Numerical simulation of gas volume motion during the gas injection into liquid metal coolant

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Abstract. Detailed description of relations and numerical approaches to simulate transport of gas phase in a vertical liquid column is presented in a current paper. These approaches are important to calculate phenomena that take place during steam generator tube rupture in fast reactors with liquid metal coolant. Presented relations determine interphase friction between gas and fluid in different flow regimes of two-phase flow. It is shown that correct definition of interphase friction coefficients determines the correct value of bubble velocity that is very important to simulate two-phase flow in steam generator and reactor core. The paper also contains numerical algorithm to calculate motion of gas volume in fluid flow. Special attention is paid to describe the algorithms for simulating two-phase flow with sharp edges between phases that are character for slug flow regime. Also some experimental results are presented in the paper. Comparison between experimental data and calculation results has been provided.

1. Introduction
The active studies of processes in two-phase flow of liquid metals been providing in the middle of the 20th century due to the development of project of fast reactors. Unfortunately, due to the inherent technological problems in operation with liquid metals, many countries refused to further develop this technology, with the exception of Russia, which is still developing projects for liquid metal-cooled reactors. There are projects of lead, lead-bismuth and sodium cooled reactors. Accidents caused by the steam generator tubes rupture and the coolant boiling due to insufficient of heat removal from the core is determined by the behaviour of the gaseous phase in liquid. The motion of bubbles in the core, pulsations of theirs volume strongly influence to the behaviour of the reactor due to the presence of a positive feedback between the core neutron power and the gas volume. Knowledge about the specific of gas bubble motions into liquid metal coolant is also important for metallurgy to calculate of boiling or blown steel-melting baths.
There is a lack of information about the processes in two-phase liquid metal flow. So it is important to provide numerical and experimental investigations of the motion of bubbles in liquid metals. During the sodium boiling in core or during the leakage in steam generator slug regime is the main two-phase [1, 2]. The feature of slug flow regime is the existence of sharp boundary between phases that make some difficulties to numerical simulating especially in one dimensional approximation.

2. Description of the models to calculate processes in two-phase flow
Common ways to simulate two-phase flow are based on two-liquid model [3]. To describe two-phase flow in frame of two-liquid model, system of mass, momentum and energy equations must be solved. The system of mass, momentum and energy equations is presented below:
\[ \frac{\partial}{\partial t} \left( \varphi_j \rho_j \right) + \frac{\partial}{\partial z} \left( \varphi_j \rho_j v_j \right) = 0, \quad (1) \]

\[ \frac{\partial (\varphi_j \rho_j v_j)}{\partial t} + \frac{\partial (\varphi_j \rho_j v_j)}{\partial z} = \frac{\partial P}{\partial z} = \tau_{ij} + \varphi_j \rho_j g \cdot \sin \vartheta, \quad (2) \]

\[ \frac{\partial (\varphi_j \rho_j h_j)}{\partial t} + \frac{\partial (\varphi_j \rho_j h_j v_j)}{\partial z} - \varphi_j \frac{dP}{dt} = Q_{ig} + Q_{ij}, \quad (3) \]

The first (1) equation is the mass conservation law; the second (2) is the momentum conservation law; the third (3) is the energy conservation equation.

The index “j” corresponds to the number of phase: j=g for gas, j=f for fluid. In the equations \( \varphi \) is \( j \)-phase volume fraction, \( \rho \) is a density of the phase (kg·m\(^{-3}\)), \( v \) is a velocity (m·s\(^{-1}\)) of the phase, \( h \) is an enthalpy of the phase. The values on the right hand of momentum equation are the interphase friction (Pa·m\(^{-1}\)) per unit length, wall friction (Pa·m\(^{-1}\)) per unit length and the gravitational forces. It should be noted that the sum of the volume fractions must be equal to unity. The sum of the interphase friction and interphase heat transfer must be equal to zero:

\[ \varphi_g + \varphi_f = 1, \quad \tau_{ig} + \tau_{if} = 0, \quad Q_{ig} + Q_{if} = 0. \quad (4) \]

The relation to calculate interphase friction depends on flow regime. The flow regime map is shown in table 1.

**Table 1. Flow regime map for vertical channel**

| № | Upper boundary of gas volume fraction | Regime        |
|---|--------------------------------------|---------------|
| 1 | 0.3                                  | Bubble        |
| 2 | 0.99                                 | Slug          |
| 3 | 1                                    | Annular-mist  |

The upper boundary of gas volume fraction has been chosen according to work [1, 2]. To calculate the interphase friction coefficients, the following relation are used:

\[ \tau_{ig} = \chi \left( v_g C_i - v_f C_0 \right) \left( v_g C_i - v_f C_0 \right). \quad (5) \]

\( C_0 \) is a distribution parameter.

\[ \chi = 0.75 \cdot \frac{C_b \rho_g \rho_f}{D_b} \cdot C_i = \left( 1 - \varphi_g C_0 \right) \left( 1 - \varphi_g \right). \quad (6) \]

For bubble regime in vertical channel:

\[ C_0 = 1.2 \cdot 0.2 \sqrt{\frac{\rho_g \rho_f}{D_b}}. \quad (7) \]

For others flow regime \( C_0 \) and \( C_1 \) are equal to unity. Friction coefficient \( C_b \) for bubble in liquid can be calculated for wide range of parameter with help of [5]:

\[ C_b = C_{b, We \to 0} + \tanh(0.021 \cdot We^{1.6}) \left( C_{b, We \to \infty} - C_{b, We \to 0} \right), \quad (8) \]

\[ C_{b, We \to 0} = \frac{16}{Re_b} \left( 1 + \frac{8}{Re_b} + \frac{1}{2} \left( \frac{3.315 \sqrt{Re_b}}{1 + 2 \sqrt{Re_b}} \right)^{-1} \right), \quad C_{b, We \to \infty} = \frac{8}{3} \cdot \frac{Re_b^2}{(3 + 3 \mu^* \mu^*)}. \quad (9) \]
In the relations (8) – (9) \( \text{Re}_b \) is a Reynolds number for bubble, \( \text{We} \) is a Weber number, \( \mu^* = \mu_f / \mu_g \) is a relative dynamic viscosity.

A slug flow regime is one of the main flow regimes that take place during sodium boiling or steam generator tube rapture in the fast reactors. Different relations have been analysed for calculating friction coefficient for slugs. The comparison of different relations is shown in the figure 1 [6].

![Figure 1. The comparison of different relations for slug friction coefficient. 1 – [7], 2 – [8], 3 – [9], experimental data – [10]](image)

There is a good agreement between all of the relations and experimental data. To simplify the calculation procedure correlation from [7] has been chosen:

\[
C_d = \frac{4}{3} \frac{d_s}{Dk^2(N_f, E_0)}, \quad k = 0.345 \left( 1 - e^{-0.01N_f^{0.345}} \right) \left( 1 - e^{-\frac{3.37 - E_0}{m}} \right),
\]

\[
m = \begin{cases} 10; & N_f > 250 \\ 69N_f^{-0.35}; & 18 < N_f < 250 \\ 25; & N_f < 18 \end{cases}
\]

3. Numerical scheme to simulate two-phase flow

To numerical simulate, the system of equations (1) – (2) should be represented in finite-difference form. Finite difference form of mass and momentum conservation equation is shown below:

\[
\frac{\phi_k^{n+1} - \phi_k^n}{\tau} \rho_k + \phi_k^n \frac{\partial \rho}{\partial P} \frac{P_{k+1/2}^n - P_{k-1/2}^n}{\tau} + \left( \phi_k^{n+1/2} \rho_{k+1/2}^{n+1/2} - \phi_k^{n+1/2} \rho_{k+1/2}^n \right) \frac{v_{k+1/2}^{n+1} - v_{k+1/2}^n}{\Delta z} = 0,
\]

\[
\phi_k^{n+1/2} \rho_{k+1/2} - \frac{v_{k+1/2}^{n+1} - v_{k+1/2}^n}{\tau} + \phi_{k+1/2}^{n+1} \rho_{k+1/2}^{n+1} \frac{v_{k+3/2}^{n+1} - v_{k+1/2}^{n+1}}{\Delta z} + \phi_{k+1/2}^{n+1} \frac{P_{k+3/2}^{n+1} - P_{k+1/2}^{n+1}}{\Delta z} = \frac{F_{ij}}{k+1/2} + \left( \tau_{ij} \right)_{k+1/2} - \phi_{k+1/2}^n \rho_{k+1/2} g \cdot \sin \vartheta,
\]

\[
= \left( \tau_{ij} \right)_{k+1/2} + \left( \tau_{ij} \right)_{k+1/2} - \phi_{k+1/2}^n \rho_{k+1/2} g \cdot \sin \vartheta
\]
“k” is a number of calculation point, “n” is a number of time level. An “upwind” scheme is used to approximate convective terms. The shortcoming of the “upwind” scheme is a large numerical diffusion. A “Kabare” scheme [11] has been realized to overcome the shortcoming of the “upwind” scheme. A comparison between the “Kabare” scheme, “upwind” scheme and analytical solution for gas transfer in channel are presented in figure 2 and figure 3. As shown in figures, simulations with help of the “Kabare” scheme more close to analytical solution than calculation with “upwind” scheme. The diffusion of the “upwind” scheme also provides a spreading of sharp boundary, especially on large times.

4. Validation of numerical approaches
To validate developed numerical model, experiments with bubble and slug motion in stagnant liquid metal have been provided. Experimental setup are shown in figure 4. Vertical tube with Rose’s alloy has been used in the experiments. Tube diameter was equal 48 mm. Initial level of the alloy was equal to 40 sm. Its temperature was 423 K. Argon has being injected into the Rose’s alloy. Injection has been made with help of round tube. Its diameter was equal to 4 mm. Volume flow rate was equal to 84, 120, 146, 180, 188, 206, 222, 240 ml/s. A conductivity sensor was mounted at height 33sm. It measured the value of gas volume fraction. The measuring error of gas volume fraction was equal to 15%.

The results of the experiments are shown in figure 5. To simulate the experiment, the calculation scheme has been made. There were two vertical tubes. The first tube was filled with Rose’s alloy. The gas was injected through the second tube. The end of the second tube was been connected to the beginning of the first tube. There is a good agreement between the calculation results and the experimental data with considering of experimental error. The presented experiment allows validating the models of motion of gas bubble in tubes. As shown in [4], gas volume fraction depends on the volume flow rate and the velocity of gas bubbles. The value of the velocity depends on the interphase friction. So the good agreement between the experimental data and the calculation results verifies chosen models to simulate motion of gas bubbles and slugs.

5. Conclusion
The approaches of simulation gas bubbles and slug motions in liquid metal are presented in the current paper. The approaches are based on two-liquid model with closing relations that determine the value of the interphase friction.
The experiments with gas injection into the Rose's alloy have been provided. The experiments allowed validating numerical approaches that have been chosen. The difference between calculation results and experimental data is equal to 12% for gas volume fraction.

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