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Formation of supersonic steam-water jets accompanied by generation of acoustic pulsations

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Abstract. The features of supersonic steam-water jets formation under outflow through a thin nozzle from a high-pressure chamber are considered. The modes of emerging vibration processes are investigated, depending on variation of initial saturation states determined by pressure and temperature. The proposed system of model equations for steam-water mixture in three-dimensional formulation, in two-temperature, single-pressure, and single-velocity approximations, takes into account the interphase heat exchange, evaporation and condensation phenomena. The numerical implementation of this problem is carried out by the authors developed solver in the OpenFOAM package. The process of supersonic jet development with the formation of Mach disk is studied and the causes of acoustic pressure pulsations are investigated. The analysis of influence of initial saturation states of vapor-water fluid located in a high-pressure chamber on intensity and frequency of acoustic vibrations is given. To validate the numerical method using the OpenFOAM package, the obtained numerical solution is compared with an experimental picture of a supersonic nitrogen jet flowing through a cylindrical nozzle from a high-pressure reservoir.

Keywords: thin nozzle, fluid outflow, Mach disk, acoustic pressure pulsations, numerical modeling, OpenFOAM package

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Формирование сверхзвуковых пароводяных струй, сопровождающееся генерацией акустических пульсаций

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Аннотация. Рассмотрены особенности формирования сверхзвуковых пароводяных струй, истекающих через тонкое сопло из камеры высокого давления. Исследованы режимы возникающих вибрационных процессов в зависимости от изменения начальных состояний насыщения, определяемых давлением и температурой. Предлагаемая система модельных уравнений пароводяной смеси в трехмерной постановке включает двухфазные уравнения динамики в двухтемпературном, однодавленческом, односкоростном приближениях с учетом межфазного теплообмена, явлений испарения и конденсации. Численная реализация поставленной задачи проведена с применением разработанного авторами решателя в среде открытого пакета OpenFOAM. Изучен процесс развития сверхзвуковой струи с образованием диска Маха и исследованы причины образования акустических пульсаций давления. Дан анализ влияния исходных состояний насыщения водного флюида, находящегося в камере высокого давления, на интенсивность и частоту возникающих акустических колебаний. Для обоснования достоверности используемого численного метода с применением пакета OpenFOAM проведено сравнение полученного численного решения с экспериментальной фотографией сверхзвуковой струи азота, истекающей через цилиндрическое сопло из резервуара высокого давления.

Ключевые слова: тонкое сопло, истечение флюида, диск Маха, акустические пульсации давления, численное моделирование, пакет OpenFOAM

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Introduction

Recently, it has been of interest the studying of processes that occur during jet supersonic flows, the consequence of which is the generation of acoustic disturbances in the form of noise or sound vibrations. The mentioned phenomena are associated with the need to solve noise reduction problems on industrial devices of various technological productions. Among the studies in this direction, it should be note the work of [1], in which various aspects of modeling the noise of pulsed jets owing from a conical nozzle are considered. In the work [2], the analysis of gas injection into closed volume with liquid at periodic pressure pulsations in the gas volume was studied. The initial stage of boiling liquid outflow during sudden depressurization of a high-pressure chamber using the numerical method of movable Lagrangian grids was carried out in [3] for the conditions of experiments series [4]. In [3] the influence of initial equilibrium water state and the frequency of nucleation on the evolution of steam-water jet shape were analyzed. In the work [5] the dynamics of vapor jet formation with supercritical state parameters outflowing from a high-pressure vessel through a thin nozzle was investigated by numerical approach implemented in the OpenFOAM package.

The proposed work is continuing of investigations [3–5] which is aimed to analysis of a spatial axisymmetric outflow through a thin nozzle of a steam-water jet in the modes of supersonic flow velocities under experimental conditions [4], in order to study the initial conditions influence for the formation of pulsation pressure disturbances with evaluation of their intensity and oscillation frequencies.

Problem statement and model equations

For solving the considered process a two-phase model of gas-liquid mixture is used with one-pressure, one-velocity, and two-temperature approximations, taking into account interfacial heat exchange, evaporation and condensation phenomena. The system of differential equations in three-dimensional Cartesian coordinate system includes the equations of continuity, momentum and energy conservation of phases [6, 7]:

$$\frac{\partial(\alpha_i\rho_i)}{\partial t}+\operatorname{div}(\alpha_i\rho_i\vec{v})=\Gamma_i,$$

$$\frac{\partial(\alpha_i\rho_i\vec{v})}{\partial t}+\operatorname{div}(\alpha_i\rho_i\vec{v}\vec{v})=-\alpha_i\nabla p+\operatorname{div}(\alpha_i\boldsymbol{\tau}_i)+\Gamma_i\vec{v},$$

$$\boldsymbol{\tau}_i=\mu_i\left(\nabla\vec{v}+\vec{v}^{\mathrm{T}}\right)-\frac{2}{3}\left(\mu_i\operatorname{div}\vec{v}\right)\mathbf{I},\qquad(1)$$

$$\frac{\partial(\alpha_i\rho_i(e_i+K_i))}{\partial t}+\operatorname{div}(\alpha_i\rho_i(e_i+K_i)\vec{v})=-p\frac{\partial\alpha_i}{\partial t}-\operatorname{div}(\alpha_i\vec{v}p)+$$

$$+\operatorname{div}(\alpha_i\gamma_{i,eff}\nabla h_i)+K_{ht}(T_j-T_i)+L_i\Gamma_i,\ \gamma_{i,eff}=\frac{c_{p_i}}{c_{V_i}}\gamma_i.$$

The mass transfer rate $\Gamma_i = dm_i/dt$ is determined by the intensity of evaporation (condensation) process in the equilibrium saturation state described by Arden Buck equation [8].

$$p_s(T)=6.1121\exp\left(\left(18.678-\frac{T}{234.5}\right)\left(\frac{T}{257.14+T}\right)\right).\qquad(2)$$

The following notations were used in the above equations: $\vec{v}$ is mass velocity vector, p is pressure, ρ_i is the density, α_i is volume fraction content, $\mathbf{I}$ is unit tensor, μ_i is dynamic viscosity, c_{pi}, c_{Vi} is specific heat capacities at constant pressure and volume, respectively, γ_i, $\gamma_{i,eff}$ is true and effective thermal diffusivities, respectively, e_i is internal energy, K_i is kinetic energy, h_i is enthalpy, T_i is temperature, L_i is latent heat of vaporization/condensation, K_{ht} is heat transfer coefficient. The subscript $i = l, g$ corresponds to liquid and vapor phases. The thermodynamic properties of water and vapor are described by perfect equations of state. For isobaric heat capacity c_p the temperature dependence in form of polynomial function JANAF [8] was applied.

a) *b*) *c*)

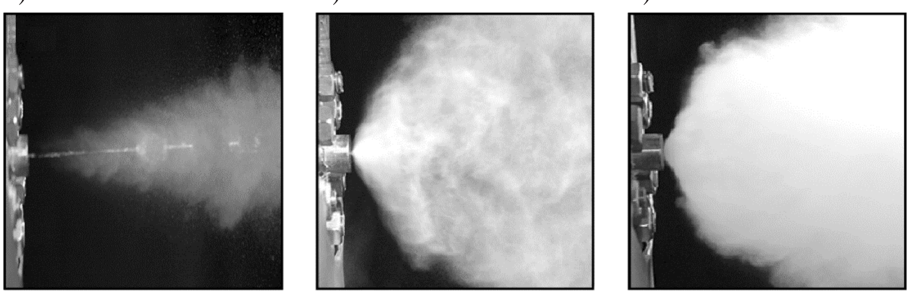

Fig. 1. Photographs of boiling water jets under outflow through a thin cylindrical nozzle at various initial states [4]. T_0 = 422 K (*a*), 490 K (*b*), 650 K (*c*)

In this article, the numerical simulation of experiments [4] was carried out. In [4] is assumed, that at the initial time moment in cylindrical high-pressure tank of length x_h = 10 mm and radius y_h = 10 mm there is a vapor-water mixture. The depressurization process resulting from the rupture of the diaphragm located at the right end of the cylindrical nozzle of length x_s = 0.5 mm and radius y_s = 0.25 mm, leads to outflow of boiling water with jet formation. The photographs of water jets outflow for various initial conditions [4], is shown in Fig. 1.

Reliability of numerical implementation method

The computer implementation of the proposed gas-vapor-liquid mixture model was carried out using the reactingTwoPhaseEulerFoam solver modified by the authors in OpenFOAM package [5, 9] in an axisymmetric formulation by an adaptive grid.

To justify the reliability of the numerical modeling method by OpenFOAM package, a comparative analysis of calculations with the experiment of [10] was carried out. In [10], the process of formation of a supersonic nitrogen jet when outflowing through a cylindrical nozzle with a diameter of d = 10 mm from a high-pressure tank with a length of l = 38 mm, at an initial pressure of p_{0r} = 4 MPa and a temperature of T_{0r} = 300 K in to the environment with p_b = 0.1 MPa, T_b = 300 K was investigated. Below, a system of equations is given for compressible medium describing the dynamics of simulated experiment, which includes the equations of conservation of mass, momentum and energy in a single-phase approximation, numerically implemented in the package OpenFOAM [8]:

$$\frac{\partial \rho}{\partial t} + \mathrm{div}\left(\rho \vec{v}\right) = 0, \quad \frac{\partial (\rho \vec{v})}{\partial t} + \mathrm{div}(\rho \vec{v}\vec{v}) = -\nabla p + \mathrm{div}\boldsymbol{\tau}, \tag{3}$$

$$\frac{\partial \left(\rho\left(e+K\right)\right)}{\partial t} + \mathrm{div}(\rho\left(e+K\right)\vec{v}) = -\mathrm{div}(\vec{v}p). \tag{4}$$

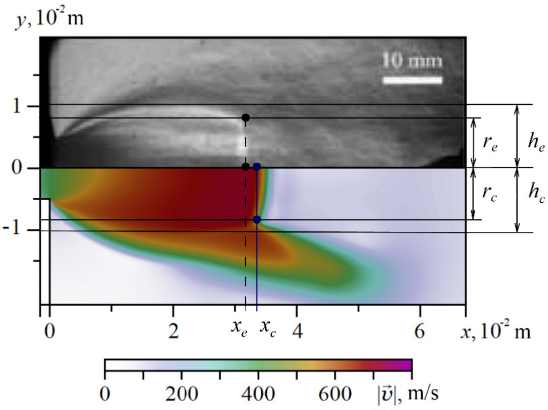

Fig. 2. Experimental photograph of nitrogen gas outflow [10] at the time moment t = 0.2 ms for initial pressure ratio p_{0r}/p_b = 40/1 (upper fragment). The calculated velocity magnitude field for the same experiment [10] obtained using the OpenFOAM package (lower fragment)

Fig. 2 shows a photograph of a nitrogen jet at time t = 0.2 ms from the beginning of outflow process [10] (upper fragment). In the lower fragment of the same Fig. the results of the numerical solution are presented at the time under consideration, in the form of the velocity magnitude field $\left|\vec{v}(x,y)\right|$ using the Eqs. (3–4) in a problem statement similar to the experiment [10]. In numerical solution, as in the experiment, a supersonic axisymmetric gas jet acquires a barrel shape with the formation of normal (Mach disk) and hanging (along the boundary of the 'barrel') compression jumps and has a degree of incalculability $n = p_a/p_b > 2$, where p_a is the pressure at the nozzle slice, p_b is ambient pressure. The distance from the nozzle outlet to Mach disk on the axis of gas jet was estimated by the formula [11]:

$$x_M = 0.67d\left(\frac{p_a}{p_b}\right)^{0.5}. \quad (5)$$

The analytical value x_M = 33.58 mm (5) corresponds to the calculated values of the simulated experiment p_a = 2.5 MPa, p_b = 0.1 MPa. The visualization of computed results (Fig. 2) showed the coincidence of the distances under consideration: $x_c = x_M$. The value x_e = 33.2 mm obtained from the experimental photo has an error compared to (5): $\delta_x = (|x_e - x_M|/x_M)\cdot 100\% \approx 1\%$. The estimates of the relative error for experimental (subscript *e*) and calculated values (subscript *c*) for the radius of Mach disk $r_e \approx 7.8$ mm, $r_c \approx 7.5$ mm, have the following values: $\delta_r = (|r_e - r_c|/r_c)\cdot 100\% < 5\ \%$, and the height of the barrel: $h_c = h_e \approx 20$ mm. The analysis showed a satisfactory agreement between the experimental data [10] and the numerical solutions obtained using the OpenFOAM package.

Analysis of numerical results

The results of numerical simulation of main problem about jet flow formation of a steam-water mixture are presented in Fig. 3 at time t = 35 μs in the form of velocity magnitude fields $|\vec{v}(x, y)|$ (left fragment) and volumetric water content α_l (right fragment). The calculated pressure dependences on time $p(t)$ at selected points of the studied experiments [4], located on the axis of symmetry of the jet are presented on Fig. 4. The notations (*a*, *b*, *c*) in Figs. 3, 4 correspond to the experimental photographs are shown in Fig. 1.

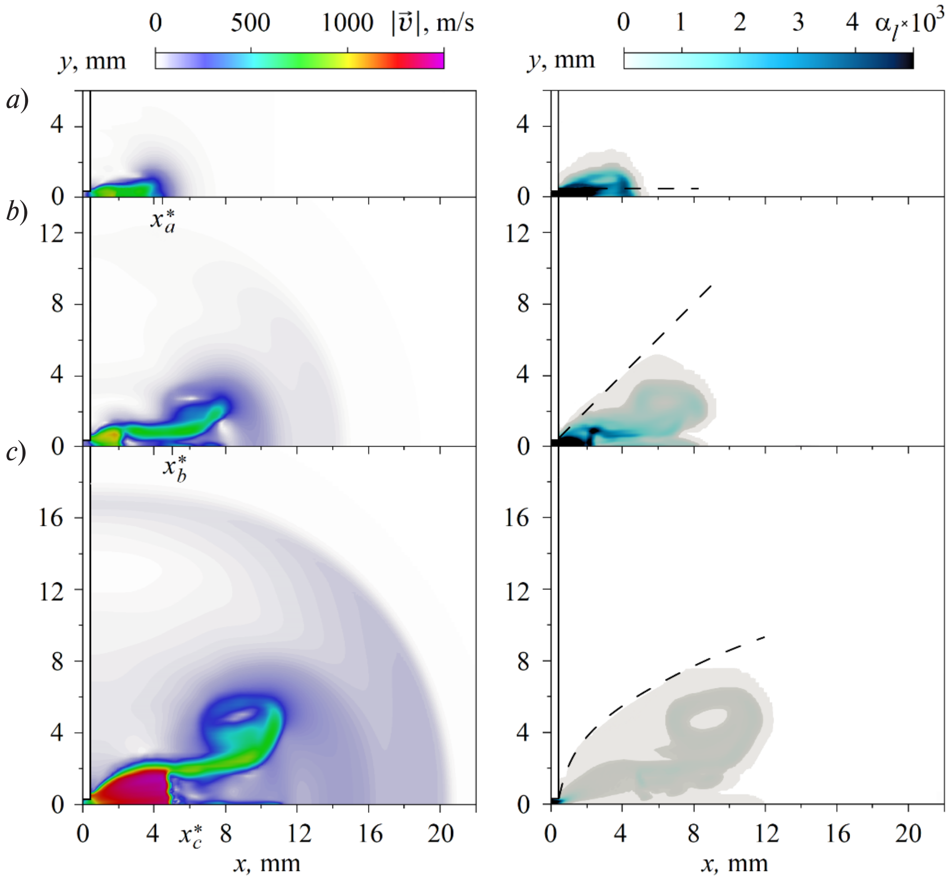

Fig. 3. The calculated velocity magnitude field $|\vec{v}(x, y)|$ (left fragment) and volumetric water content α_l (right fragment) of jet formation process at time moment t = 35 μs for different initial conditions shown in Fig. 1, *a*, *b*, *c*

Fig. 3, *a* shows the results of simulation of the outflow process for the initial values of saturation pressure p_0 = 0.43 MPa and temperature T_0 = 422.6 K [4]. As in the experiment [4] (Fig. 1, *a*), in the calculations it is not jet expansion, and subsonic outflow regime is maintained with Mach number M ≈ 0.8. The time dependence of calculated pressure $p(t)$ in control point x_a^* = 4.5 mm on the jet axis fixes a single pressure pulse due to the moment of arrival of the jet leader. Periodic pressure pulsations were also not detected in this case (Fig. 4, *a*).

The process of forming a vapor-water jet at initial values of saturation pressure p_0 = 2.14 MPa and temperature T_0 = 490.1 K in accordance with the experiment [4] (Fig. 1,*b*) is shown in Fig. 3,*b*. In this case, as in [4], the jet acquires a close to conical shape, which is shown in the right fragment of Fig. 3,*b* as a dashed line skirting the boundary of existence the volumetric water content in jet stream. In this outflow regime a supersonic jet with a maximum value of velocity $|\vec{v}|$ ≈ 900 m/s (M ≈ 1.7) is formed.

In Fig. 3,*c*, the results of calculation are given for the outflow regime with an initial temperature of T_0 = 650 K and pressure p_0 = 22.73 MPa, which corresponds to the initial state near critical point of the vapor-water fluid. As noted in the experiment [4], under the given initial conditions, there is an intense expansion of the jet, which acquires a shape close to parabolic, shown in the right fragment of Fig. 3, *c* by the dashed line. Supersonic (M ≈ 2.22) expiration velocity of $|\vec{v}|$ ≈ 1200 m/s are achieved here.

At the boundary of expanding supersonic jets (see the left fragment of Fig. 3, *b*, *c*) hanging and normal (Mach disk) compression jumps are formed. The lateral boundaries of jet are also characterized by a supersonic flow mode. The formed jet supersonic flow in the near zone of the axis of symmetry forms regions of periodically changing pressure (Fig. 4).

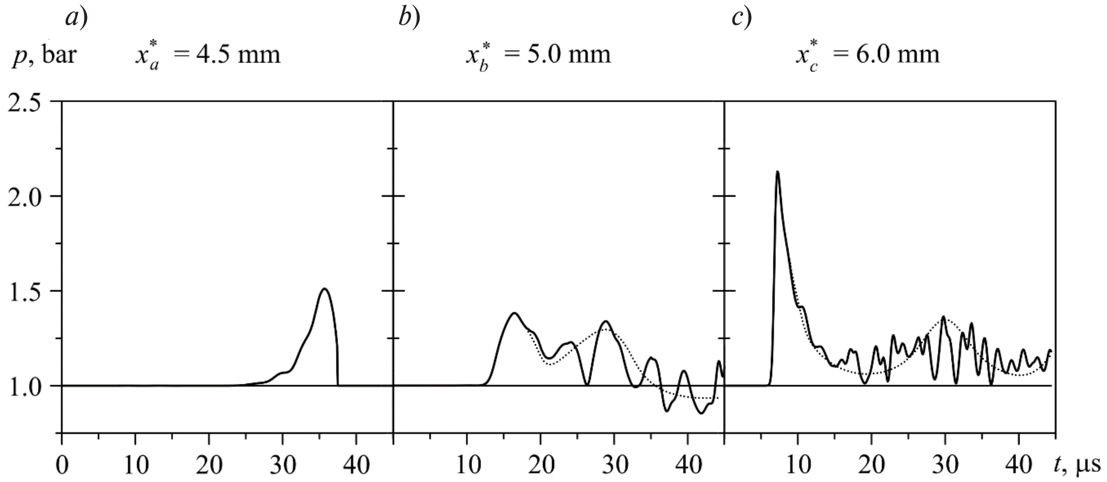

Fig. 4. Calculated pressure time dependences $p(t)$ on the points x^* for different initial conditions shown in Fig. 1, *a*, *b*, *c*

The calculated small-scale high-frequency pressure pulsations have a characteristic oscillation period of $\tilde{T} \approx 8$ μs, which correspond to frequency of $\tilde{\upsilon} \approx 125$ kHz for outflow regime at T_0 = 490.1 K (Fig. 4, *b*) and $\tilde{T} \approx 2$ μs ($\tilde{\upsilon} \approx 500$ kHz) at T_0 = 650 K (Fig. 4,*c*).

On Fig. 4, *b*, *c* by dotted lines marked the initial stage on formation of large-scale and low-frequency pressure pulsations with $\tilde{T} \approx 30$ μs ($\tilde{\upsilon} \approx 33$ kHz) (Fig. 4,*b*) and with $\tilde{T} \approx 20$ μs ($\tilde{\upsilon} \approx 50$ kHz) (Fig. 4,*c*).

Conclusion

The non-stationary process of the outflow of a vapor-water mixture from a high-pressure chamber through a thin nozzle on basis of developed two-phase model in two-temperature, one-pressure, one-velocity approximations with take into account interphase heat exchange, evaporation and condensation phenomena was investigated. Numerical modeling of considered problem using by the authors solver developed in the OpenFOAM package was carried out. The calculations the influence of initial saturation states of aqueous fluid on the formation of the jet flow were estimated.

It is shown that with an increase the initial saturation temperature and pressure, the outflow process transformed from subsonic for supersonic regime. Supersonic outflow regimes was accompanied by the formation of conical and then parabolic jet shapes, and are characterized by supersonic pressure pulsations in a range of 30–50 kHz. It was not the jet pulsations when the initial temperature decreases.

The calculations obtained are in qualitative agreement with the photographs of experiments on the boiling water outflow, and with the experiment on outflow of nitrogen jet, confirming the reliability of used numerical simulation method.

The results will be important and useful as recommendations in solving issues related to noise reduction problems in various industrial plants.

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