

Numerical analysis of experiments with gas injection into liquid metal coolant

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Abstract. Presented paper contains results of a numerical analysis of experiments with gas injection in water and liquid metal which have been performed at the Institute of Thermophysics Russian Academy of Science (IT RAS). Obtained experimental data are very important to predict processes that take place in the BREST-type reactor during the hypothetical accident with damage of the steam generator tubes, and may be used as a benchmark to validate thermo-hydraulic codes. Detailed description of models to simulate transport of gas phase in a vertical liquid column is presented in a current paper. Two-fluid model with closing relation for wall friction and interface friction coefficients was used to simulate processes which take place in a liquid during injection of gaseous phase. It has being shown that proposed models allow obtaining a good agreement between experimental data and calculation results.

1. Introduction

During the hypothetical accident with damage of a steam generator tubes in the reactor with lead coolant water steam under high pressure may enter the lead coolant. It may cause a pressure spike in coolant with amplitude much more than nominal pressure. A vapour bubble forms as a result of a steam injection and starts to move along a reactor loop. Changing of bubble volume causes the oscillations of coolant pressure and free level of liquid.

To simulate the accidents with steam generator tubes rupture system thermal-hydraulic codes can be used. In the Nuclear Safety Institute of the Russian Academy of Sciences in frame of Federal Target Program “Nuclear Power Technologies of the New Generation for 2010–2015 and until 2020” HYDRA-IBRAE/LM code [1,2] has been developed for best-estimate transient simulation of fast reactors during postulated accidents including SGTR.

To simulate processes that take place in heavy liquid metal coolant during injection of gaseous phase two-fluid [3] model with constitutive relations for wall and interphase friction and heat transfer coefficients is used. Constitutive relations depend on the flow regime map. HYDRA-IBRAE/LM code contains database with thermo physical properties for different type of coolants: air, water, sodium, lead, lead-bismuth and Rose’s alloy

To check the correctness of HYDRA-IBRAE/LM code to model SGTR it should be widely validated. For this purpose experiments with gas injection into the Rose’s alloy have been conducted. Experiments with water have been carried out to validate models for gas transfer in the water coolant due to fuel rod discharge. These experiments have been performed at the IT RAS with water and Rose’s alloy as a coolant and argon and air as a gas.

2. Brief description of experimental setup

The main goal of experiments performed at the Institute of Thermophysics was to obtain data on the pressure evolution in heavy liquid metal and water during gas injection. Dependences of pressure amplitude and its oscillation frequencies on an inlet gas flow rate and duration of injection have been



received. A vertical circular tube has been used in the experiments. The tube diameter – 25 mm, its height – 1.2 m. The tube has been partially filled with water or liquid metal. Height of liquid has been equal to 1 m. A gas tank has been placed under the tube. Tank and vertical tube have been connected with valve. The gas has been injected from the gas tank through the valve. The valve has been opened by electrical signal. The time of full valve opening has reached 5 ms and depended on the experiment. The time of injection has been changed from 0.05 to 0.2 s. Experiments with water have been carried out with air. Some experimental parameters are shown in the table 1. Experiments with a Rose's alloy have been carried out with inert gas argon due to high chemical activity of the Rose's alloy. Experimental parameters with Rose's alloy and water are shown in the table 1.

Table 1. Experimental parameters

№	Coolant type	Volumetric flow rate (l s ⁻¹)	Valve opening time (ms)
1	Water	0.88	50
2	Water	0.98	100
3	Rose's alloy	0.66	50
4	Rose's alloy	0.52	100

It is important to tell about accuracy of the experimental data. The error of the valve opening time measurements is 20%, the pressure measurement error is 15% and the volumetric flow rate measurement error is 10% for water and 15% for Rose's alloy. For test with water flow rate was measured with flow meter. For Rose's alloy flow rate was found by the measuring of the liquid free level position due to experimental difficulties in rate measuring with the flow meter at high temperatures. So the flow rate measurement data has less accuracy for Rose's alloy than for water. Also, there are several difficulties in measurement of the flow rate time dependence. To provide calculation we assume that there are fixed flow rate during injection. But this assumption adds errors in the simulations.

3. Mathematical models of the HYDRA-IBRAE/LM code

A basic system of equations for two-phase flow calculation is presented below:

$$\frac{\partial}{\partial t}(\varphi_i \rho_i) + \frac{1}{A} \frac{\partial}{\partial z}(A \varphi_i \rho_i v_i) = \Gamma_i \quad (1)$$

$$\frac{\partial(\varphi_i \rho_i v_i)}{\partial t} + \frac{1}{A} \frac{\partial(A \varphi_i \rho_i v_i v_i)}{\partial z} + \varphi_i \frac{\partial P}{\partial z} = \Gamma_i v_i + \tau_{inter i} + \tau_{wi} - \varphi_i \rho_i g \cdot \sin \vartheta \quad (2)$$

$$\frac{\partial(\varphi_i \rho_i h_i)}{\partial t} + \frac{1}{A} \frac{\partial}{\partial z}(A \varphi_i \rho_i h_i v_i) - \varphi_i \frac{dP}{dt} = \Gamma_i h_i + \Gamma_w h_i^w + Q_{i,diss} + Q_{inter i} + Q_{wi} + Q_i \quad (3)$$

$$\sum \varphi_i = 1, \sum \Gamma_i = 0, \sum \tau_{inter i} = 0 \quad (4)$$

The first equation is the mass conservation equation for i-phase. The second one is the momentum conservation equation. And the third is the energy conservation equation. In the equations φ is i-phase volume fraction, ρ is a density of phase (kg·m⁻³), h is a phasic specific enthalpy (J·kg⁻¹) and v is a velocity (m·s⁻¹) of phase. The values on the right hand of mass equation determine mass exchange rate (kg·m⁻³·s⁻¹). The values on the right hand of momentum equation are the interphase friction (Pa·m⁻¹) per unit volume, wall friction (Pa·m⁻¹) per unit volume and the gravitational forces. For the energy equation the right hand contains heat flux from the interphase heat transfer (J m⁻³·s⁻¹) and wall heat transfer rates per unit volume. The last equations determine the connections between phases.

There are six unknown variable (ϕ , pressure, enthalpy of gas and fluid and velocity of gas and fluid) and six differential equations. Other variables (density, interphase friction, wall friction, mass and heat transfer) are functions of the basic variables.

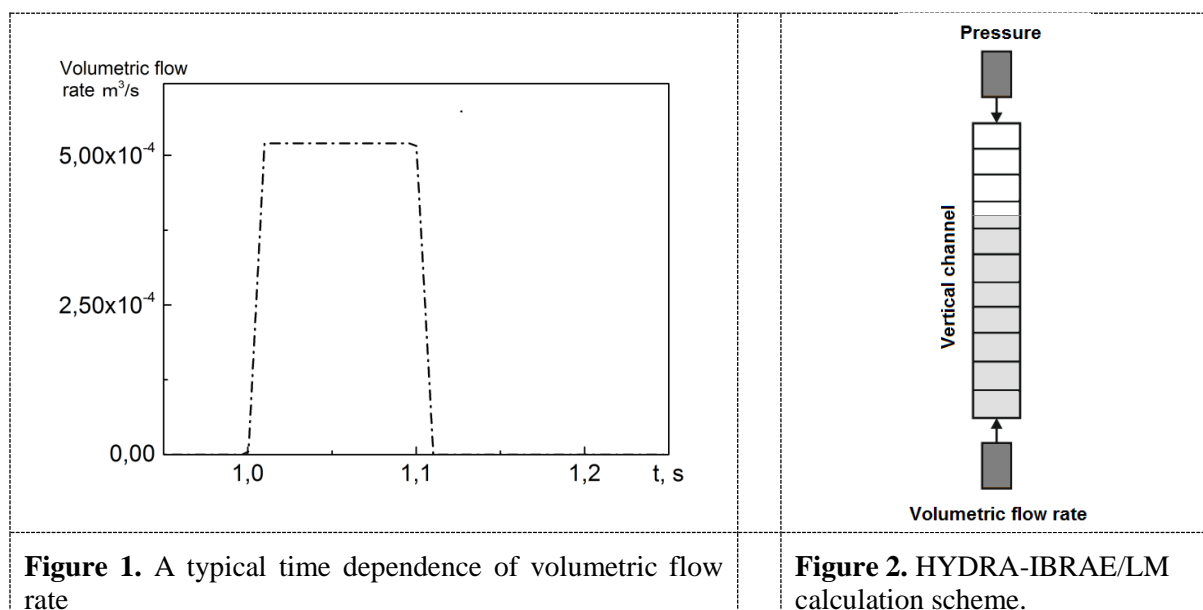
Two-phase flow regime map for vertical channel that is used in HYDRA-IBRAE/LM for heavy liquid metal coolant with noncondensable is shown in the table 2. According to works [4] and [5] it is considered three two-phase regimes for liquid metal: bubble, slug and annular-mist. Different constitutive relations for different flow regime is used in the HYDRA-IBRAE/LM code. For example, interphase friction for bubble regime is calculated according to [6]. For slug regime data from [7] are used. Relations for interfacial area calculation are presented in [8]. Some relation for interfacial and wall heat transfer can be found in works [2], [9] and [10].

Table 2. 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

4. HYDRA-IBRAE/LM calculation scheme

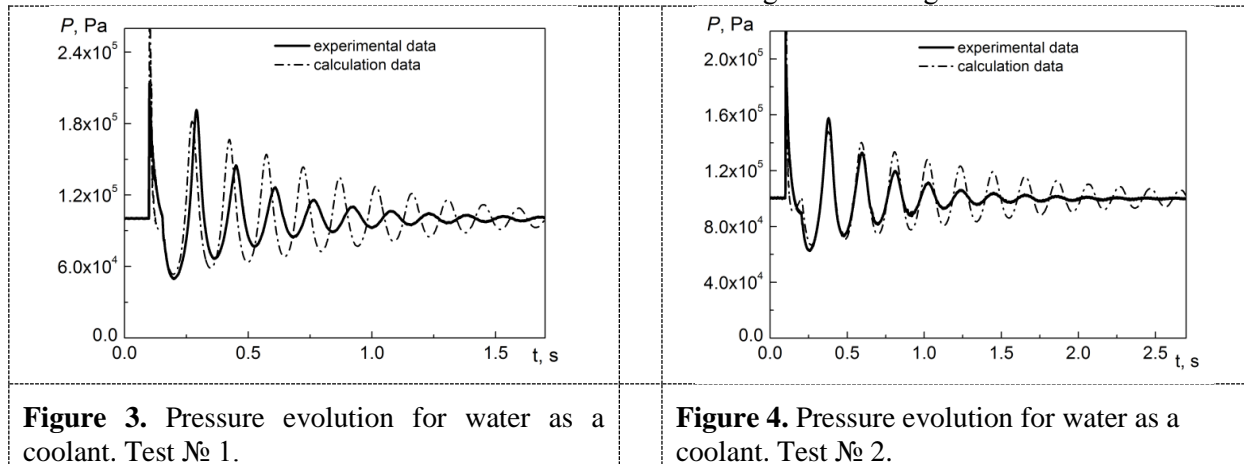
HYDRA-IBRAE/LM nodalization scheme has been developed to simulate experiments with gas injection. The scheme consisted of a vertical channel with an upper and bottom boundary condition. A volumetric gas flow rate is defined as the bottom boundary condition. At the beginning of the calculation the flow rate was equal to zero. Then it was increased to nominal level and stayed at this level during time while the valve had been opened. At the end volumetric gas flow rate was decreased to zero level. A typical time dependence of volumetric flow rate is shown in the figure 1. A fixed pressure is defined as an upper boundary condition. A bottom part of the channel was filled with liquid (water or Rose's alloy). An upper part of the channel was filled with argon. The scheme is shown in the figure 2. Proposed calculation scheme contains 200 computational cells in the upper part of the channel and 200 cells in the bottom part of the channel. The value of time step was equal 10^{-4} s.



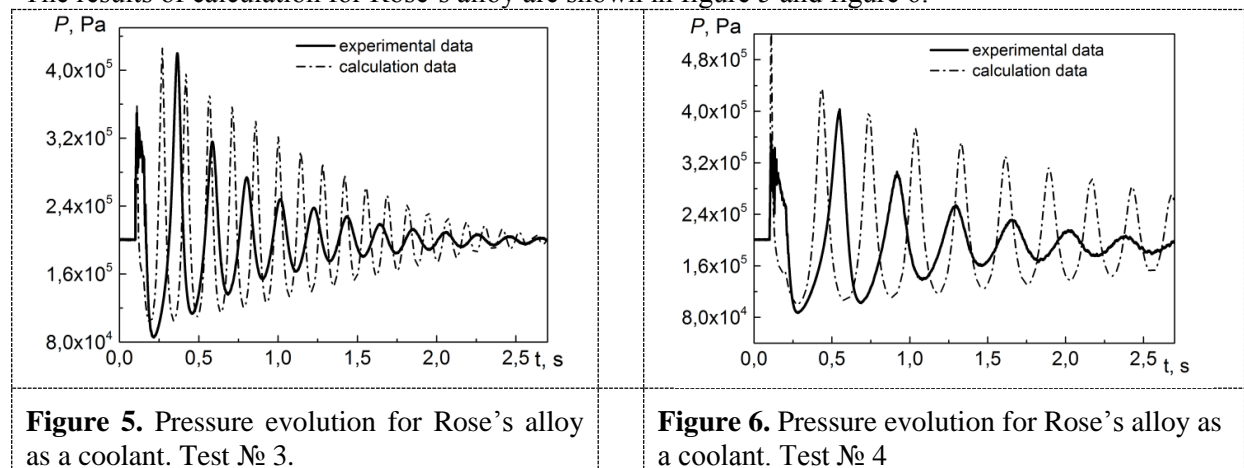
5. Calculation results

Liquid pressure evolution has been received as a result of the calculation. A pressure transducer was placed at the bottom of the vertical channel as in the experiment. Series of calculations has been carried out. Different valve opening times and different volumetric gas flow rate has been used in calculations.

The results of calculation for water as a coolant are shown in figures 3 and figure 4.



The results of calculation for Rose's alloy are shown in figure 5 and figure 6.



It may be seen that calculation results for Rose's alloy have worse accuracy than the results obtained in water. There are several factors that can influence on results. The first one is the experimental errors. Actually, the flow rate measurement data have a bad accuracy for Rose's alloy. Also, it may be caused by shortcomings of closing relations that have been used for heavy liquid metal due to lack of experimental information on bubble motion in liquid metal coolant.

6. Conclusion

The results of the gas injection experiments have been presented in current paper. The experiments allow receiving information about pressure evolution during gas injection in stagnant heavy liquid metal and water column. Presented data can be used to validate thermal hydraulic code such as developed in Nuclear Safety Institute HYDRA-IBRAE/LM code. With help of the thermal hydraulic code HYDRA-IBRAE/LM simulations of the experiments have been provided. A good agreement between the experimental data and the results of calculation has been obtained. The paper also contains description of the experimental set up, experimental conditions and brief descriptions of the calculation models of the HYDRA-IBRAE/LM code that allow providing independent calculation of presented experiments.

7. References

- [1] Alipchenkov V M, Anfimov A M, Afremov D A, *et al* 2016 *Thermal Engineering* **63** (2) 130
- [2] Usov E V, Pribaturin N A, Kudashov I G, *et al* 2015 *Atomic Energy* **118** (6) 382
- [3] Nigmatulin R I 1978 *Fundamentals of Mechanics of Heterogeneous Media* (in Russian) (Moscow: Nauka)
- [4] Tobita Y 2006 *Exp. Nucl. Tech.* **153** (3) 2006 245
- [5] Marten K, Baumgartner E, Khan M, Hoffman H 1982 Impact of Gas in Sodium Flow on the Temperature Variation of an LMFBR Rod Bundle *KFK* (3253) 47
- [6] Loth E 2008 *Int. J. of Multiphase Flow* **34** 523
- [7] Wallis G B 1969 *One-dimensional two-phase flow* (New York: McGraw Hill)
- [8] Schor A L, Kazimi M S and Todreas N E 1984 *Nuclear Engineering and Design* **82** 127
- [9] Barry R E and Balzhiser R E 1966 *Proc. of 3rd Int. Heat Transfer Conf. (Chicago)* vol 2 p 318
- [10] Ninokata H and Okano T *Nuclear Engineering and Design* 1990 **120** 349.