Some approaches to numerical modelling of a phenomenon observed during steam generator tube rupture in the reactor with liquid metal coolant

Eduard V. Usov[1], *Pavel* Lobanov[1,3*], *Oleg N.* Kashinskiy[3], *Nikolai A.* Pribaturin[1,3], *Nastasya A.* Mosunova[2], *Vladimir I.* Chuhno[1,4], *Alexander E.* Kutlimetov[1,4], and *Alexander I.* Svetonosov[4]

[1]Nuclear Safety Institute of the Russian Academy of Sciences, Novosibirsk Branch, Novosibirsk, 630090, 1 Lavrentiev Ave., 1, Russia
[2]Nuclear Safety Institute of the Russian Academy of Sciences, Moscow, 115191, 52 B. Tulskaya Str., Russia
[3]Institute of Thermophysics of the Russian Academy of Sciences, Siberian Branch, Novosibirsk, 630090, 1 Lavrentiev Ave., Russia
[4]Novosibirsk State University, Novosibirsk, 630090, 2 Pirogova Str., Russia

Abstract. The presented paper contains a description of approaches to simulate processes, observed during leakage in the steam generator of the reactor with liquid metal coolant. These approaches have been implemented in thermal hydraulic code HYDRA-IBRAE/LM. To calculate motion of gas bubbles in liquid metal flow and heat transfer of gas bubbles with metal, different relations are used in HYDRA-IBRAE/LM code. The code contains models of chemical interaction between water and sodium for modelling of tube rupture in sodium cooled fast reactors, Modelling of the experiments has been made using HYDRA-IBRAE/LM code. The results of the modelling with determined main factors are presented in the article.

1 Introduction

Development of the new generation of fast reactors with liquid coolant leads to requirement of safety research of this type of reactor. One of the most important accidents is a damage of steam generator tubes. Investigation of processes with steam and gas injection into liquid metals, motion of gas bubbles in liquid metal flow and heat transfer between liquid metal and gas bubbles is necessary for understanding the specificity of reactor operation during this type of accidents. To study these processes theoretical and experimental investigations on different experimental setups were performed. For example, investigations with heavy liquid metal coolant have been provided at LIFUS test facility [2] and test facilities of the Institute of Thermophysics of Siberian Branch of Russian Academy of Science [3]. Some

* Corresponding author: lobanov@itp.nsc.ru

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experiments with sodium coolant are presented in [4]. Theoretical investigation of steam generator tube rupture could be done using thermal hydraulic code HYDRA-IBRAE/LM [1]. This code allows modelling of thermal hydraulic processes in sodium, lead, lead-bismuth, Rose's alloy and water coolants during gas injection. Two-fluid model with constitutive relations for coefficients of wall friction, interphase friction and heat transfer is used for modelling of processes in heavy liquid metal and sodium coolant during gas injection. Constitutive relations depend on the flow regime type.

2 HYDRA-IBRAE/LM relations for numerical modelling of processes in a two-phase liquid metal coolant

HYDRA-IBRAE/LM code have been developed by the Nuclear Safety Institute Russian Academy of Science as a part of the Federal Target Program "Nuclear Power Technologies of the New Generation for 2010-2015 and until 2020". There is a system of closing relations in HYDRA-IBRAE/LM code for modelling of motion and heat transfer between gas bubbles and liquid metal. The system consists of correlations for calculation of interphase and wall friction coefficients, interphase and wall heat transfer coefficients and interfacial area.

Closing relations depend on flow regime type. For bubbly flow the interfacial area a_i is calculated as:

$$a_i = 6\,\varphi_g / D_b, \tag{1}$$

where D_b is a diameter of bubble, φ_g is a gas volume fraction. For slug flow the interfacial area is defined as:

$$a_i = 4.5\,(\varphi_g - \varphi_{gs}) / (1 - \varphi_{gs}) / D_h + 6\,\varphi_{gs}\,(1 - \varphi_g) / (1 - \varphi_{gs}) / D_h, \tag{2}$$

where D_h is a diameter of channels. The interphase friction coefficient ξ_i for the bubbly flow regime can be calculated as [5]:

$$\xi_i = 24\,(1 + 0.15\,Re_b^{\,0.687}) / Re_b + 0.42 / (1 + 4.25\,10^4\,Re_b^{\,-1.16}). \tag{3}$$

This relation is used for spherical bubbles. For spherical caps correlation from [6] can be used:

$$\xi_i = 8/3\,Eo / (Eo + 4), \tag{4}$$

where Eo is an Eotvos number.

The interphase friction for slugs can be defined as [7]:

$$\xi_i = 1/k,\ k = 0.35\,(1 - e^{-0.01\,N/0.345})\,(1 - e^{(3.37 - Eo)/m}), \tag{5}$$

$$N = (g\,D_h\,(\rho_f - \rho_f)\,\rho_f)^{0\,5} / \mu_f\,. \tag{6}$$

The coefficient m is equal to 10, if N more than 10; m is equal to 25, if N less than 18. And m is equal to $69 \cdot N^{-0.35}$ in the other cases.

The interphase heat transfer coefficient (α_{fi}) also depends on the flow regime type. For the bubbly flow the liquid-side heat transfer coefficient is given by:

$$\alpha_{fi} = Nu \cdot k_f / D_b,\ Nu = 2 + 0.386\,Pe^{0.5},\ [8] \tag{7}$$

The gas-side heat transfer coefficient is given by:

$$\alpha_{gi} \cdot a_i = C_{pg} \cdot \rho_g\, \varphi_g / \tau,\ \tau = D_b^2\, C_{pg} \cdot \rho_g / (4\pi\, k_g). \qquad (8)$$

Liquid-side heat transfer coefficient for slug flow can be defined by the following semianalytical relation:

$$\alpha_{fi} = 2 \cdot k_f / \delta,\ \delta = D_h\, (1 - \varphi_g^{0.5}) / 2 \qquad (9)$$

The gas-side heat transfer coefficient can be defined as [9]:

$$\alpha_{gi} \cdot = Nu \cdot k_g / D_h / \varphi_g^{0.5},\ Nu = 0.023\, Re_g^{0.8}\, Pr_g^{0.4}. \qquad (10)$$

Model of interaction between water and sodium has been implemented for modelling of processes in sodium coolant during tube rupture. Chemical reaction between water and sodium is considered as:

$$Na \cdot + H_2O \longrightarrow {}^1\!/_2\, H_2 + NaOH + \Delta h, \qquad (11)$$

where Δh is an enthalpy change due to chemical reaction. The value of the enthalpy change is added to the right-hand side of the energy equation of the two-fluid model.

3 HYDRA-IBRAE/LM code validation

The experiments with gas injections have been modelled for validation of models implemented in HYDRA-IBRAE/LM code.The experiments have been provided on the HLM-FIT facility at the Institutes of Thermophysics SB RAS. A vertical circular tube has been used in the experiments. The tube diameter was equal to 48 mm (fig.1). The tube has been filled with liquid lead. The lead temperature was equal to 400^0C. Temperature measurements have been made by thermocouple.

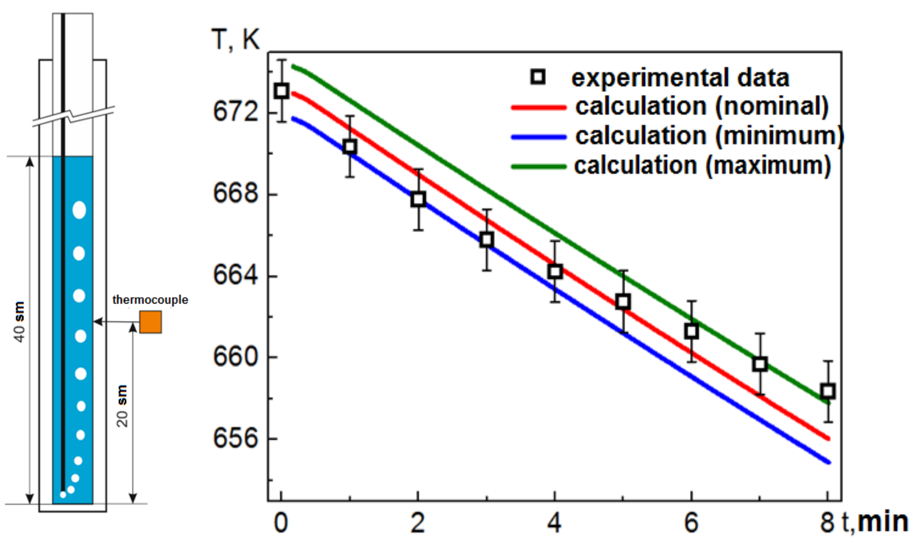

Fig. 1. Scheme of the experiments at the IT SB RAS (left) and the calculations results (right).

Comparison between experimental data and calculation results for volume flow rate equal to 180 ml/sec is shown in fig.1. Fig. 1 contains the results of calculations performed with nominal parameters and the results of uncertainty analysis.

Experiments with water–sodium interactions [4] have been modelled to validate the model of water-sodium reaction. The experimental setup is consisted of the sodium

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container, water storage and pressure sensor line (fig.2). Pressure evolution in the tank has been measured during the sodium-water reaction. The results of calculation in comparison with experimental data are shown in fig.2.

4 Conclusions

The models implemented in the HYDRA-IBRAE/LM code are presented in the current paper. The paper contains the relations that are used for calculation of the heat transfer and interphase friction coefficients in the bubbly and slug flow regimes. Modelling of the experiments with gas injection into lead and sodium-water interaction experiment has been performed using thermal hydraulic code HYDRA-IBRAE/LM. A good agreement between the experimental data and the calculation results has been obtained.

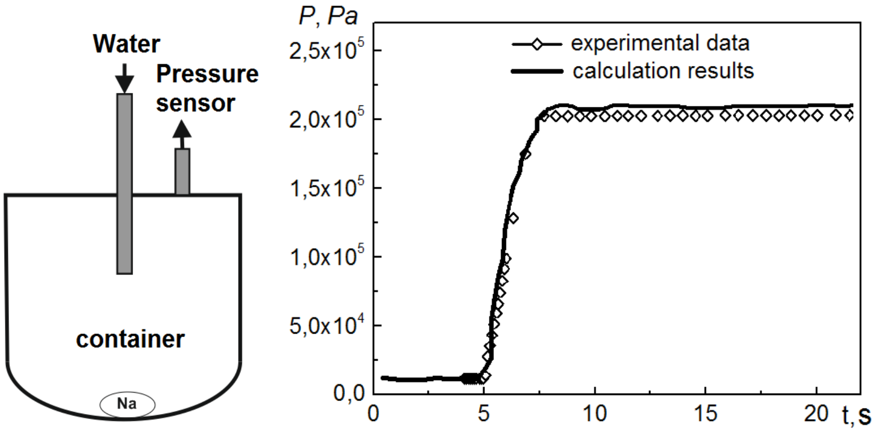

Fig. 2. Scheme of the experiments (left) and the calculation results (right) [4].

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