Experimental and numerical simulation of gas bubbles motion in liquid metal

E V Usov¹, P D Lobanov², V I Chuhno¹, A E Kutlimetov¹, A I Svetonosov², N A Pribaturin¹², N A Mosunova¹

¹Nuclear Safety Institute of the Russian Academy of Sciences, Novosibirsk Branch, Novosibirsk, 630090, Ak. Lavrentiev Ave., 1, Russia
²Institute of Thermophysics, Siberian Branch of Russian Academy of Sciences, Novosibirsk, 630090, Ak. Lavrentiev Ave., 1, Russia

Abstract. Motion and heat transfer of bubbles with liquid metal have been investigated in the present paper. Theoretical studies have been provided with help of modern numerical approaches and the HYDRA-IBRAE/LM code to simulate two-phase flows. Two-fluid model has been used in the presented code to calculate thermal hydraulic processes into two-phase liquid metal coolant. To close two-fluid model, the system of constitutive relation has been used. The brief description some of the constitutive relations has been presented in the current paper. For example, some features of the wall friction coefficient calculation have been discussed. Gas injection experiments and experimental investigations of the bubbles motion and heat transfer have been provided on a liquid metal test facility. Obtained results can help to receive new information about two-phase liquid metal flows. On the base of this information a validation of numerical codes, which are already have an industrial application, can be carried out.

1. Introduction

Investigations of gas volume motion in heavy liquid metal have become important lately. The main reason is a construction of new types of reactors with liquid metal coolant. Fast breeder reactors with liquid-metal coolant are designed to create a new class of self-protective reactors. It is a very complicated problem. Justification of a safety operation for these types of reactors is a very time-consuming process with a large number of theoretical and experimental investigations to prove reactor's safety. So it is important to provide theoretical and experimental studies of processes that occur during the accidents at the nuclear power plant. There are loops with different type of coolants in fast breeder reactors. The accidents with steam generator tube rapture are very difficult to analyse. Steam bubble, that is formed during leakage, start to move and heat transfer to coolant flow. Low Prandtl number is the main distinction between liquid metals and usual coolants such as water. This fact determines the features of heat transfer in liquid metals. Experimental and theoretical investigations of motion and heat transfer of gas bubbles in liquid metal coolant have been provided in the frameworks of presented project study to understand the features that take place during the loss-of-coolant accidents in reactors with liquid metal coolant. Obtained data have scientific and practical importance and can be used for validation of thermal hydraulic codes.

There are different thermal hydraulic codes to simulate processes in water and liquid metal coolants. Most of codes have been developed to simulate accident in certain type of nuclear power reactors. For example, the RELAP5-3D [1] code has been created in the United States to calculate...
processes in Light and Boiling Water Reactors (LWR and BWR). The TRACE code has been developed to simulate processes in LWR and BWR too, but the last version of the code can also calculate processes in sodium flow [2]. To simulate processes in water, sodium and heavy liquid metal in the existing and projected Russian types of nuclear reactors, the HYDRA-IBRAE/LM [3] code has been developed. The brief description of the HYDRA-IBRAE/LM code will be presented below.

2. Brief description of the experiments
To investigate gas bubbles motions in heavy liquid metal, experimental installations have been built. Two different types of the installations have been constructed. The first type was used for investigations of gaseous bubble motions in a stagnant liquid metal column. A vertical circular tube was used in these experiments. The tube diameter was 25 mm, its height – 1.2 m. The tube was partially filled with heavy liquid metal (Rose’s alloy). Height of liquid was equal to 1 m. A gas tank was placed under the tube. Tank and vertical tube have been connected with solenoid valve. The gas was injected from the gas tank through the valve. The valve was opening by electrical signal. The time of full valve opening was 5 ms and depended on the experiment. The time of injection was changing from 50 to 200 ms. The test section is shown in the figure 1. Detailed description of the experimental installation can be found in the [4, 5]. Pressure evolution and the position of the liquid level were measured in the experiments.

The second type of the experimental setup was used in the experiments of heat transfer between gas bubbles and heavy liquid metal. A vertical circular tube was used in the experiments. The tube diameter was equal to 48 mm. The tube was filled with liquid lead. The lead temperature was equal to 400°C. Temperature measurements were carried out by thermocouple. The test section is shown in the figure 2. Temperature of the liquid metal was measured as well.

![Figure 1](image1.png)  
**Figure 1.** Test section of the first series of the experiments. 1, 2 – pressure transducers.  

![Figure 2](image2.png)  
**Figure 2.** Test section of the second series of the experiments.

3. HYDRA-IBRAE/LM code
HYDRA-IBRAE/LM/V1 code is being developed for numerical simulation and safety assessment of Nuclear Power Plant (NPP) with liquid metal coolant (lead, lead-bismuth, sodium). HYDRA-IBRAE/LM may be used for simulating processes in BN-1200 and BREST-OD-300 reactors under
nominal, transient and accident condition. The code is used for simulating thermohydraulic processes in sodium coolant with and without boiling and processes in lead coolant in the presence of non-condensable gases. With comparison to other thermal hydraulic codes [1, 2] the HYDRA-IBRAE/LM has been developed and verified to simulate processes in Russian types of nuclear power reactors. To calculate processes in two-phase flow the code solves the system of equations of non-homogeneous and non-equilibrium two-fluid model. The system of equations is closed by relations that determinate the intensity of heat and momentum exchange between coolant and walls and between different phases.

To predict pressure losses in two-phase flow, two-phase multiplier is used. Two-phase multiplier is calculated by Chisholm correlation [6].

\[ \phi^2 = 1 + \frac{C}{X_{LM}} + X_{LM}^{-2}, \]

\( X_{LM} \) is the Lockhart-Martinelli’s parameter. Another closing relation can be found in a work [7]. The HYDRA-IBRAE/LM code has been validated on the base of analytical tests, in-pile and out of pile experiments. Some results of verification on the base of sodium boiling experiments are presented in figure 3. These experiments were carried out in in ML-4 test facility (Italy, ISPRA) [8]. More results of the HYDRA-IBRAE/LM calculation on the base of sodium boiling experiments can be found in [9].

![Figure 3](image.png)

**Figure 3.** Pressure at different points along the assembly length as a function of the volume flow rate (12 kW/pin)

To choose grid for calculation with help of the HYDRA-IBRAE/LM code, the next procedure are provided. At the first stage the sequences of the calculation on different grids that differ by orders of magnitude are provided. If the results obtained are close, then we can assume that the errors associated with the discretization of the computed area are minimized and excluded from further consideration. The grids with the biggest size of cells are used in the further calculation. The example of calculation with different grids is shown in figure 4.

To validate HYDRA-IBRAE/LM models for simulating bubbles motion in heavy liquid metal the experiments that were described in the chapter 2 have been calculated.

4. **HYDRA-IBRAE/LM simulation of the experiments of bubble motions in heavy liquid metal**

Numerical scheme to simulate bubble motion in heavy liquid metal has been developed. In the first series of the experiments the scheme consisted of one vertical channel with stagnant Rose’s. Gas was injected through the bottom cell. There were two channels in the second series of the experiments. The first channel contained stagnant lead. The second was used for gas injection into liquid lead. The results of simulation are presented in the figure 5 for the first series and in the figure 6 for the second series. The difference between calculation results and experimental data is equal to 11% for the first
series of experiments. The difference between calculation results and experimental data is equal to 1 K for the second series of experiments.

Figure 4. Calculations with different grids

Figure 5. Pressure evolution during the experiments

Figure 6. Temperature evolution during the experiments

5. Conclusion
The brief descriptions of experiments with gas injection into liquid metal coolants are presented in the current paper. These experiments can be used as benchmarks for thermal hydraulic codes. Current paper present also the description of the HYDRA-IBRAE/LM code. The HYDRA-IBRAE/LM is a thermal-hydraulic code that can simulate processes in the different types of liquid metal coolant. The calculations of the presented experiments were made using HYDRAIBRAE/LM/V1 code. A good agreement between the experimental data and the results of the calculations has been obtained.

References
[1] Fletcher C, Schultz R 1995 RELAP5/MOD3 Code Manual
[2] Chenu A, Mikityuk K, Chawla R 2009 Nucl. Engn. Des. 239 p. 2417
[3] Alipchenkov V M, Anfimov A M, Afremov D A, et al. 2016 Thermal Engineering 63 (2) p. 130
[4] Lobanov P D, Usov E V, Butov A A, et al. 2017 Thermal Engineering 64 (10) p. 770
[5] Alekseev M V, Vozhakov I S, Lobanov P D, et al. 2018 Proceedings XXXIV Siberian thermophysical seminar (IT SB RAS) (in press, in Russian)
[6] Chisholm D 1967 Int. J. Heat and Mass Transfer 10 (12) p. 1767-
[7] Usov E V, Butov A A, Dugarov G A, et al. 2017 Thermal Engineering 64 (7) p.48
[8] Savatteri C, Warnings R, Kottowski H 1988 Proc. Liq. Metal Boiling Working Group 1 p. 99
[9] Usov E V, Pribaturin N A, Kudashov I G et al. 2015 Atomic Energy 118 (6) p. 382