Simulation of liquid-steam critical flow from a pipe filled with granular layer

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Abstract. Based on the method of smoothed particles hydrodynamics a computational model of the critical flow of a vapor-liquid mixture from a pipe with a granular backfill has been developed. The dependence of critical mass flow rate from linear dimensions of the work area, the diameter of the grain filling and pipe length was determined. Numerical results were compared with available experimental data and numerical calculation demonstrates consistency with experimental data. Numerical data on the intensity of vaporization by the cross section of a pipe filled with granular backfill at initial values of the mass fraction of steam from 0.05 to 0.2 were obtained. The non-linearity of the vaporization rate during the mixture moving along the pipe with a decrease in intensity when moving along the length of the pipe is shown.

1. Introduction

In the field of oil refining, organic synthesis and power equipment, the infrastructure is characterized by the usage of technologies associated with high pressures and two-phase flows. Due to operation at high pressures, there is a risk of depressurization of pipes and valves [1] in such infrastructure, which can lead to serious accidents with damage to the infrastructure and leakage of the working fluid [2]. The possibility of such two-phase critical flow leads to a choked flow, when increase in pressure drop does not increase mass flow rate of the mixture [3, 4]. The danger of this situation is that the combination of pressure increases and constant mass flow rate of the mixture leads to an increased risk of pipe fracture and consequential damage to the whole infrastructure. Recent developments in the nuclear power industry propose new models of nuclear reactors based on fuel cells in the form of spherical particles. In such reactor fuel particles are loaded into the working area through which the liquid is pumped and the fuel cells emit heat to liquid which may lead to its vaporization. In this reactor model, it is important to ensure that the liquid flow rate is at level that eliminates excessive evaporation. In case of failure of the pumps, an emergency situation similar to the one described above may occur, when excessive vapor formation in the working channel can lead to depressurization of the working area with a critical flow of coolant in the form of a liquid-vapor mixture. Thus, the problem of numerical simulation of the critical outflow of a two-phase liquid-vapor flow is relevant and in this work a numerical model of a liquid-steam critical flow mixture in a pipe filled with a granular backfill was developed and numerical simulations were performed in order to identify key characteristics of
such flow. The availability of experimental data obtained for a similar model environment [5] allows verification of the numerical model based on experimental data.

2. Numerical model

Numerical models of hydrodynamics and heat transfer problems are frequently based on the finite element method [6]. At the same time, modeling of complex problems involving multiphase media, phase transitions, non-stationary environment and complex geometric shape of channels, such as presence of granular layer, lead to difficulties in using classical computational methods, in particular when setting boundary conditions and ensuring the stability of the numerical scheme, including the case of modeling critical flows [7]. New computational fluid dynamics methods can be used to model such complex environments, such as the smoothed particle method, which belongs to the class of mesh-free Lagrangian methods [8].

The computational model is based on the smoothed particles hydrodynamics method and is a modification of the model previously developed by the authors, which was intended for modeling the hydrodynamic processes of gas bubbles movement in pipes filled with a granular layer [9] and was implemented by the authors in [10] taking into account the inhomogeneity of the medium. The developed model makes possible to calculate the hydrodynamic and thermophysical processes of a two-phase flow in a three-dimensional setting, taking into account the presence of granular backfill in the channel. The calculated data were compared with experimental results obtained in [5].

In the smoothed particle method, the computational domain is considered as a set of discrete particles. In this case, the particle is an abstract mathematical object, and not a physical element of the system. Each smoothed particle approximates physical quantities in its neighborhood, with neighboring particles influencing each other. In this case, a step function is used to exclude the numerical effect of the penetration of liquid and gaseous phase particles into solid boundaries. This function increases abruptly as the distance between the particles of the mobile phase and the solid boundary decreases. The question of the minimum number of smoothed particles required to obtain correct simulation results is particularly important when modeling inhomogeneous structures, such as a granular layer, due to sharp changes in the geometric characteristics of the space between the backfill. The use of the smoothed particle method in hydro-gas dynamics problems shows that to obtain correct results, at least 10-20 smoothed particles are needed in the case of a one-dimensional problem [8]. Smoothed particle hydrodynamics method is applicable for solving multiphase problems, involving gas-liquid flows in channels of complex geometries, like granular layer, including modeling microfluid dynamics [12]. Regarding the application of smoothed particle to the problem of critical two-phase flows, the developed model is applicable to the range of initial pressures up to 3 MPa, volume void fractions up to 0.3 and spherical particles in granular layer with diameters above 0.5 mm.

In this work, the experimental setup consisted of a working area with granular backfill. The steam-water mixture was pumped through the working section and the mass flow rate of the mixture was calculated at the exit from the section. At the same time during the flow of the steam-water mixture through the working section its evaporation was observed due to a pressure drop during entering the working area.

3. Results and Discussion

The steam-water mixture enters the working area filled with granular layer at a pressure 9 atm. At the same time, in the initial state, the pressure in the channel is equal to atmospheric pressure. Due to a significant pressure drop in the pipe, the mixture boils with the release of steam. Thus, the proportion of steam in the mixture increases during the flow in the pipe, and the proportion of water in the mixture decreases. A relationship was established between the initial steam mass fraction in the mixture and the corresponding final value for different channel lengths and backfill diameters, which were presented as a dimensionless geometric parameter $\sqrt{d/H}$, that was introduced in [11]. When pressure drop reaches 8 atm, which corresponds to initial mixture pressure of 9 atm and atmospheric pressure in the pipe, an effect of gas-dynamic locking due to the acoustic effects is observed [11], in
which a further increase in pressure drop does not increase mass flow rate of the mixture. This effect was also observed in the experiments [5]. In this case, the critical mass flow rate of the mixture is observed. The properties of the critical flow were studied depending on the geometric parameters of the pipe and backfill and the initial vapor fraction.

3.1. Relation of critical mass flow rate with geometric properties of a pipe

In [5] a dimensionless geometric parameter $\sqrt{d/H}$ was introduced, which combine the influence of the backfill spheres diameter and channel length on the critical mass flow rate of the two-phase mixture, where $d$ – diameter of a spherical filling, $H$ – the length of the working section. The dependence of the critical mass flow rate on the values of this parameter was obtained (figure 1).

![Figure 1. Dependence of the critical flow rate on the dimensionless criterion $\sqrt{d/H}$.](image)

Both in the experiment and in the numerical simulation, dependence demonstrates linear behavior, while the critical mass flow rate decreases with an increase in the dimensionless geometric parameter. Reducing the diameter of the filling grain and increasing the length of the working area leads to a reduction in critical mass flow rate.

This dependence can be related to increase in hydraulic resistance with decrease in the diameter of spherical particles. At the same time, an increase in the length of the granular layer also leads to an increase in hydraulic resistance. Thus, the combination of these two factors leads to a reduction in the mass flow rate of the mixture.

3.2. Evaporation during the flow through the pipe

The steam-water mixture enters the working area with a granular layer at pressure of 9 atm. At the same time, in the initial state, the pressure in the channel is equal to atmospheric pressure. Due to a sharp pressure drop in the working area, the mixture boils up with the release of steam. Thus, the
proportion of steam in the mixture increases during the flow in the pipe, and the proportion of water in the mixture decreases. The dependence of the change in the vapor content in a pipe with a granular backfill of 4 mm diameter for working sections of 250 and 355 mm in length at the initial mass vapor deposition of 0.05 (figure 2) and 0.2 (figure 3).

**Figure 2.** Distribution of vapor content in the mixture along the length of the working area at the initial vapor content 0.05. Pipe length 355 mm: 1 – 3, 250 mm – 4-6. Spherical particles diameter 4 mm – 1,4; 2 mm – 2,5; no spherical particles: 3, 6.

**Figure 3.** Distribution of vapor content in the mixture along the length of the working area at the initial vapor content 0.2. Pipe length 355 mm: 1 – 3, 250 mm – 4-6. Spherical particles diameter 4 mm – 1,4; 2 mm – 2,5; no spherical particles: 3, 6.

In both cases, a nonlinear, monotonous increasing dependence is observed. With the movement of the vapor-liquid mixture along the channel, the fraction of steam increases. At the same time, the growth rate of the newly released vapor phase slows down when moving along the channel, and the
maximum vapor formation is observed in the area from 0 to 100 mm. This peculiarity may be related to heat exchange processes between the vapor-liquid flow and spherical backfill, when part of the heat of the flow is absorbed by the backfill, which slows down the growth of vapor formation.

4. Conclusions

In the course of computational experiments, the dependence of the critical mass flow rate of a vapor-liquid mixture on a dimensionless geometric parameter that combines the diameter of the filling grain and the length of the pipe was obtained. It shows a decrease in the critical flow rate with a decrease in the diameter of the filling grain and an increase in the length of the working area. Thus, in order to reduce the critical flow rate of the working fluid in the event of an emergency depressurization of the working area, a smaller filling diameter and a longer pipe length can lead to fewer leaks of the mixture compared to short working areas filled with a larger filling diameter. The dependence of the void fraction along the channel length shows a non-linear increase in void fraction over the channel with a decrease in the growth rate of the vapor phase during movement through the pipe. This dependence demonstrates the influence of the thermophysical properties of backfill on the intensity of vaporization, which should be taken into account when developing energy equipment with a granular layer.

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