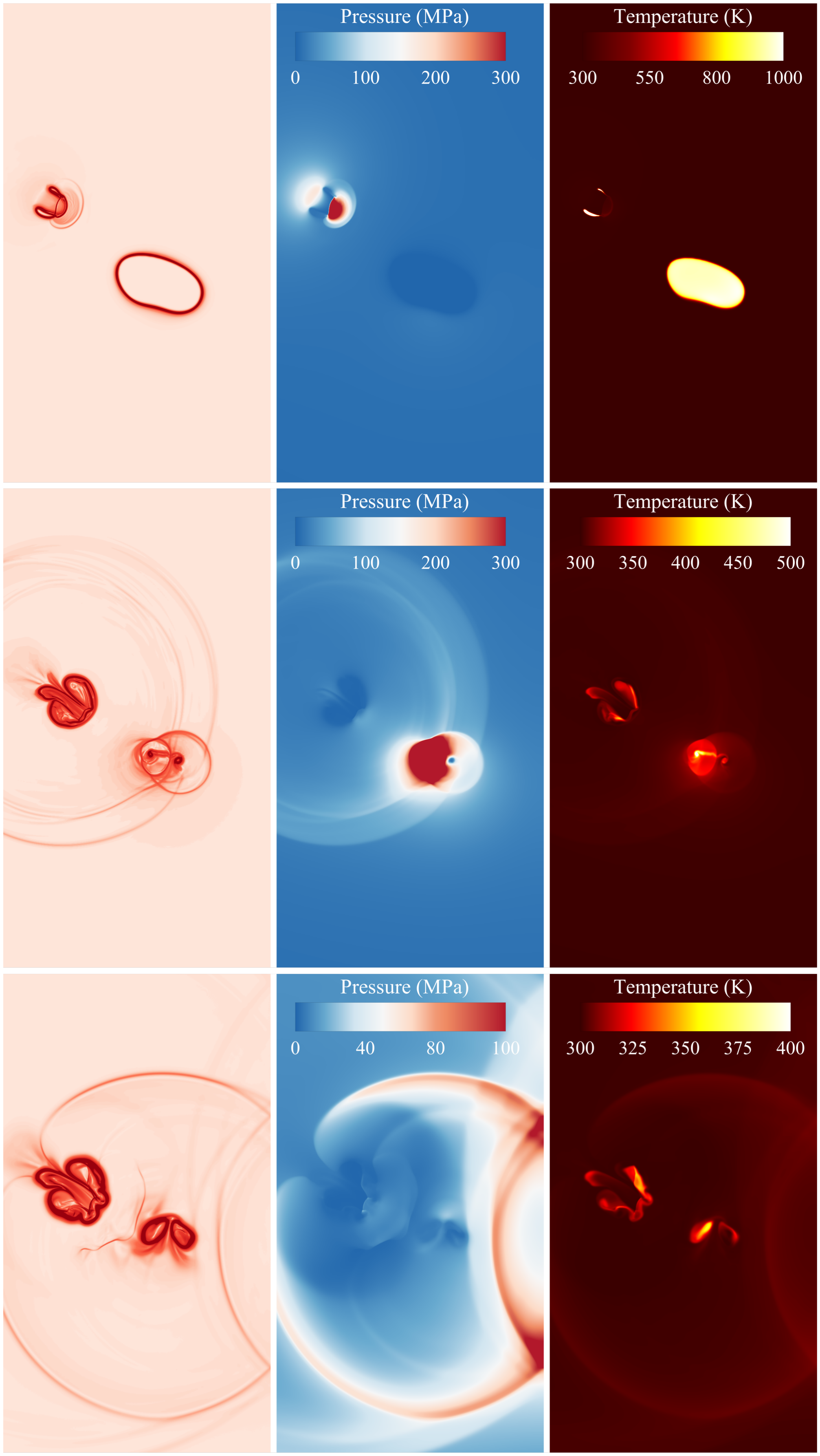

Figure 4: Collapse of a bubble pair near a solid wall. 2D slices of numerical schlieren (left), pressure (middle), and temperature (right) fields during the collapse.

these interactions. Fig. 4 shows contours of numerical schlieren, pressure, and temperature of the collapse at three different instances. It can be observed that due to the interactions between the bubbles and the waves, the secondary bubble (the one initially farther away from the wall) collapses, while the front bubble is deforming and creating the re-entrant jet (top row). The shock wave from the collapse of the secondary bubble interacts with the other bubble, and boosts its collapse. The primary bubble collapses and generates a strong shock wave (middle row). The shock wave from the collapse hits the neighboring wall, and create a high pressure region on the its surface. The collapsed bubbles take the form of convoluted hot vortex rings and convect toward the wall (bottom row). The bubble-bubble interactions increase the non-sphericity of the collapse and lead to a very more complicated process than the collapse of a single bubble. These interactions may increase or decrease the collapse intensity depending on the flow configuration. These simulations are then paramount to quantify the bubble-bubble interactions in order to develop a cloud model that includes these interactions between the collapsing bubbles.

This work will be continued to explore and analyze more detailed physics of cavitation bubble collapse.

3 List of publications associated with this work

- S. A. Beig, B. Aboulhasanzadeh, and E. Johnsen, "Mystery of temperature in cavitation", in preparation for submission to *Journal of Fluid Mechanics*.
- S. A. Beig and E. Johnsen, "The detailed dynamics of a collapsing bubble near a solid boundary", in preparation for submission to *Journal of Fluid Mechanics*.
- S. A. Beig and E. Johnsen, "Inertial collapse of bubble pairs near a solid surface", in preparation for submission to *Journal of Fluid Mechanics*.