Modeling of critical filtration regimes of vapor-liquid flow

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Abstract. Critical flows are widely used in power engineering. Such flows are characterized by non-stationary processes, active vaporization due to a sharp drop in pressure when the mixture flows from a high-pressure medium to an atmospheric pressure medium, which especially necessitates the study of the parameters of such flows in emergency situations, such as an emergency depressurization of a pipeline or cooling system. Due to the presence of two phases and the transiency of the processes, it is necessary to develop methods for numerical simulation of this process. The energy apparatus with a granular layer adds an additional level of complexity to the study of critical flows, namely, the effect of granular backfill on the characteristics of a two-phase flow. A new model for numerical simulation of the critical outflow of a vapor-liquid flow from a channel with a granular backfill has been created. The values of the mass flow rate of the mixture, the effect of vapor content on the critical flow rate, and the effect of geometric parameters of the granular backfill on the critical mass flow rate are obtained. The calculated data were compared with the experiment, and new data were obtained in a wider range of mass vapor content compared to experimental study.

1. Introduction

Due to the widespread use of critical infrastructure in the energy industry that operates at high pressures in the presence of heat and mass transfer effects and phase transitions, the problem of simulating such processes is very relevant. It is especially important to understand such processes in emergency situations with a potential depressurization of pipes [1], particularly in reactors [2]. In case of emergency depressurization of a pipe with liquid under high pressure, a process of critical flow of the vapor-liquid mixture occurs with a possible effect of a flow choking [3].

Several models are describing the critical two-phase flow [4, 5], including those designed to assess the loss of coolant during an emergency depressurization of the cooling system of a nuclear reactor [6]. In the study of critical flows, the main attention is paid to the problem of critical outflow from a free channel. There is a class of problems related to heat and mass transfer in reactors [7]. Particularly, in case of the critical flow observed during the outflow from a channel filled with granular layer, which corresponds to prototypes of nuclear reactors based on fuel in a form of pebbles (micro fuel elements) [8].

For this class of problems, experimental and numerical studies are practically not available in the literature. Experimentally, the case of the critical flow of a vapor-liquid mixture from a channel with a granular layer was studied in [9], where data were obtained on the critical flow rates of a vapor-liquid mixture at various vapor fractions and geometric parameters of the backfill. In this regard, obtaining
numerical characteristics of critical flows in channels filled with granular backfill is of interest for theoretical study and industry applications, especially data on the speed of sound in such critical flows.

2. Numerical model

To determine the sound speed in a critical vapor-liquid flow when it flows out of a pipe with a granular backfill, a model was developed using the smoothed particle hydrodynamics method [10] based on the previously developed model for the two-phase flow in a granular layer [11]. Two modifications of the calculation model were implemented. The first modification makes it possible to calculate the evolution of the vapor and liquid phases, and thus obtain an estimate of the slip ratio, which is an important parameter for analytical calculations of critical flows [11] based on [12]. In the case of three-dimensional modeling of the critical vapor-liquid flow, where the vapor and liquid phases are represented separately, the flow in the orifice is inhomogeneous, and therefore it is not possible to unambiguously estimate the speed of sound of such a flow. To solve this problem, a modification of the model was implemented, based on the representation of the flow as homogeneous, having averaged characteristics of the vapor-liquid medium. This model does not allow studying the dynamics of the liquid and vapor phases separately but allows estimating the sound velocity of the critical flow.

The dependences of the sound velocity in the critical flow are obtained depending on the vapor volume fraction and the geometry of the granular backfill in a three-dimensional setting. The velocity ratio of the vapor and liquid phases in a three-dimensional channel filled with spherical backfill is estimated. The calculated results are compared with existing experimental data showing good consistency of analytical calculations.

2.1. Computational domain

The computational domain represents a pipe filled with a solid phase of a spherical shape. The length of the calculated area was 250 and 355 mm, and the internal diameter was 39 mm to reproduce the geometry close in parameters to the experimental setup described in [9]. The vapor-liquid flow through a channel with a granular backfill with diameters of 2 and 4 mm was considered. The backfill porosity was determined by the selection method where for various configurations of spherical backfill whose properties were considered in [12], the configuration with the porosity closest to the experiment was selected. For spherical backfill of 2 mm, the porosity in the calculated model was 0.351, and for backfill of 4 mm – 0.411, respectively. The deviations from the backfill porosity used in the experiment were 5 and 4%, respectively.

2.2. Equations and initial conditions

The initial pressure drop varied from 200 to 800 kPa, corresponding to the pressure drops used in experimental studies. The initial pressure in the channel was set to 100 kPa. At the outlet of the channel, the mass flow rate of the two-phase flow was calculated by:

\[ V_m = \rho \cdot w \]  

where \( V_m \) is the mass flow, \( \rho \) is the density, and \( w \) is the flow velocity. The mass conservation law was formulated in the interpretation of the smoothed particle method:

\[ \frac{d\rho_a}{dt} = \sum_b m_b (u_a - u_b) \nabla W_{ab} \]  

(2)

Indexes a and b indicate neighboring smoothed particles that interact with each other. To simplify further calculations, the smoothed particle interaction operator is introduced:

\[ Z = \frac{m_a (r_a - r_b) \nabla W_{ab}}{\rho_a \rho_b (r_{ab} + \xi)} \]  

(3)

The additional component \( \xi \) is used to eliminate the singularity effect in the case of high velocities and pressures. Next, the energy conservation law is formulated, approximated by the smoothing operator:

\[ \frac{d\rho_a u_a}{dt} = \sum_b m_b (u_a - u_b) \nabla W_{ab} \]  

(4)
\[
\frac{du_a}{dt} = g - \sum_b m_b \left( \frac{p_a + p_b + \Pi_{ab}}{p_a p_b} \right) \nabla W_{ab} + \sum_b Z(\mu_a + \mu_b)(u_a - u_b)
\]  \hspace{1cm} (4)

An additional component of \( \Pi \) denotes the artificial viscosity. This component is used to stabilize the computational scheme in a wide range of parameters.

For heat transfer phenomenon the thermal conductivity equation is approximated similarly:

\[
\frac{dT_a}{dt} = \frac{1}{C_p} \sum_b Z(k_a + k_b)(T_a - T_b)
\]  \hspace{1cm} (5)

The calculation of the phase transformation process includes a system consisting of the continuity equation and boundary conditions for pressure, the thermal conductivity equation, and the dynamic viscosity at the phase interface:

\[
\frac{dN_a}{dt} = \sum_b Z(\rho_a D_a + \rho_b D_b)(N_a - N_b)
\]  \hspace{1cm} (6)

\[
p_{\text{жг}} = \frac{2p_a p_r}{p_a + p_r}
\]  \hspace{1cm} (7)

\[
k_{\text{жг}} = \frac{2k_a k_r}{k_a + k_r}
\]  \hspace{1cm} (8)

\[
\nu_{\text{жг}} = \frac{2\nu_a \nu_r}{\nu_a + \nu_r}
\]  \hspace{1cm} (9)

Given that the flow parameters may differ for each individual particle, the total mass flow is calculated as the sum of the appropriate characteristics of each smoothed particle:

\[
V_m = \sum_i^N \rho_i \cdot W_i
\]  \hspace{1cm} (10)

Hence the total mass flow rate was considered as the aggregation of values for each smoothed particle presented in the orifice during the outflow.

3. Results and Discussion

Calculated dependences of the mass flow rate of the vapor-liquid mixture depending on the pressure drop ranged from 200 to 800 kPa were obtained (figure 1), and comparison with the corresponding experimental data from [9] was made. The range of pressure drops was chosen based on the calculation of the critical flow rate of the vapor-liquid mixture, which was achieved in [9] at the pressure drops ranged from 750 to 800 kPa.
Figure 1. Mass flow rate vs pressure drop, pipe length 355 mm. Vapor mass fraction: 1 – 0.022, 2 – 0.033, 3 – 0.055, 4 – 0.096, 5 – 0.178. Continuous lines – numerical simulation.

When the critical flow is reached, the flow rate of the vapor-liquid mixture reaches the local speed of sound and a further increase in the pressure drop does not lead to an increase in mass flow rate. Dependencies are obtained for various vapor mass fractions. At that, considered void fraction ranged from 0.022 to 0.178. The presence of granular backfill leads to the homogenization of the flow by the mixing of the vapor and liquid during the flow through the granular layer. The obtained dependences demonstrate a monotonically increasing nonlinear character with a plateau in the area of pressure drops corresponding to the achievement of the critical flow regime.

Based on the obtained data, the dependence of the critical flow rate on the vapor content was obtained (figure 2). This dependence is of interest because it allows evaluating the influence of vapor content on the mass flow rate in the critical flow regime.
Conducting numerical simulation, it was possible to obtain data on the critical flow for vapor mass fractions from 0.02 to 0.3, whereas in experiments data were available only within the range from 0.022 to 0.178. The dependence shows a nonlinear monotonically decreasing character.

In the process of filtering the critical flow through a granular layer, it is necessary to determine the influence of the geometric parameters of the nozzle on the characteristics of the critical flow. Based on experimental and numerical data, the dependence of the critical flow rate on the diameter of the bead and the length of the pipe was obtained (figure 3).

Figure 2. Critical mass flow rate vs vapor mass fraction: 1 – experiment, 2 – numerical model.
Figure 3. Dependence of critical mass flow rate on bead diameter and length of bead packing.
1 – numerical simulation, 2 – experimental data

Different combinations of beads and bead package lengths were tested to determine how the bead size and length of the bead package influence the critical mass flow rate. Bead diameters of 2 and 4 mm and the length of a pipe of 250 and 355 mm were considered in the experimental study [9]. In numerical model additionally beads with a diameter of 8 mm and bead package length of 300 mm were tested. Both in the experiment and numerical simulation, the dependence shows linear character, while the critical flow rate decreases with the increase in the length of the pipe and decrease in the bead diameter. The highest mass flow rate was obtained for a bead diameter of 8 mm and a package length of 250 mm, while the lowest value corresponded to the case of bead diameter of 2 mm and package length of 355 mm. Hence data demonstrate that critical mass flow rate reduces with a decrease of bead diameter and increase in bead package length.

Conclusions
Reaching the critical mode is observed for all the studied values of vapor content. At the same time, when the mass fraction of vapor in the initial mixture increases, the critical mass flow rate decreases from 700 kg/m$^2$s for the vapor mass fraction of 0.022 to 300 kg/m$^2$s for the vapor mass fraction of 0.178, respectively. The range of pressure drops at which the critical flow is observed remains unchanged for the entire studied range. A decrease in the mass flow rate of the critical flow with an increase in the vapor fraction in the mixture can be associated with a decrease in the average density of the vapor-liquid mixture. Reducing the diameter of the backfill and increasing the length of the
granular layer reduces the mass flow rate of the liquid-vapor mixture, which is caused by the fact that the decrease in the bead diameter leads to a decrease in the size of the channels formed in the granular layer, and increasing the length of the pipe leads to the increase of losses during filtration of two-phase flow.

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