Modeling Of Interaction Between Laser-Induced Cavitation Bubble And Rigid/Elastoplastic Membranes

Ahmad Gad[1], Mikhail Ovchinnikov[1]

[1]Alcon Labs, Lake Forest, CA, USA

Abstract

The mechanical effects associated with the collapse of laser-induced cavitation bubbles are central to numerous medical and industrial applications, particularly where precise, localized energy delivery is required. This study examines the interaction of nanosecond-pulsed infrared laser radiation with water, where strong optical absorption leads to rapid, localized energy deposition. The resulting thermodynamic excursion causes abrupt volumetric expansion of the fluid, initiating a high-amplitude shock wave and forming a vapor bubble that undergoes a violent life cycle of expansion and collapse. Understanding these dynamics, and their impact on nearby structures, is essential for leveraging cavitation phenomena in confined liquid environments.

We present a high-fidelity Finite Element (FE) model that simulates the complete sequence of events following a nanosecond laser pulse deposited into a quiescent water domain. The model captures the initial shock wave generation, cavitation bubble expansion, and eventual collapse—each phase producing distinct mechanical effects. The interaction of the bubble with rigid boundaries and an elastoplastic aluminum membrane is examined at various distances from the optical fiber tip that emits the laser pulses. To model the complex fluid dynamics involved, the compressible Euler equations are employed, neglecting viscous and thermal diffusion effects. The thermodynamic behavior of water is governed by the full IAPWS equation of state, enabling accurate representation of water compressibility and high-pressure/temperature levels. Phase change and bubble nucleation are modeled using the Homogeneous Equilibrium Model (HEM), assuming local thermodynamic equilibrium between phases throughout the domain. This approach offers a significant computational advantage over explicit interface tracking methods such as level-set or phase-field formulations, while still capturing the essential physics governing the cavitation dynamics.

Simulation results reveal that fluid elements near the optical fiber are rapidly driven into the supercritical regime, reaching pressures on the order of several gigapascals and temperatures of several thousand kelvins. This extreme localized energy deposition launches a shock wave with a steep front, imparting a substantial outward radial momentum to the surrounding liquid. The resulting inertial effect creates a transient low-pressure zone that gives rise to the cavitation bubble. The bubble subsequently expands until the inertial forces dissipate, after which it undergoes an accelerated collapse driven by the pressure differential between its interior and the surrounding liquid. When the collapsing bubble interacts with an elastoplastic membrane, the model predicts a highly localized region of plastic strain, indicating the potential for permanent material damage.

Reference

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Figures used in the abstract

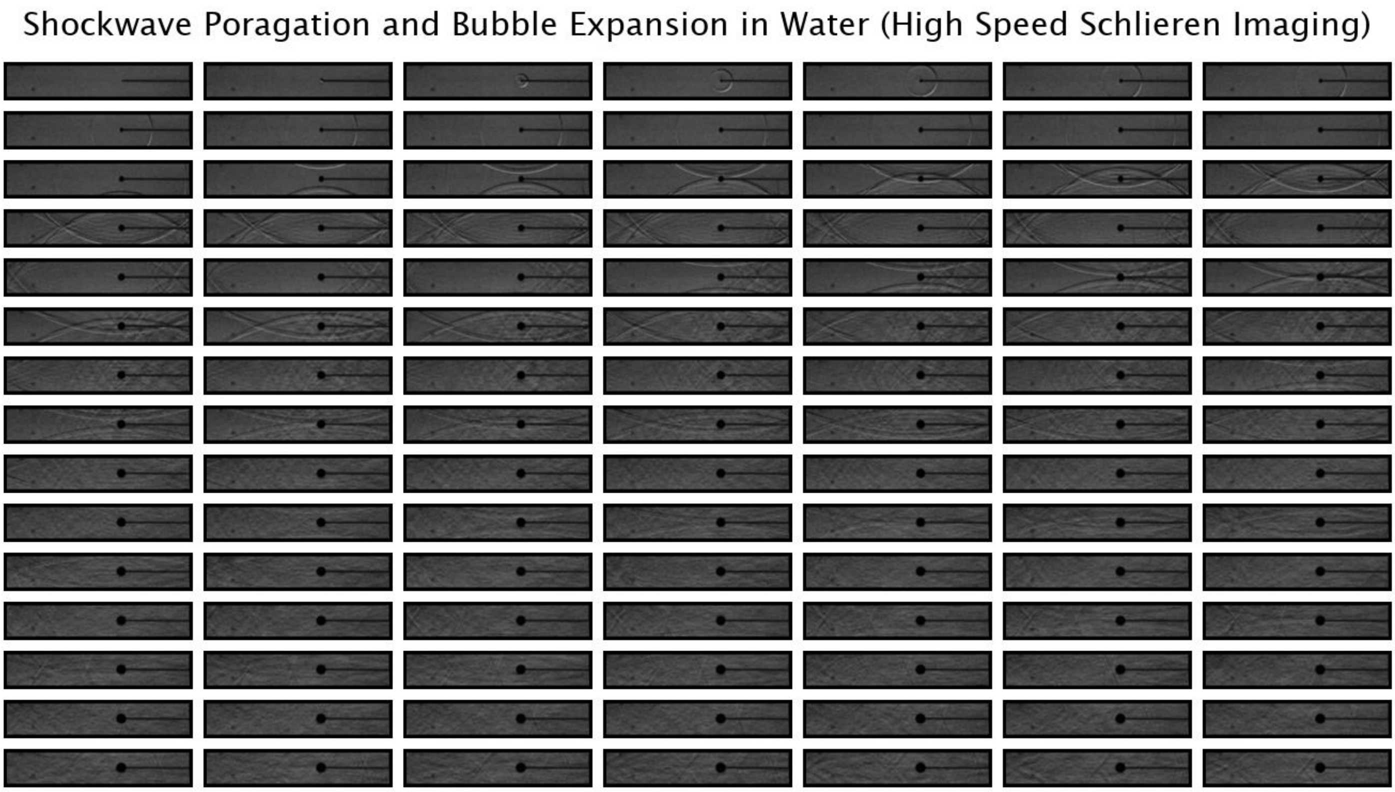

Figure 1 : Shockwave propagation and bubble expansion in water (high speed Schlieren imaging)

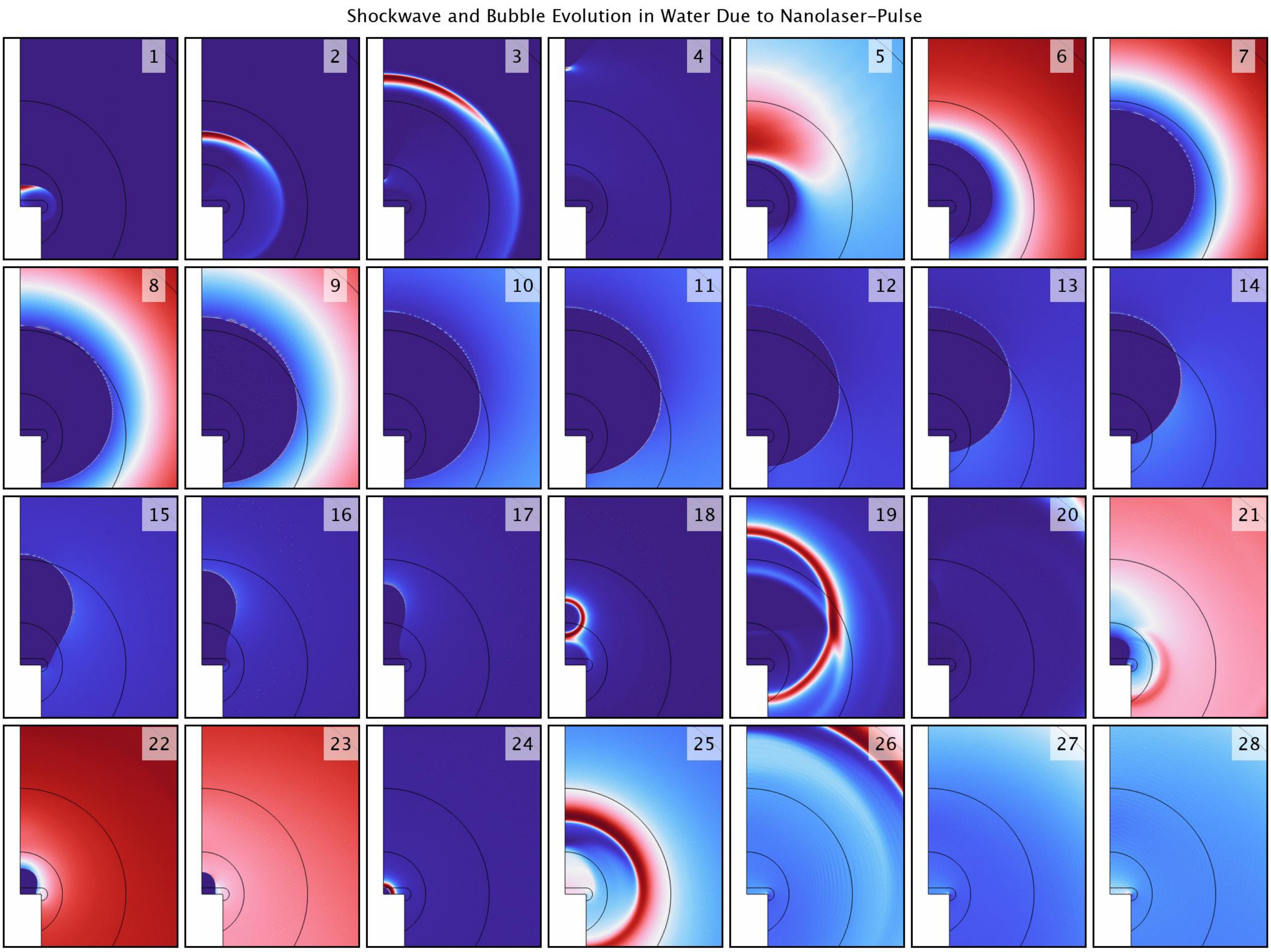

Figure 2 : Shockwave and bubble evolution in water due to nanolaser pulse

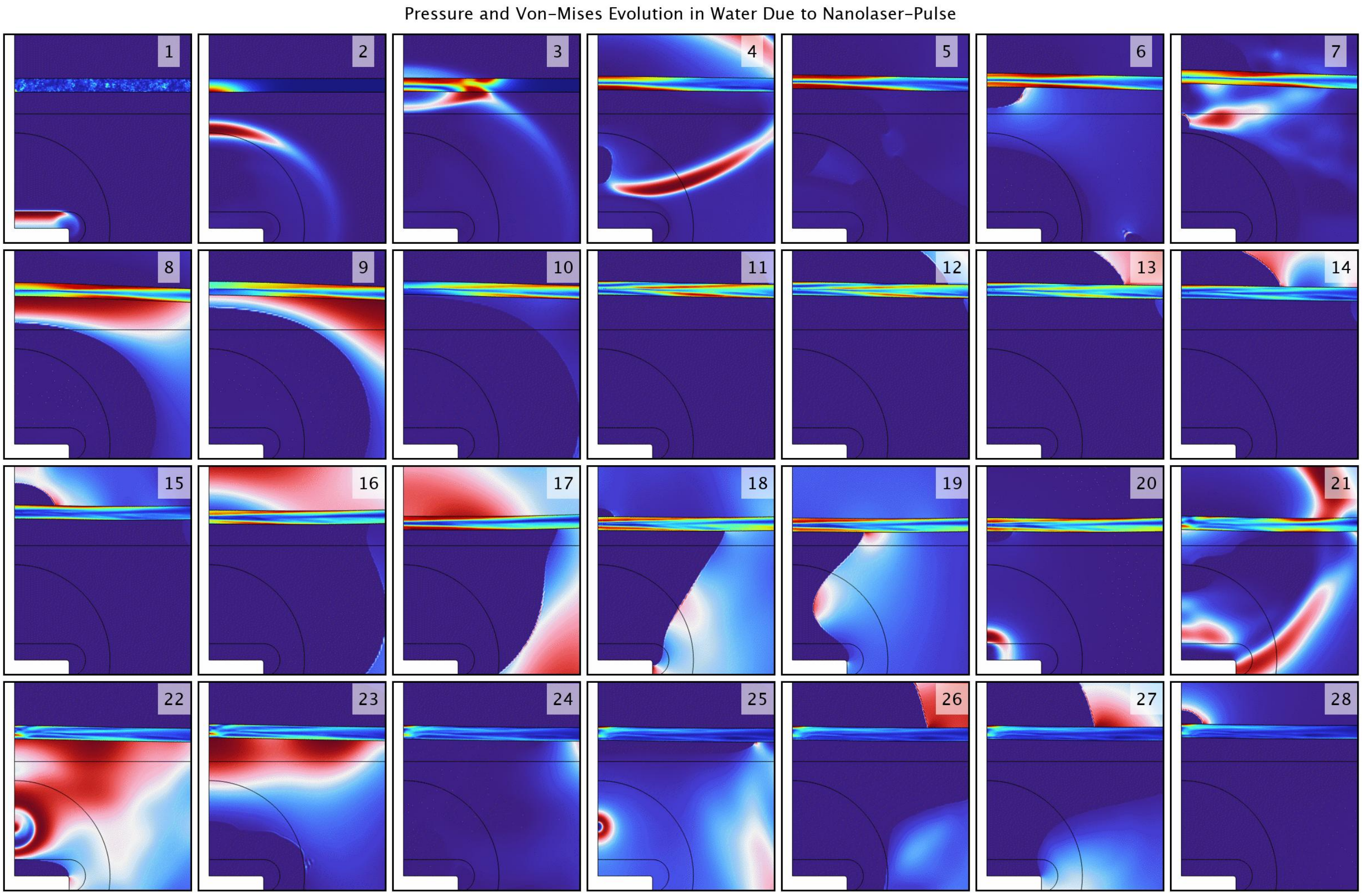

Figure 3 : Pressure and von-mises evolution in water due to nanolaser-pulse

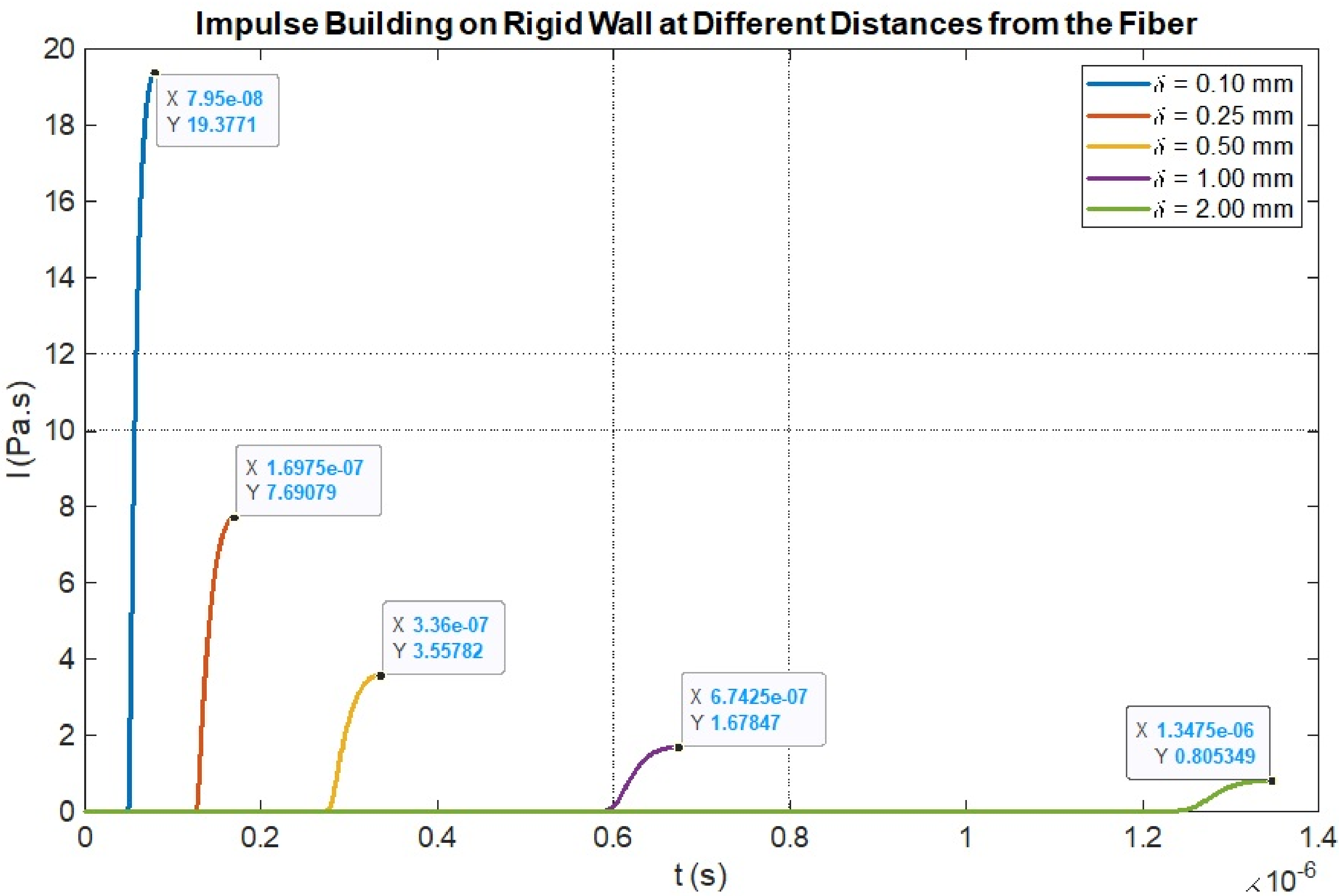

Figure 4 : Impulse building on rigid wall at different distances from the fiber