Dynamics of a spherical explosion in aqueous foam taking into account heat-exchange and dissipative processes

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Abstract. Numerical study of the features of spherical explosion propagation process in a cylindrical pipe surrounded by an inner layer of aqueous foam with liquid volume fraction $\alpha_{10} = 0.2$ has been carried out. The solution method is based on a two-phase model of gas-liquid mixture under conditions of single-pressure, two-temperature, two-velocity approximations and is implemented using the twoPhaseEulerFoam solver of the OpenFOAM software. In order to test the proposed model, a comparison was made of the calculations and experimental data on a spherical explosion in aqueous foam with liquid volume fraction $\alpha_{10} = 0.0083$. When solving the main task, the efficiency of the considered foam barrier is shown in a comparative analysis with the solution obtained in the absence of a foam layer.

1. Introduction
Relevance of studying the shock waves (SW) dynamics in gas-liquid foam structures is explained by a wide range of practical applications: ensuring dust and noise suppression, fire and explosion safety of technological processes, etc. Efficiency of aqueous foams as protective barriers, localizing the explosion effect, is manifested in a significant decrease in the amplitude and speed of SW propagation due to the high compressibility of gas-liquid mixtures.

Among the first works, in which the damping properties of foam structures were investigated, it should be noted [1], where the passage of weak SW through a column of aqueous foam was experimentally studied. In [1] it was found that gas-liquid foams effectively absorb the explosion energy, allowing the reduction of SW parameters by more than an order of magnitude in comparison with the gaseous medium. In [2], a numerical simulation of the propagation of SW through the vertical column of gas-liquid foam was carried out on the basis of the gas-droplet model using the modified Godunov scheme. In [3], the process of SW attenuation in relaxing media using a mixture model is analyzed. Numerical simulation of high explosive (HE) explosion in a foam and comparison of the spherical explosion numerical results with experimental data is considered in [4]. In this, the movement of gas-liquid foam was also described on the basis of a mixture model taking into account heat relaxation of the phases and dispersed medium features. In the papers [5]–[8], study of dynamic processes for spatial problems associated with the interaction of air SW with aqueous foam barriers was conducted. Numerical simulation of SW propagation process in aqueous foam in [5]–[6] was carried out by a through counting method using moving Lagrangian grids and a two-phase gas-liquid mixture model. In [7]–[8] the
solution was obtained by using the compressibleMultiphaseInterFoam solver of OpenFOAM [9]. In [6]–[8], the modes of forming internal flows in the process of an air shock-wave pulse reflection from a plane boundary between gas and foam, leading to vortex formation, are investigated.

In this work, in contrast to [8], computational modeling and investigation of the two-dimensional axisymmetric wave flows dynamics in a cylindrical gas region are conducted in comparison with the problem containing the surrounding inner layer of aqueous foam. Numerical implementation of the problem is based on the twoPhaseEulerFoam solver [9]. To verify the proposed solution method, a comparative analysis of the numerical simulation results for attenuation process of the SW, resulting from a powerful HE explosion in aqueous foam, and experimental data [10] is carried out.

2. Model equations

It is supposed that foam is decayed behind the front of strong SW and represented by microdroplets of diameter \( d_0 = 30 \, \mu m \) [4] described by the gas-liquid mixture model. The system of model equations for two-phase medium, according to the problem under study, includes the continuity, momentum and energy equations for each phase in accordance with single-pressure, two-speed, two-temperature approximations for a gas-liquid mixture [11].

- Mass conservation laws for the phases

\[
\frac{\partial (\alpha_i \rho_i)}{\partial t} + \text{div}(\alpha_i \rho_i \vec{v}_i) = 0. \tag{1}
\]

- Momentum conservation laws for the phases

\[
\frac{\partial (\alpha_i \rho_i \vec{v}_i)}{\partial t} + \text{div}(\alpha_i \rho_i \vec{v}_i \vec{v}_i) = -\alpha_i \nabla p + \text{div}(\alpha_i \vec{\tau}_i) + \vec{F}_i. \tag{2}
\]

Viscous stress tensor \( \vec{\tau}_i \) has the form

\[
\vec{\tau}_i = \mu_i (\nabla \vec{v}_i + \nabla \vec{v}_i^T) - \frac{2}{3} (\mu_i \text{div} \vec{v}_i) I.
\]

Density of the interfacial forces [11] is represented by the sum of interfacial drag force \( \vec{F}_{i,\text{drag}} \), determined by Schiller-Naumann drag model [12], and virtual mass force \( \vec{F}_{i,\text{vm}} \):

\[
\vec{F}_i = \vec{F}_{i,\text{drag}} + \vec{F}_{i,\text{vm}}, \quad \vec{F}_{i,\text{drag}} = \frac{3}{4} \alpha_2 C_D \frac{\rho_1}{d_0} (\vec{v}_i - \vec{v}_j)[\vec{v}_i - \vec{v}_j], \quad \vec{F}_{i,\text{vm}} = 0.5 \alpha_2 \rho_1 \left( \frac{d_j \vec{v}_j}{dt} - \frac{d_i \vec{v}_i}{dt} \right).
\]

- Energy conservation laws for the phases

\[
\frac{\partial (\alpha_i \rho_i (e_i + K_i))}{\partial t} + \text{div}(\alpha_i \rho_i (e_i + K_i) \vec{v}_i) = -p \frac{\partial \alpha_i}{\partial t} - \text{div}(\alpha_i \vec{v}_i p) + \text{div}(\alpha_i \gamma_i c_{p,i} C_{V,i} (\nabla h_i)) + K_{ht}(T_j - T_i). \tag{3}
\]

The Ranz-Marshall model [13] is used to determine the heat transfer coefficient \( K_{ht} \):

\[
K_{ht} = \frac{\kappa_1 N u}{d_0}, \quad N u = 2 + 0.6 R e^{1/2} P r^{1/3}.
\]

- Equations of state for gas and water:

\[
\rho_1 = p \psi_1 + \rho_{10}, \quad \rho_2 = p \psi_2, \tag{4}
\]

where \( \rho_{10}, \psi_1 = m_i/(RT_i) \) — the density of water under normal conditions and the compressibility for the \( i \)-th phase.

The equations (1)–(4) use the generally accepted notations, where \( i, j \) — designations of phases, for which numerical values 1, 2 correspond to liquid and gas, respectively.
3. Problem statement and calculation results
In order to test the proposed gas-droplet mixture model, implemented using the twoPhaseEulerFoam solver, calculations were made for the impaction of spherical shock pulse on aqueous foam for experimental conditions [10], where a spherical HE explosion in a dry aqueous foam with an initial liquid volume fraction \( \alpha_{10} = 0.0083 \) was performed. In accordance with the simulated experiment, in the center of the three-dimensional region, at the initial moment of time, the pressure, temperature and liquid fraction distributions were set, approximated by the exponential function proposed in [14].

A comparative analysis of the experimental [10] and calculated time dependences for pressure at the location of the gauges at a distance \( l_1 = 0.41 \) m and \( l_2 = 0.53 \) m from the explosion point is shown in Fig. 1. The calculated and experimental profiles have a satisfactory agreement on both the amplitude and the duration of the formed pressure pulse. Both in experiments and in calculations at time instants \( t \sim 1.5 \) ms and \( t \sim 1.8 \) ms the pressure jump is recorded, which is a consequence of the unloading wave reflection from the boundary of HE explosion initiation region.

![Figure 1. Pressure dependence on time at the locations of the gauges \( l_1 = 0.41 \) m and \( l_2 = 0.53 \) m from the point of explosion; 1 - results of the calculations; 2 - experimental data [10].](image)

In order to solve the problems of spherical explosion in a pipe filled with gas and the surrounding inner layer of aqueous foam, the computational mesh in the form of cylinder with a length of \( x = 2.6 \) m and radius \( y = 1.4 \) m is formed with symmetry conditions on the axis \( Ox \) and the plane \( x = 0 \). Zone \( 0 \leq y < 1 \) m, \( 0 \leq x \leq 2.6 \) m is filled with gas; aqueous foam layer of thickness \( 0.4 \) m (\( 1 \) m \( \leq y \leq 1.4 \) m, \( 0 \leq x \leq 2.6 \) m) with an initial liquid volume fraction \( \alpha_{10} = 0.2 \) is located in accordance with the scheme of the computational domain (see Fig. 2).

The numerical solution of the equations (1)–(4) was performed using the twoPhaseEulerFoam solver based on the two-step iterative PIMPLE method, which allows significantly speed up the calculations and obtain solution with a predetermined accuracy [9].

The initial pressure pulse, as in [6, 7, 8], has the form:

\[
p(x, y) = p_0 + \Delta p e^{-(x^2+y^2)/a^2},
\]

where \( \Delta p = 1000 \) bar, \( p_0 = 1 \) bar, \( a = 0.15 \) m. The no-slip wall boundary condition, surrounding the symmetry center of radius 0.1 m, cuts off the instability region in numerical simulation.

Fig. 3 presents numerical solutions in the form of calculated pressure fields, velocity vector fields and streamlines at specified times for problems on the air shock pulse propagation in...
the gas region surrounded by aqueous foam barrier (fragment ”a”) and in the case of only the
gas region (fragment ”b”). Distribution of liquid volume fraction is shown by a green color spectrum. Maximum amplitude of the pressure pulse (5), initially equal to 700 bar, decreases as the spherical SW propagates and by the time $t = 0.5$ ms is $\approx 9$ bar. During the interaction process of the air SW with aqueous foam, the last one is compressed to $\alpha_1 = 0.45$ ($t = 3$ ms, ”a”), what leads to a significant decrease in the velocity of SW propagation. In Fig. 3, the process of SW reflection from the foam layer is presented at time $t = 1.0$ ms (a). Formation in gas (b) of a SW, reflected from the side surface of a cylinder, is shown at time $t = 0.9$ ms. The SW reflection dynamics is accompanied by a change in direction of the velocity field and bending of the streamlines. The interaction process of the main radial SW with the one reflected from the side boundary leads to increase in the pressure intensity in the interaction zone. The pressure in the region near the boundary of foam layer is $\approx 5$ bar ($t = 1$ ms, ”a”) and $\approx 8$ bar in pure gas ($t = 0.9$ ms, ”b”).

By the time $t = 2.1$ ms, the process of SW reflection leads to the local zone of low pressures ($\approx 0.6$ bar) formation near the boundary between gas and foam (a) and the side boundary of the cylinder (b). An extensive area close to the axis of symmetry is formed with pressure values $\approx 1.8$ bar (a) and $\approx 2.4$ bar (b). In the region of SW initiation by the time $t = 2.1$ ms, the mass velocities decrease, what leads to the spatial toroidal vortex flows formation. In the (b) fragment, the zone located beside the shock front and the side surface of the cylinder retains high pressures ($\approx 5$ bar) compared with the case of foam barrier presence ($\approx 3$ bar). Starting from $t = 2.1$ ms, the graphs show a bending of the shock front due to an increase in its velocity near the side boundary by reason of the additional influence of the SW reflection from the side surface of the cylinder. A similar effect in the presence of a foam layer is missing. Front of the main SW acquires a two-wave configuration with peak pressures of 2 bar (a). In case (b), a two-wave structure is also formed with a more powerful second peak, whose amplitude reaches 3 bar. As the process develops, the second peak increases to 5 bar due to the additional influence of the SW reflected from the side surface of the pipe and directed to the axis of symmetry.

Further dynamics of wave processes leads to a shift of the vortex formation zone follow the main SW, what can be observed at $t = 2.5$ ms. In the considered time interval, the region of low pressures is maintained both close to the foam layer (a) and the side boundary of the cylinder (b). In the central zone of the vortices formation, pressures are $\approx 1.5$ bar (a) and $\approx 1.7$ bar (b). In both cases considered, by the time $t = 3.0$ ms a stable toroidal vortex is formed, rotating with an angular velocity, which is 1.8 times less in the presence of foam layer relative to calculations.
in a pure gas ($\omega_1 \approx 250$ rad/s, "a"; $\omega_2 \approx 450$ rad/s, "b"). For pure gas, an expansion of the increased pressure zone is observed, reaching $\approx 2.2$ bar at the side boundary of the pipe. At the front of the main SW high pressures zone also remains.

**Figure 3.** Dynamics of pressure fields, velocity vector fields and streamlines in the SW propagation problem in a cylindrical pipe filled with gas (b) and the inner aqueous foam layer surrounding the gas (a). Foam barrier is indicated by a green color spectrum.
4. Conclusion
The problem of air spherical shock pulse propagation in a cylindrical pipe, surrounded by internal aqueous foam layer, was numerically investigated using the modified twoPhaseEulerFoam solver of the OpenFOAM package. As a result of comparative analysis of the process under study with a similar task for the case of the foam barrier absence, it was shown, that the presence of an internal foam layer protects the pipe walls from the impact of a spherical explosion at its center, reduces the intensity and velocity of SW propagation in the pipe and weakens the speed of the formed vortex flows. The reliability of the proposed model is confirmed by satisfactory agreement of numerical solutions, obtained using the twoPhaseEulerFoam solver, with experimental data on the spherical explosion impaction on aqueous foam [10].

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