Numerical investigation the dynamics of vaporization at the flow of liquid methane in channel with variable section

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Abstract. Numerically transient dynamics of vaporization of the liquid bubbling up methane flow in the Laval nozzle are analyzed. The equation conservation of mass, momentum and energy with averaging of Favre are used. For numerical modeling of cavitation the additional equation for transport the volume fraction of vapour with special source terms for evaporation and condensations is used. Non-stationary process of evaporation is analyzed in various checkpoints in diffuser portion of the nozzle are investigated. By the study of the unsteady dynamics of changes the characteristic hydrodynamic quantities of two-phase gas-liquid flow, the main jet stream pattern of destruction of the process of liquid methane at the expiration of the nozzle throat are identified.

1. Introduction

Two-phase flows are the primary working fluid in power plants, chemical engineering, in different elements of the new technology. The processes of formation and evolution of bubbles play an important role in physics, chemistry, technology, medicine and many other areas of life. The great practical and the fundamental interest in the problem of boiling liquids, in which the decisive role played by the emergence and evolution of steam bubbles are important and still far from the final solution. The raging streams are used in many technological processes. Among them two-phase flow in boilers and steam generators, flow saturated and subcooled liquid in channels of the cooling system, a special role is played by the two-phase expires in accidents at nuclear reactors, and many others [1-2]. The increase in the rate of intensification technological processes, further increasing the technical level of production leads to the fact that you are using the ultimate and critical thermal load in the power equipment. Wherein the liquid the coolant may be in a nonequilibrium or metastable state, when is rapid reduction of the pressure in the liquid at the end of the boiling liquids from vessel high pressure through short channels or of the Laval nozzle to the atmosphere. The initial parameters of the liquid, close to the thermodynamic critical point, overheating can achieve the limit values and the flow can be substantial homogeneous vaporization. The relevance of the study the critical conditions of the flow and explosive boiling in superheated liquid flows is connected with the problem of safety of energy equipment, in particular, with the objectives description of gap elements cooling systems, in relation to the needs of nuclear power engineering, cryogenic engineering, environment [1-2].

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2. Governing equations

To simulate the motion of a mixture of liquid and vapor phases Favre-averaged Navier-Stokes equation for a homogeneous medium with a variable density are used, supplemented with the equation for the enthalpy transfer in the form [2-4]:

$$\frac{\partial \rho_m}{\partial t}+\frac{\partial(\rho_m u_j)}{\partial x_j}=0, \tag{1}$$

$$\frac{\partial(\rho_m u_i)}{\partial t}+\frac{\partial(\rho_m u_i u_j)}{\partial x_j}=-\frac{\partial \hat{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\left(\mu_m+\mu_t\right)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right)\right], \tag{2}$$

$$\frac{\partial}{\partial t}\left[\rho_m\left(h+f_V L\right)\right]+\frac{\partial}{\partial x_j}\left[\rho_m u_j\left(h+f_V L\right)\right]=\frac{\partial}{\partial x_j}\left[\left(\frac{\mu_m}{\mathrm{Pr}_L}+\frac{\mu_t}{\mathrm{Pr}_t}\right)\frac{\partial h}{\partial x_j}\right], \tag{3}$$

$$\frac{\partial \alpha_L}{\partial t}+\frac{\partial(\alpha_L u_j)}{\partial x_j}=\frac{1}{\rho_L}(\dot{m}^+ + \dot{m}^-) \tag{4}$$

There x_i - Cartesian coordinates, u_i - the components of the velocity vector, t -time, $\hat{p}=p+(2/3)\rho_m k$, p - pressure, k - kinetic energy of turbulent pulsations, $\rho_m=\alpha_L\rho_L+(1-\alpha_L)\rho_V$ - the density of the mixture, ρ_L - the density of the liquid, ρ_V - vapor density, α_L - the volume fraction of the liquid phase in the mixture, δ_{ij} - the Kronecker symbol, $\mu_m=\alpha_L\mu_L+(1-\alpha_L)\mu_V$ - dynamic coefficient viscosity of the mixture, μ_L , μ_V - the coefficients of dynamic viscosity of the liquid and vapor respectively, $h=c_p T$ -specific enthalpy, T - temperature, c_p - thermal capacity coefficient at constant pressure, f_V - is the mass fraction of vapor, defined by the relation $f_V=\rho_V(1-\alpha_L)/\rho_m$, L - latent heat of vaporization, Pr_L, Pr_t - molecular and turbulent ($\mathrm{Pr}_t=0.9$) Prandl number, $\dot{m}^-$, $\dot{m}^+$ - model source components, taking into account the process of vapor condensation and liquid evaporation. Assuming the presence of non-condensable gases in the liquid with a mass content f_g, in the paper [4] are represented equations for $\dot{m}^-$, $\dot{m}^+$ in the form of

$$\dot{m}^+=C_e\frac{\max(1.0,\sqrt{k})(1-f_V-f_g)}{\gamma}\rho_L\rho_V\sqrt{\left(\frac{2}{3}\frac{p_V(T)-p}{\rho_L}\right)},\quad p<p_V(T), \tag{5}$$

$$\dot{m}^-=C_c\frac{\max(1.0,\sqrt{k})\,f_V}{\gamma}\rho_L\rho_V\sqrt{\left(\frac{2}{3}\frac{p_V-p}{\rho_L}\right)},\qquad p\geq p_V(T) \tag{6}$$

In relations (5) - (6) $p_V(T)$ - saturation pressure of methane at the temperature T , γ - coefficient of surface tension of liquid methane. Empirical constants C_e, C_c that determine the rate of evaporation and speed of condensation and have values $C_e/\gamma=1.665\cdot10^3$, $C_c/\gamma=1.225\cdot10^3$. The coefficient of turbulent viscosity is calculated according to the formula of Kolmogorov-Prandl $\mu_t=C_\mu\rho_m k^2/\varepsilon$, where to determine the kinetic energy of turbulence k and rate of dissipation ε two-parametrical model of turbulence $k-\varepsilon$ is applied [5].

3. Results

The study of flushing flows of liquid methane at various modes for a plane Laval nozzle are investigated, the design scheme of which is shown on figure 1. Minimum cross-section of the nozzle is located at $x_1 =$ 0.1 m ($l_6 =$ 100 mm in figure 1), the height is $l_4 =$ 4 mm. The widening of the nozzle ($0.1 \le x_1 \le 0.25$ m) has a length of $l_3 =$ 150mm, width of the nozzle at the cut in a section $x_1 =$ 0.25 m have the size $l_2 =$ 46 mm. The cone angle of the diffuser nozzle is $\gamma = 6^0$. To study the dynamics of the jet breaking the unsteady changing of physical quantities, characterizing the gas-vapor stream, was investigated, namely, the value of the longitudinal rate u_1, the value of the local void fraction α_V, density mixture ρ_m, the static P_{st} and the total pressure P_{tot} in the three control points with coordinates $x_p^i (i = 1,3) =$ 0.11m, 0.15m, 0.23m. The control points are located on the axis of the nozzle, as shown in figure 1. For simulation of flow in a Laval nozzle a grid with 124000 finite volumes with a significant concentration in the area of throat constriction was used. In the calculation of turbulent flows special attention should be paid to mesh quality near the walls, in regions of large gradients of flow parameters.

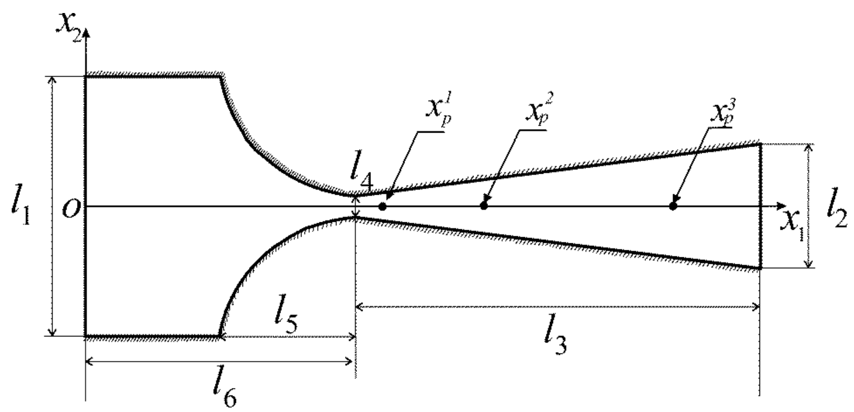

Figure 1. Computational domain of the Laval nozzle with control points $x_p^i (i = 1,3)$.

For low pressure flow the inlet pressure is P_0 = 0.57 MPa, the outlet of P_b = 0.30 MPa and the inlet temperature of liquid methane $T_0 =$ 124 K. On figure 2 the distribution over time at the control points $x_p^i (i = 1,3)$ of variables α_V, u_1 are shown. The curves marked with numbers corresponding to the respective number of control points. From the distribution of void fraction α_V, shown in figure 2, this demonstrates that the dynamics of the jet breaking happens over time as the waves of pressure in diffuser part of the nozzle are moved. Upon reaching the control point 1, in the neighborhood of a given point the phase transitions processes are intensified, leading to changes the liquid medium to the gas-droplet state in a very short period of time $\Delta t \le 0.001$ s. Volumetric gas content in the given point rises sharply to the value of α_V = 0.15 and further reaches steady-state value. As the distance from the throat of nozzle the destruction of the jet increases and volumetric gas content increases in the points 2, 3 to α_V = 0.55, 0.75 respectively. After the passage the pressure wave the value of α_V in all the control points reaches a certain steady-state value and does not change. The figure 2 shows changes the axial velocity distribution at three points as the distance from the throat of the nozzle. Dynamics of change the speed over time in the diffuser part of the nozzle into three sections can be divided. The first part is a linear plot of growth rate, then at the passage of the pressure wave and the strong intensification of phase transitions of the second portion with a sharp speed increase is formed.

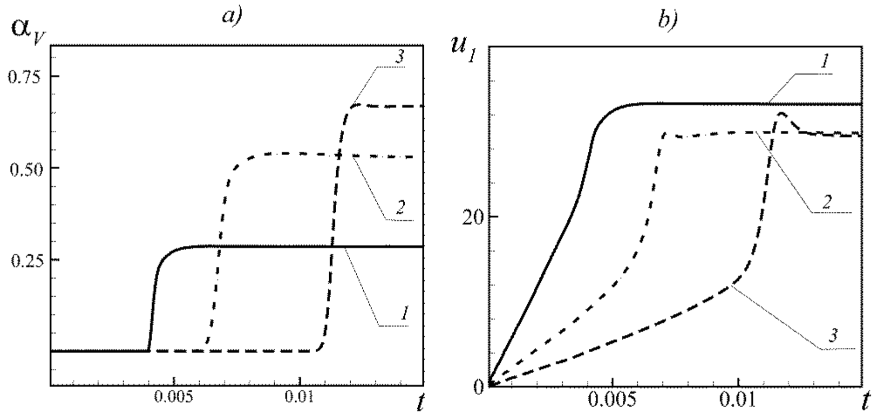

Figure 2. The distributions over time of different variables in control points $x_p^i (i = 1,3)$:
$a)\ \alpha_V$; $b)\ u_1$

The third section characterizes the speed for steady state. Then upon reaching a certain time when a steady state is established in the flow, the speed also changes not much. The some differences in the dynamics of speed in different control points, that describe the processes of destruction of the jet we will note. Closer to the throat the gradients increasing of speed in the initial stage of destruction are greatest, but as the distance from the nozzle throat they are reduced. The figure 3 shows contours for the case of low-pressure flow at P_0 = 0.57 MPa, $\varepsilon_a = 0.76$, $\Delta t_H = 4.0^0$ K for three points time t_i = 0.005, 0.025, 0.2s. From the figure 3a shows that the process of destruction the jet is initiated, when an intensive formation of bubbles near the walls of the channel in the diffuser part of the nozzle is started. The intensification of the process of growth of bubbles near the throat accompanied by the formation of the pressure zone equal to the vapor pressure of the saturated methane. The area of low pressure (figure 3*b*) is displaced downward stream, accompanied by the destruction of the jet liquid methane and increase in the content of bubbles in the flow core. The complete destruction of the jet occurs at time t_3 = 0.2 s., as illustrated in figure 3*c*. This figure shows that in the minimum section of the nozzle incompressible fluid is moving, and the process of vaporization develops directly after passing the nozzle throat. The characteristic "stretching" of the contours of the volumetric gas phase in the central part of the nozzle shows that vapor phase are intensively formed in the boundary layer along the channel walls and then extends to the axis of the nozzle. At some distance from the minimum section the liquid kernel disappears and bubble transitional structure will be transformed to the vapor-bubble flow. In this paper to simulate the vaporization process a model with an additional transport equation of volume of phase with the source terms for modeling the speed of condensation and evaporation is used [5,6]. The model assumes that the rate of change of phase state is proportional to the characteristic speed, as which the relative velocity between the liquid and bubbles is selected. The relative velocity V_{ch} of the same order as the velocity of turbulent fluctuations, for which the estimate $V_{ch} \sim \sqrt{k}$ is fair. Comparing the calculated data on the distribution of the void fraction of vapor, is shown in figure 2 it can be concluded that the structure of wet steam flow in the diffuser part of the nozzle for low-pressure have the some characteristic features. The vapor phase initially is greater formed in the boundary layer near the walls of the channel and then will extend with the flow to the nozzle axis. The characteristic feature seen in the fact that the increase the velocity of bubbling flow in the Laval nozzle is accompanied by a decrease in the volumetric void fraction in the central part of the expanding portion of nozzle, but and in the near-wall regions it increases. For high-pressure flow rate of vaporization in the region near the wall increases due to the increase of turbulent kinetic energy near the walls and consequently the growth of the characteristic speed. Small nucleation particles that appeared near the walls, growing in size and are carried by flow to the central portion of the nozzle.

Due to the increased flow rate, the time for the growth of bubbles decreases, and they more quickly propagate downstream, which leads that the volumetric void fraction near the axis of the nozzle is decreased.

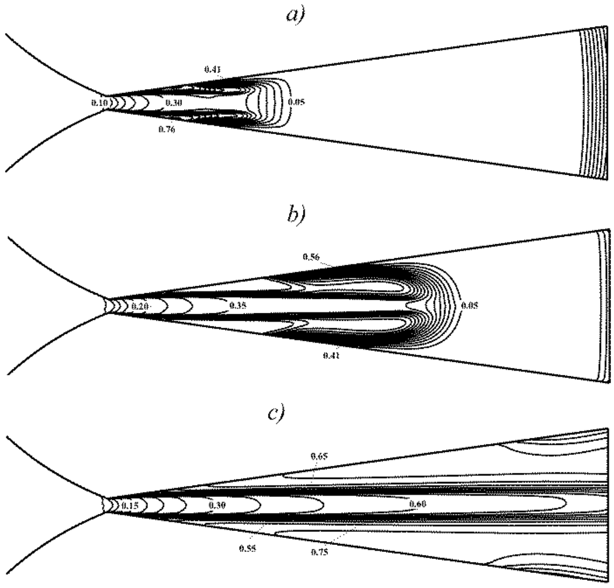

Figure 3. The contour of distributions of α_V for different times *a*) $t = 0.005$ s; *b*) 0.025 s; *c*) 0.2 s

The transient dynamics of the flow of liquid methane bubbling up in the Laval nozzle is numerically analyzed, specific processes of evaporation in the various control points in the diffuser section of the nozzle are studied. By the study of non-stationary dynamics of characteristic hydrodynamic values of two-phase gas-liquid flow changing over time, the basic laws of the flow of process failure methane liquid stream flowing out from the nozzle throat is revealed.

Work is performed with financial support of the Ministry of Education and Science of the Russian Federation, the Agreement on a subsidy No. 14.577.21.0151 of 28.11.2014. The identifying number of the project RFMEFI57714X0151.

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