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Analysis the influence of aqueous foam rheological properties on the structure of wave impulse

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Abstract. The dynamics of a low-intensity plane shock wave during its propagation into a foam layer is numerically investigated for experimental data conditions performed in a horizontal shock tube. To describe the behavior of aqueous foam under weak impact, the model of aqueous foam developed by the authors was used, describing it as an elastic-viscoplastic system taking into account elastic properties in accordance with Hooke's law, and describes viscoplastic behavior by the Herschel—Bulkley conditions. The model was numerically implemented by creating the new solver in the OpenFOAM software. The analysis of the wave flow dynamics during the propagation of a weak air shock wave into the foam layer is carried out. The features of the elastic precursor formation are shown. Based on the results of calculations, the influence of the initial liquid volume fraction on the elastic-viscoplastic properties of the aqueous foam, on which the structure of the shock wave profile, its intensity and propagation velocity depend, is estimated. The reliability of the obtained calculations is confirmed by satisfactory agreement of numerical solutions with experimental data.

Keywords: aqueous foam, weak shock wave, elastic-viscous-plastic properties, numerical modeling, OpenFOAM software

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Анализ влияния реологических свойств водной пены на структуру и интенсивность слабых ударных волн

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Аннотация. Изучена динамика волнового течения при распространении в пенный слой слабых воздушных ударных волн различной интенсивности для условий литературных экспериментальных данных. При численном исследовании рассматриваемых процессов использована модель водной пены, описывающая ее поведение с учетом упруго-вязко-пластических свойств и численно реализованная в решателе, созданном авторами в пакете OpenFOAM. Проанализировано влияние начального объемного водосодержания пены на скорости распространения и амплитуды давлений упругого предвестника и основной волны сжатия. Достоверность полученных решений подтверждена их сравнительным анализом с экспериментальными осциллограммами давлений в пене.

Ключевые слова: водная пена, слабая ударная волна, упруго-вязко-пластические свойства, численное моделирование, пакет OpenFOAM

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Introduction

Study of aqueous foams as media with damping properties is the important area of scientific research, since the development of impact protection methods is of great scientific and practical importance.

Aqueous foam in a quasi-static state exhibits elastic properties at small deformations with the structure preservation [1]. When describing the dynamic response of the foam to a weak impact load, the existing theoretical models are mainly limited to specifying its viscoplastic behavior. The new experimental data, concerning shock impact on aqueous foam [2, 3], indicate the elastic precursor formation ahead of main wave. In this regard, the studies aimed at modeling and investigating wave processes in aqueous foam, taking into account its rheological features, namely, elastic-viscoplastic properties, are of interest [4, 5].

In the present work, dynamics of low intensity plane air shock wave (SW) during its interaction with the aqueous foam layer under experimental data conditions [3] is studied in order to analyze the effect of the foam elastic-viscous-plastic properties on the wave profile structure formation.

Governing equations

The proposed two-phase model of aqueous foam is based on the use of approaches [6, 7] and includes the conservation equations for phases mass and energy, mixture momentum and equation of the liquid volume fraction dynamics of the foam:

$$
\begin{gathered}
\frac{\partial(\alpha_i\rho_i)}{\partial t}+\operatorname{div}(\alpha_i\rho_i\vec{v})=0,\\
\frac{\partial(\alpha_i\rho_i(u_i+K_i))}{\partial t}+\operatorname{div}(\alpha_i\rho_i(u_i+K_i)\vec{v})=-p\frac{\partial\alpha_i}{\partial t}-\operatorname{div}(\alpha_i\vec{v}p)+\operatorname{div}(\alpha_i\vec{v}\cdot\boldsymbol{\tau})+\\
+\operatorname{div}(\alpha_i\vec{v}\cdot\boldsymbol{s})+\operatorname{div}(\alpha_i\gamma_{i,eff}\nabla h_i),\\
\frac{\partial(\rho\vec{v})}{\partial t}+\operatorname{div}(\rho\vec{v}\vec{v})=-\nabla p+\operatorname{div}\boldsymbol{\tau}+\operatorname{div}\boldsymbol{s},\\
\frac{\partial\alpha_1}{\partial t}+\operatorname{div}(\alpha_1\vec{v})-\alpha_1\operatorname{div}\vec{v}=\alpha_1\alpha_2\left(\frac{1}{\rho_2}\frac{d\rho_2}{dt}-\frac{1}{\rho_1}\frac{d\rho_1}{dt}\right),
\end{gathered}
\tag{1}
$$

where α_i, ρ_i, u_i, K_i, $\gamma_{i,eff}$, h_i are volume fraction, density, internal and kinetic energy, effective thermal conductivity and enthalpy for i-th phase ($i = 1$ corresponds to water, $i = 2$ corresponds to air), respectively; t is time, p is pressure, $\rho = \alpha_1\rho_1+\alpha_2\rho_2$ is aqueous foam density, $\boldsymbol{s}$ is stress tensor deviator.

Viscous stress tensor $\boldsymbol{\tau}$ is related to the mass velocity vector $\vec{v}$ by the ratio [7]:

$$
\boldsymbol{\tau}=\mu_{eff}(\nabla\vec{v}+\nabla\vec{v}^T)-\frac{2}{3}(\mu_{eff}\operatorname{div}\vec{v})\boldsymbol{I},
$$

where μ_{eff} is effective viscosity, $\boldsymbol{I}$ is unit tensor.

The system of equations (1) is closed by the perfect equations of state for liquid and gas.

To describe the elastic properties of aqueous foam in the case when the shear stresses do not exceed the elastic limit s_0, it is proposed to use Hooke's elasticity law [6]:

$$\boldsymbol{s} = \mu_s(\nabla\vec{e} + \nabla\vec{e}^T) - \frac{2}{3}(\mu_s \mathrm{div}\vec{e})\boldsymbol{I},$$

where μ_s is shear modulus, $\vec{e}$ is deformation vector.

The foam transition from the elastic to viscoplastic state occurs when the shear stress limit is exceeded and is determined by the von Mises yield fluidity criterion [8] with correction the components of stress tensor deviator $\boldsymbol{s}$:

$$\begin{cases} |I_2(\boldsymbol{s})| - \frac{1}{3}s_0^2 \le 0, \quad \tilde{s}_{kl} = s_{kl}, \\ |I_2(\boldsymbol{s})| - \frac{1}{3}s_0^2 > 0, \quad \tilde{s}_{kl} = s_{kl}\dfrac{s_0}{\sqrt{3|I_2(\boldsymbol{s})|}}. \end{cases}$$

To describe the viscoplastic properties of aqueous foam as a non-Newtonian fluid, the Herschel–Bulkley model with effective viscosity μ_{eff} is used [10]:

$$\mu_{eff} = k|\dot{\gamma}|^{n-1} + \tau_0|\dot{\gamma}|^{-1}.$$

Here k is consistency index, $\dot{\gamma}$ is shear rate, n is flow index [10], τ_0 is yield stress.

Numerical implementation of the model (1) was performed in the new solver created by the authors in OpenFOAM software [9].

Problem definition

The weak air SW dynamics in a shock tube containing the aqueous foam layer is studied in accordance with experiments [3]. The shock tube 3.79 m long consists of high pressure (HP, 0.75 m) and low pressure (LP, 2.0 m) chambers, filled with air, and movable tube segment with aqueous foam (FS, 1.04 m). The used foams of two types differ in the initial liquid volume fraction: $\alpha_{10}^1 = 0.0125$ and $\alpha_{10}^2 = 0.0333$. Pressure oscillograms on the SW were recorded by sensors l_1 and l_2 located in the foam layer at a distance of 3.52 m and 3.19 m from the left boundary of the experimental setup, respectively. Scheme of the experiment is shown in Fig. 1.

Process of the air SW formation with amplitude p_{air} occurs after the rupture of diaphragm ($t = 0$) located between the high and low pressure chambers. As in experiments [3], in this work two types of compression wave formation in the aqueous foam under the impact of SW, initiated in the gaseous region, were studied. Table 1 shows the values of pressure p_{air} and velocity of SW propagation D_{air} in air for the Mach numbers M = 1.3 (I) and M = 1.5 (II), as well as the location of pressure sensors l in the corresponding experiments. To determine the SW pressure amplitude in gas by Mach number $\mathrm{M} = D_{air}/c_{air}$ (c_{air} = 346 m/s is local speed of sound), the relations, following from the conservation laws of mass, momentum, and energy flows when passing through a shock jump, were used [7]:

$$\frac{p_{air}}{p_0} = \frac{2\gamma}{\gamma+1}\mathrm{M}^2 - \frac{\gamma-1}{\gamma+1},$$

where p_0 = 1 bar is pressure in undisturbed medium, γ = 1.4 is air adiabatic index.

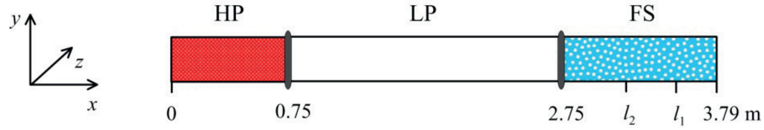

Fig. 1. Experiment scheme [3]: HP, LP are high and low pressure chambers, FS is the tube segment filled with aqueous foam, l_1 = 3.52 m, l_2 = 3.19 m are pressure sensors

Table 1

SW parameters in air for the considered experiments [3]

No	M	D_{air}, m/s	p_{air}, bar	l, m
I	1.3	450	1.8	3.52
II	1.5	520	2.5	3.19

Modeling results

The compression waves dynamics in aqueous foam, initially initiated in air for Mach numbers M = 1.3 ($p^{I}_{air} \approx 1.8$ bar) with $\alpha^1_{10} = 0.0125$, $\alpha^2_{10} = 0.0333$ (**I**) and M = 1.5 ($p^{II}_{air} \approx 2.5$ bar) with $\alpha^1_{10} = 0.0125$ (**II**) (see Table 1) was numerically studied. The computed results and corresponding experiments [3] are presented in Fig. 2 as pressure oscillograms at the sensor locations $l_1 = 3.52$ m (2,*a*) and $l_2 = 3.19$ m (2*b*) (see Fig. 1). Solid (*1*) and dashed (*2*) black lines indicate calculations with (*1*) and without (*2*) elastic properties of the foam, colored lines indicate experimental data [3].

Numerical solutions obtained on the basis of the elastic-viscous-plastic model of aqueous foam demonstrate two-stage structure of compression wave in the foam, consisting of the main wave and elastic precursor ahead of it, which is consistent with the experimental data [3].

Fig. 2,*a* shows the first series of calculations (**I**). In this case, the pressure amplitude of the main wave, recorded by the sensor l_1 located in the far zone from the gas-foam contact boundary, reaches $p_{foam} \approx 1.9$ bar in the foam with initial liquid volume fraction $\alpha^1_{10} = 0.0125$ and $p_{foam} \approx 1.85$ bar in the foam with $\alpha^2_{10} = 0.0333$.

The pressure amplitudes of elastic precursors are defined by the elastic limit s_0 and equal to $p^1_{prec} = s^1_0 = 0.19$ bar and $p^2_{prec} = s^2_0 = 0.23$ bar, respectively. When the compression wave moves through the foam layer, its velocity decreases by ~2.4 ($\alpha^1_{10} = 0.0125$) and ~3.9 ($\alpha^2_{10} = 0.0333$) times compared to the SW velocity in air. The elastic precursor velocity in a less dense foam layer ($\alpha^1_{10} = 0.0125$) is $D^1_{prec} \approx 233$ m/s, which is ≈ 1.6 times higher than the velocity $D^2_{prec} \approx 142$ m/s in the foam of high initial liquid volume fraction $\alpha^2_{10} = 0.0333$.

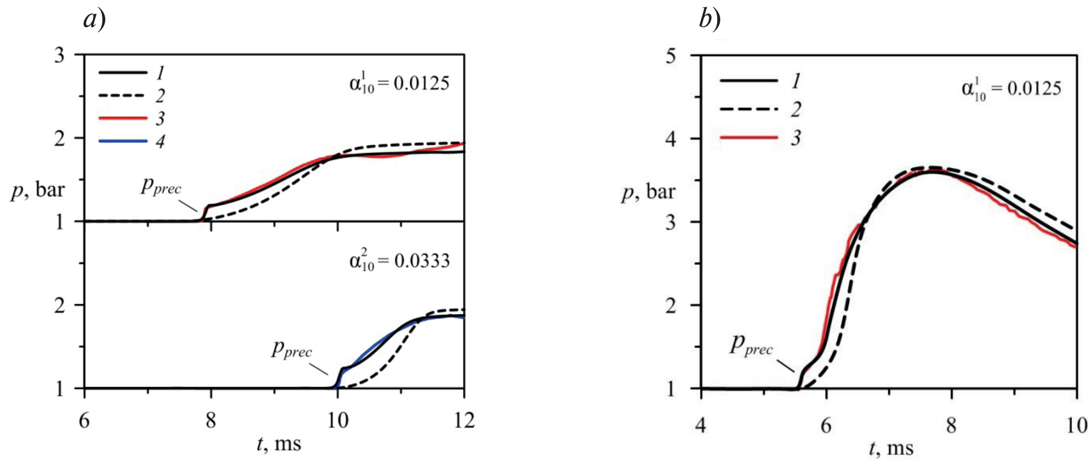

Fig. 2. Time dependencies of pressure $p(t)$ in aqueous foam for the first (**I**, *a*) and second (**II**, *b*) series of experiments, recorded by the sensor in positions l_1 (*a*) and l_2 (*b*). *1*, *2* correspond to calculations with and without taking into account elastic properties of the foam, *3*, *4* correspond to experimental data [3]; p_{prec} is elastic precursor. Approximation dependencies of the elastic precursor velocity (*1*) and main compression wave average velocity (*2*) on the initial liquid volume fraction of the foam α_{10} for calculation series **I** (blue curves) and **II** (black curves); points *3*, *4* correspond to calculated and experimental data

Fig. 2,*b* presents the comparative analysis of calculations (**II**) and the corresponding experimental data [3] obtained from the sensor l_2 = 3.19 m, located in the near zone from the boundary of foam layer and gas (see Fig. 1). This case matches the air SW propagation with Mach number M = 1.5 and amplitude $p^{II}_{air} \approx$ 2.5 bar into the foam with α^1_{10} = 0.0125. As in **I**, the compression wave in the foam has a two-stage structure. The main wave pressure amplitude reaches $p_{foam} \approx$ 3.6 bar, the elastic precursor amplitude in the considered case **II**, as in **I**, is $p^1_{prec} = s^1_0 =$ 0.19 bar (Fig. 2).

The calculated parameters of simulated problems and obtained values of pressures, main wave average propagation velocities D_w and elastic precursor velocities D_{prec} are summarized in Table 2.

To analyze the effect of foam initial liquid fraction on the dynamics of wave flow, additional calculations were performed for the case of air SW ($p^{II}_{air} \approx$ 2.5 bar) interaction with the foam layer of α^2_{10} = 0.0333. Fig. 3 shows the obtained approximation curves for the elastic precursor velocity D_{prec} (solid lines *1*) and average velocity of the main compression wave D_w (dashed lines *2*) depending on the foam initial liquid volume fraction α_{10}, calculated (*3*) and experimental (*4*) points [3]. Given in Fig. 3 numerical solutions correspond to series of experiments **I**, **II** (see Table 1) initiated in the air zone for SW velocities D_{air} = 450 m/s (M = 1.3) and D_{air} = 520 m/s (M = 1.5). The analysis of results showed that increase in the density of foam layer leads to a slowdown in velocities of elastic precursor and the main compression wave, which is consistent with the experimental data [3]. Extrapolation of obtained solutions and experimental data (see Fig. 3) shows that in the studied modes of dynamic action on aqueous foams, with a further increase in the initial liquid volume fraction the velocities of the elastic precursor and the main wave slow down, which can lead to a single-stage structure of compression wave front.

Table 2

Parameters of the wave flow formed during the air SW propagation in aqueous foam

p_{air}, bar	x, m	α_{10},%	τ_0, bar	μ_s, bar	p_{foam}, bar	D_w, m/s	D_{prec}, m/s
1.8	3.52	1.25	0.19	0.16	1.7	187	233
2.5	3.19			0.22	3.6	200	275
1.8	3.52	3.33	0.23	0.03	1.8	115	142
2.5	3.19			0.04	3.8	120	160

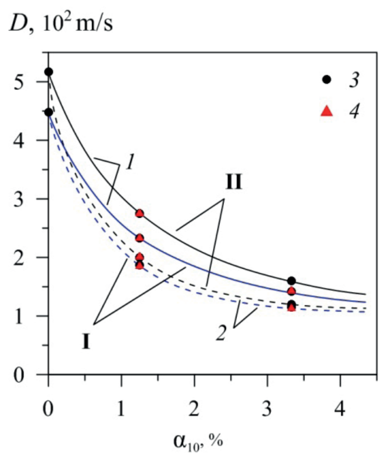

Fig. 3. Approximation dependences of the elastic precursor velocity (*1*) and main compression wave average velocity (*2*) on the initial liquid volume fraction of the foam α_{10} for calculation series **I** (blue curves) and **II** (black curves); points *3*, *4* correspond to calculated and experimental data

Conclusion

The propagation process of different intensity air SW in a shock tube containing the aqueous foam layer is studied in accordance with the experimental conditions [3]. The behavior of aqueous foam under a weak impact is described by the model of gas-liquid elastic-viscous-plastic medium developed by the authors, which takes into account the elastic properties of the foam in accordance with Hooke's law and the viscoplastic behavior by using the Herschel – Bulkley conditions. Numerical implementation of the model equations is carried out in the author's solver of the OpenFOAM package. The calculation results revealed a two-stage structure of the compression wave front in aqueous foam, caused by the elastic precursor formation ahead of the main wave. It has been established, that the pressure amplitude of elastic precursor is determined by the initial liquid volume fraction of the foam and does not depend on the initial intensity of the impact, limited by the condition of preserving the foam structure. The extrapolation of obtained solutions for the conditions of shock wave initiation in air with Mach numbers M = 1.3, 1.5 showed that velocities of the elastic precursor and main compression waves in aqueous foam decrease as the initial density of the foam increases, which can lead to equalization of their velocities, i.e. to the elastic precursor degeneration. Reliability of the obtained solutions is confirmed by their satisfactory agreement with the corresponding experimental data.

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