Simulation of shock-waves in water induced by nanosecond-laser pulse

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Introduction

This contribution presents a numerical model which describes the propagation of shock-wave in liquid (water) induced by nanosecond-laser pulse. This 2D numerical model will be compared with Schlieren images obtained by experiment and it should lead to deeper insight into propagation and behavior of laser induced shock-waves in liquid. This phenomenon was first observed and described in the 1970s. The main mechanism of generating shock-waves in liquid by laser pulse were found to be: linear optical absorption with subsequent bulk thermal expansion, explosive evaporation and dielectric breakdown and ionization [1, 2].

Model description

One of the best simulation software for modeling fluid dynamics using finite volume method is without doubt OpenFoam [4]. This open source software offers few basic compressible flow solvers, which are able to capture the propagation of shock-waves in fluid. The first in mind would be *sonicLiquidFoam*. This solver describe a liquid, where the equation of state is assumed to be a simple baratropic function known as Tait equation [3]. It does not use an equation for energy, which leads to the impossibility of using this solver in case of shock-wave formation in water by laser pulse. Another solver within OpenFoam environment would be *rhoCentralFoam*, which is density-based compressible flow solver based on central-upwind scheme of Kurganov and Tadmor. The main governing fluid equations in an Eulerian frame of reference are equation of mass conservation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \tag{1}$$

equation for conservation of momentum:

$$\frac{\partial(\rho\vec{u})}{\partial t}+\nabla\cdot[\vec{u}(\rho\vec{u})]+\nabla p+\nabla\cdot\hat{T}=0 \tag{2}$$

and conservation of energy:

$$\frac{\partial(\rho E)}{\partial t}+\nabla\cdot[\vec{u}(\rho E)]+\nabla\cdot(\vec{u}p)+\nabla\cdot(\vec{T}\cdot\vec{u})+\nabla\cdot\vec{j}=0 \tag{3}$$

where ρ is the mass density, p is the pressure, $\vec{u}$ is the fluid velocity, $\hat{T}$ is the viscous stress tensor, $\vec{j}$ is the diffusive flux of heat and E is total energy density.

Since the shock-wave is generated by a laser pulse we have to include a new term Q in the eq. 3. The power term Q was applied to the circle area (with radius 1 mm) in the middle of our geometry using another OpenFoam utility called *funkySetFields*, which set the value for the scalar field Q using function prescription. Since the *rhoCentral-Foam* was developed mainly for gas dynamics, it use primarily equation for perfect gas as an equation of state. We had to implement a different equation of state from the thermophysical modelling library, equation for perfect fluid:

$$\rho=\frac{1}{RT}p+\rho_0 \tag{4}$$

where ρ_0 is density of liquid in equilibrium.

Results

With regard to the usual experimental condition we set in our simulation the background temperature to 300 K and the background pressure to 1 bar. The laser single shot power pulse lasted for 4.9 ns with energy of 1.3 J. The formation and time evolution of a shock-wave can be seen in the figure 1, which show the pressure field, since the Schlieren imaging visualize temporal variation in the pressure field. This pulse yields to shock-wave which propagates with velocity around 1500 m.s^{-1}. This value is in good agreement with the experimental data from paper [1], even though they used different laser pulse properties (35 fs with energy 2.25 mJ). The shock front velocity in both cases had similar value in our simulations.

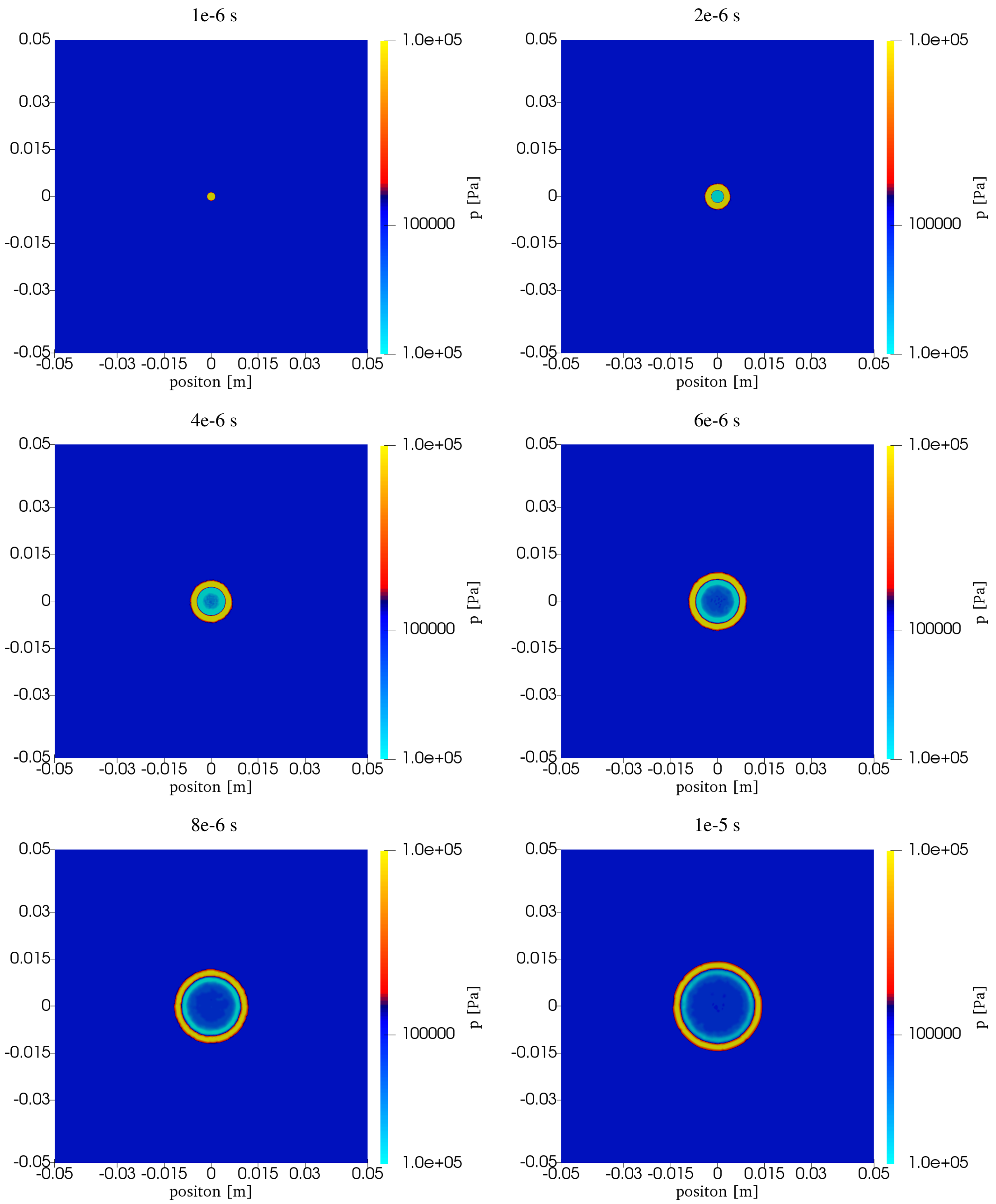

Figure 1: Time evolution of shock-wave in water induced by 4.9 nanosecond-laser pulse with energy of 1.3 J.

Conclusion

The numerical model describing propagation of shock-wave induced by nanosecond-laser pulse was presented, where the *rhoCentralFoam* density-based solver was manually modified for proper description of the fluid dynamics under our special conditions. Validation of this model was performed by comparing data obtained by simulation and experimentally acquired data.

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