NUMERICAL SIMULATIONS OF THE INERTIAL COLLAPSE OF INDIVIDUAL GAS BUBBLES NEAR A RIGID SURFACE

Allocation: GLCPC/880 Knh
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EXECUTIVE SUMMARY

Cavitation, or the formation of vapor bubbles in a liquid flow, occurs in applications ranging from naval hydrodynamics to medicine to energy sciences. Vapor cavities can collapse violently in an inertial fashion that concentrates energy into a small volume, producing high pressures and temperatures, generating strong shock waves, and even emitting visible light. One of the main outcomes of inertial cavitation is structural damage to neighboring solid objects due to bubble collapse. While cavitation erosion is a negative outcome in naval hydrodynamics, it is exploited in medicine in the context of cavitation-based therapeutic ultrasound; e.g., for pathogenic tissue ablation.

To better understand this phenomenon, we used highly resolved numerical simulations of the inertial collapse of individual bubbles near a rigid surface to predict pressures and temperatures thereby produced. For this purpose, we developed a novel numerical multiphase model combined with high-performance computing techniques to perform large-scale, accurate, and efficient simulations of the three-dimensional compressible Navier–Stokes equations for a binary, gas–liquid system. This knowledge will paint a clearer picture of the detailed physics of such complex flows, it will elucidate the damage mechanisms, and it will inform the development of mitigation strategies for cavitation erosion.

RESEARCH CHALLENGE

Cavitation—the process whereby vapor cavities are produced in a liquid—is a ubiquitous phenomenon in high-Reynolds-number flows of liquids [1]. In contrast with boiling, in which liquid vaporizes as the temperature rises, cavitation happens due to local pressure reductions that lead to the formation of initially small bubbles. These bubbles respond to the surrounding flow field by growing and collapsing, sometimes with extreme violence. During the collapse, the cavitation bubbles undergo a rapid compression such that the bubble volume decreases by several orders of magnitude [1]. This implosion, usually occurring within a few microseconds, concentrates energy into a small volume, creates regions of high pressure and temperature, emits radially propagating shock waves, and is capable of damaging nearby objects [2,3]. The destructive nature of cavitation erosion is a significant challenge in naval hydrodynamics, e.g., eroding turbine blades, propellers, and rudders [2,3]. On the other hand, if controlled, damage can be exploited for therapeutic purposes in biomedical applications. In the context of therapeutic ultrasound, the pressure pulses from the collapse of cavitation bubbles are employed to fragment kidney stones, a treatment called shock wave lithotripsy [4]. Owing to its wide range of applications, cavitation erosion has been the topic of numerous studies in the past decades.

Cavitation-induced erosion is a multiphysics and multiscale problem at the intersection of fluid and solid mechanics. The interactions of many bubbles with turbulence, the compressibility effects of the multiphase mixture, and the propagation of shock waves produced by bubble collapse and their interactions with material interfaces are challenging nonlinear and multiscale phenomena in fluid dynamics. Diagnosing these flows experimentally is particularly challenging because of the wide range of spatial and temporal scales, difficult optical access, and intrusiveness of measurement devices. Thus, highly resolved numerical simulations have emerged as beneficial complements to experimental studies, providing valuable insight into the detailed dynamics of the inertial collapse of cavitation bubbles.

METHODS & CODES

To perform the desired simulations, we developed a novel numerical algorithm to solve the three-dimensional compressible Navier–Stokes equations for a multiphase system [5]. This numerical framework prevents spurious pressure and temperature oscillations across the material interfaces and is capable of accurately and robustly representing shock waves and high-density-ratio material discontinuities. For discretization, we developed a solution-adaptive central/discontinuity-capturing approach. Our spatial scheme is of high-order accuracy in smooth regions and is nominally nondissipative; high-order discontinuity-capturing is applied only at sharp gradients detected by a discontinuity sensor. This approach was especially designed to simulate nonspherical dynamics of individual bubbles and the resulting shock waves produced during collapse. An in-house computational code, utilizing Message-Passing Interface for parallelization and Hierarchical Data Format for I/O, was developed in C++ to perform the proposed three-dimensional high-resolution simulations. The code was verified and validated using a suite of problems, and its parallel scaling was demonstrated on Blue Waters.

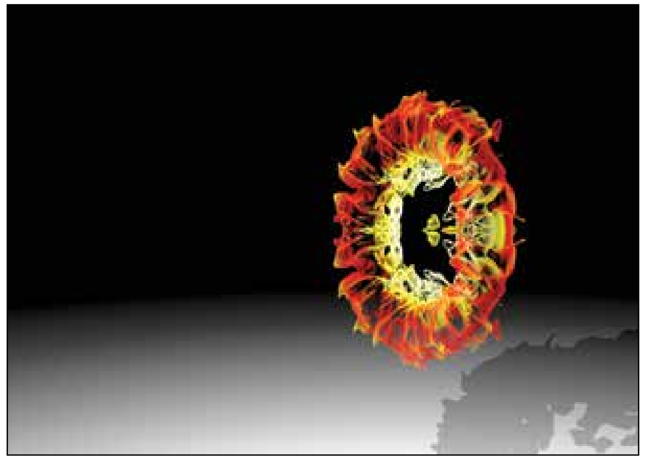

Figure 1: Volume rendering of the bubble shape, colored by its temperature. After the collapse, the bubble takes the form of a hot vortex ring moving in the direction of the jet impact toward the rigid boundary.

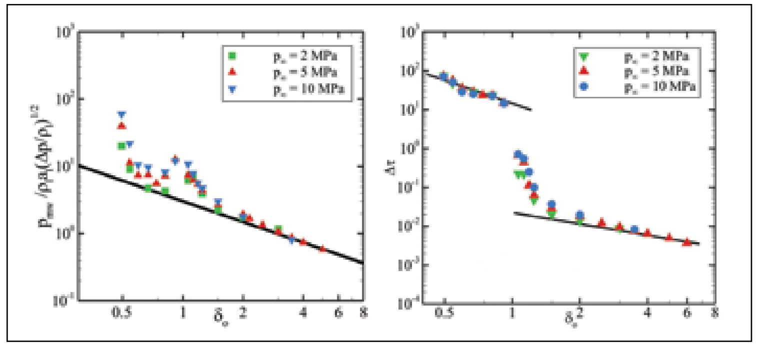

Figure 2: Scaling of the maximum pressure (left) and maximum temperature (right) along the wall as a function of initial stand-off distance from the wall for different driving pressures.

RESULTS & IMPACT

This project focuses on the detailed dynamics of the collapse of individual gas bubbles near a solid object for different geometrical configurations and driving pressures. We have shown that the presence of a rigid boundary breaks the symmetry of the collapse and leads to the formation of a high-speed re-entrant jet directed toward the neighboring wall [6–8]. The jet impact on the distal side of the bubble generates a water-hammer shock impinging on the adjacent surface that can cause structural damage. The bubble then takes the form of a hot vortex ring convecting toward the object (Fig. 1), and if close enough to the object wall, the rise in surface temperature may lead to thermal damage. We further developed scaling for important collapse properties (e.g., wall pressures/temperatures), in terms of the initial stand-off distance and driving pressure. This not only illustrates the universality of nonspherical bubble dynamics but also provides the means to predict these phenomena (Fig. 2).

Since real flows involve many bubbles, we also simulated the inertial collapse of a pair of gas bubbles near a rigid surface to investigate the bubble–bubble interactions and their effects on collapse dynamics. Through this work, we have fully solved the problem of a single bubble collapsing near a rigid boundary. This problem is the central problem to cavitation damage; solving it will enable more accurate prediction of cavitation-induced damage in naval hydrodynamics, therapeutic ultrasound, and other fields. Based on this information, control strategies can be developed. In naval hydrodynamics, mitigation strategies would improve overall performance and reduce maintenance costs. In medicine, this knowledge would result in the development of safer and more efficient procedures.

WHY BLUE WATERS

In this project, we utilized an in-house production code for the large-scale simulations. The code foundation is based on high-order accurate algorithms, explicit in time and in space, naturally lending itself to massive parallelization. To carry out accurate three-dimensional simulations of the collapse of cavitation bubbles that effectively resolve the small-scale features of the flow, high resolution (of up to 2.5 billion grid points) is paramount. Performing such simulations requires a substantial computational power that is difficult to achieve on any other NSF-funded computing machines. Therefore, a leading-edge petascale high-performance computing system like Blue Waters is essential for the success of the present study. This project will help us to gain valuable insights and understanding of these complex flows that previously were not possible.

PUBLICATIONS & DATA SETS

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