Validation of the two-fluid model of interaction of a water jet with a melt

O I Melikhov[1*], *V I* Melikhov[1], *S E* Yakush[2], and *D V* Finoshkina[1]

[1]National Research University Moscow Power Engineering Institute, Moscow, 111250, Russia
[2]Ishlinsky Institute for Problems in Mechanics of the Russian Academy of Sciences, Moscow, 119526, Russia

Abstract. The model of interaction of a water jet with a melt was validated using experimental data from experiments in which a water jet was injected into a vessel filled with a melt of a eutectic alloy of lead and bismuth. The model is based on the VOF method for immiscible liquids. In the experiments, the experimental data of which were used to validate the model, high-speed X-ray photography was carried out to trace the evolution of the shape of a water jet after its injection into a vessel with a melt. The configurations of the water jet that disintegrates in the melt volume obtained in the calculations were compared with photographs taken during the experiment. Good qualitative agreement between calculations and experiment was obtained. A quantitative comparison of the jet propagation in the melt showed that the jet propagation speed in the calculations is overestimated relative to the experiments at a high water injection rate. This is due to the fact that the model does not take into account the boiling of water on the surface of a hot melt, which is planned to be done in future activity.

1 Introduction

Study of the interaction of a water jet with a melt located in a pool is stimulated by the need to ensure the safety of reactors with lead or lead-bismuth coolant. In such reactors, the hot coolant after the reactor enters the steam generator. The coolant pressure has the order of 1 MPa. In the heat exchange tubes of the steam generator, water moves under high pressure (about 20 MPa). The water is heated by the coolant, begins to boil and turns into steam. Designs of reactors with lead or lead-bismuth coolant take into account an accident with a rupture of the steam generator tube. Under such an accident, water or a steam-water mixture under high pressure will blowdown of the rupture. High-pressure water, after entering the coolant, where the pressure is an order of magnitude lower, becomes overheated and boils. As a result, there is always a steam-water mixture in the rupture area.

When a steam generator tube ruptures in a reactor with a lead or lead-bismuth coolant, several physical factors can occur that affect the safety of the reactor [1]. The water flowing from the rupture exerts a force on the adjacent heat exchange tubes, which can be classified as follows: 1) the impact of a shock wave propagating through molten lead, which was

* Corresponding author: oleg.melikhov311@yandex.ru

formed at the moment of rupture due to the large pressure difference in the heat exchange tube and in the coolant; 2) the impact of molten lead, which acquired additional velocity (relative to the flow before the accident) due to its displacement by the steam-water mixture in the rupture area; 3) the impact by flowing steam-water jet.

As was experimentally revealed in [2], when a steam generator tube ruptures, due to the instability of the interphase surfaces, fragmentation of the water jet can occur and the formation of a mixture of water droplets and molten lead can take place. In this case, water droplets are separated from direct contact with molten lead by a steam film. Thus, a multiphase system arises: "continuous melt of lead and droplets of water located in it, surrounded by steam films." Under the influence of the buoyancy force, droplets of water surrounded by steam films will rise upward to the free surface of molten lead. Since heat transfer from lead to a droplet of water occurs through a steam film, its intensity is low, and the evaporation of the droplet occurs slowly. Therefore, the duration of existence of such a steam-water particle is determined by the time of its lifting from the rupture location to the free surface of molten lead in the steam generator. This time is about a few seconds.

In the study [1], an assumption was made about the possibility of realizing in the forming system "continuous lead melt and drops of water located in it, surrounded by vapor films," the energetic interaction of the melt with water (vapor explosion), which is realized in the form of a thermal detonation wave. The interaction occurs as follows. As the shock wave propagates through the initial multiphase mixture in the region of the pressure jump, the vapor films collapse, which intensifies the heat exchange between lead and water. In addition, due to the difference in the densities of water and lead, water droplets are accelerated by the shock wave much more than heavy lead. Therefore, a velocity difference arises between the water droplets and the surrounding liquid lead, which leads to fragmentation of the droplets according to the boundary layer stripping mechanism [3] and a corresponding increase in the heat exchange area surface between lead and water. These factors provide energy supply to the wave, which supports its propagation.

The formation of a mixture of water droplets with a melt occurs due to the development of hydrodynamic instability of the interface. In [4], a classification of various mechanisms of jet fragmentation was proposed depending on the value of the external Weber number of the jet We, which determines the nature of the development of hydrodynamic instability. The external Weber number of the jet is defined as follows:

$$We = \frac{\rho_a V_j^2 D_j}{\sigma}, \tag{1}$$

Where V_j and D_j are the velocity and diameter of the jet, ρ_a is the density of the surrounding (external) liquid, σ is the surface tension coefficient.

At small external Weber numbers ($We < 0.4$), the so-called varicose mechanism of jet fragmentation takes place, when the determining factor is surface tension. In this case, a random local decrease in the diameter of the jet (an increase in the curvature of the surface) leads to an increase in pressure in this place and a flow of liquid from this place to a neighboring area in which the diameter of the jet is larger. This mechanism enhances the initial perturbations of the jet shape and leads to capillary disintegration of the jet into droplets with a diameter close to the diameter of the jet.

At large Weber numbers ($We > 100$), inertial forces dominate, which determine the jet atomization regime, in which intensive formation of small droplets occurs immediately behind the nozzle. In the intermediate range of values of the external Weber number, other regimes of jet fragmentation are observed.

The situation described above refers to the case when the density of the jet is higher than the density of the surrounding environment. As research [5] has shown, the evolution

of a light jet penetrating into a volume occupied by a heavy liquid has different features. In this work, a numerical study was performed using the VOF method [6] of injecting a jet of water into a volume occupied by liquid lead. The high density of liquid lead made it difficult for a jet of water to penetrate, so the jet was deformed upon entering the volume of liquid lead, and then transformed into a conglomerate of fragments of various sizes, which were gradually crushed into small drops.

In our work, the mathematical model [5] was validated using experimental data [7-8], obtained in experiments in which the injection of a jet of water into the volume occupied by a molten eutectic mixture of lead-bismuth was studied.

2 Materials and methods

In experiments [7-8], a melt of a eutectic lead-bismuth mixture with a density of 10600 kg/m^3 and a melting point of 125 °C was placed in a slice vessel of 10 mm thick. The vertical dimension of the vessel was 150 mm, and the horizontal dimension was 170 mm. The vessel had semicircular closed bottom and an open top.

Subcooled water was injected vertically onto the surface of the melt through a nozzle with an internal diameter of 6 mm. The nozzle has a cylindrical shape; its exit is located in the air atmosphere 50 mm above the initial level of the melt. The shape of the water jet in the melt was recorded using a high-speed neutron radiographic method.

In the experiments, the temperature of the water in the jet had the following values: 25, 60, 80, 90 degrees Celsius; melt temperature was: 273, 280, 290, 480, 500, 530 degrees Celsius. The velocity of the water jet varied from 5.8 m/s to 7.8 m/s.

A mathematical model of fragmentation of a water jet in a melt is based on the VOF (Volume Of Fluid) method and is described in detail in article [5], so below is a brief description of it. It is considered 2 immiscible liquids: water and melt, thermal processes and phase transition (vaporization and condensation) are not considered. In the VOF method, the hydrodynamics of two immiscible liquids is described by introducing an effective fluid, the physical properties of which in each local volume are equal to the properties of the liquid (water or melt) located in this volume. If there are two different liquids in a computational cell, then the physical properties of the effective fluid in this cell are determined by averaging over the volume the properties of the liquids located in this cell. In the VOF method, the surface tension is converted into an equivalent volumetric force acting within the transition layer between liquids. It is calculated by the model CSF (Continuum Surface Force) [9].

The mathematical model was implemented in the open software package OpenFOAM [10], using the version OpenFOAM-v2106.

3 Results

Calculations were carried out in a rectangular area 170x100 mm, the vertical size of which corresponds to the depth of the melt in the experiments [7-8]. The air atmosphere above the melt surface was not modeled. In the calculations, a grid size of 500x300 cells was used, the cell side was 0.33 mm. Since the calculations were carried out in a two-dimensional approach, in order to conserve the total water flow rate, the jet diameter D_j was replaced by the equivalent one for 2D case, D_{eq}, which was determined from the relation:

$$D_{eq} = \frac{\pi D_j^2}{4L_w}, \tag{2}$$

Where $L_w = 10$ mm is the transverse width of the experimental vessel. For the experimental parameters [7-8], we obtain $D_{eq} = 2.83$ mm.

In the calculations, only the initial (hydrodynamic) stage of the experiments was modeled until the moment when in the experiments the water was heated to saturation and its violent boiling occurred.

Figure 1 shows at successive moments of time the distributions of the volume fraction of water obtained in the calculations of the experiment in which the velocity of the water jet $V_j = 6.2$ m/s. For comparison, the same figure shows the configurations of the water jet recorded in the experiment. The moments of time in this and the next figures are indicated, as in [7-8], in dimensionless form, $t^* = tV_j / D_j$, where D_j is the internal diameter of the tube through which water was supplied, which determines the initial diameter of the water jet.

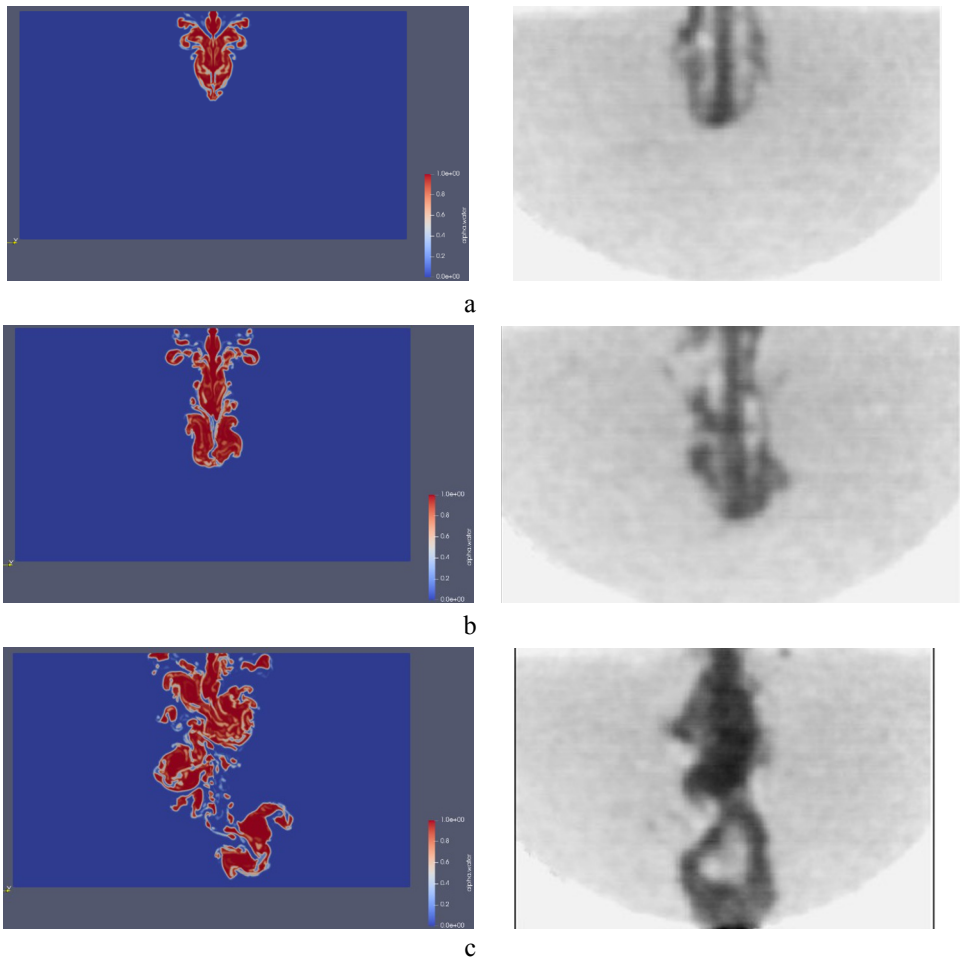

Fig. 1. Evolution of a water jet in a melt at $V_j = 6.2$ m/s. On the left is the calculation, on the right is the experiment. $t^* = 33$ (a), 55 (b), 122 (c).

As follows from Figure 1, in general, the pattern of jet penetration in a melt qualitatively corresponds to the experimental picture: strong fragmentation of the jet is visible upon entering the melt with the formation of both large-scale and small-scale fragments. It is necessary to keep in mind that in calculations the vessel has a rectangular shape, while in experiments its lower part is a semicircle. This helps establish symmetry of

the water jet in the experiment when it reaches the bottom of the vessel. In addition, due to the rectangular shape of the vessel in the calculation, there is more melt in this calculation vessel than in the experimental vessel, which affects the hydrodynamics of the process.

In Figure 2 similar results are shown for the calculation of the experiment [7-8] with a higher jet speed, V_j =7.5 m/s and the corresponding experimental configurations of the water jet.

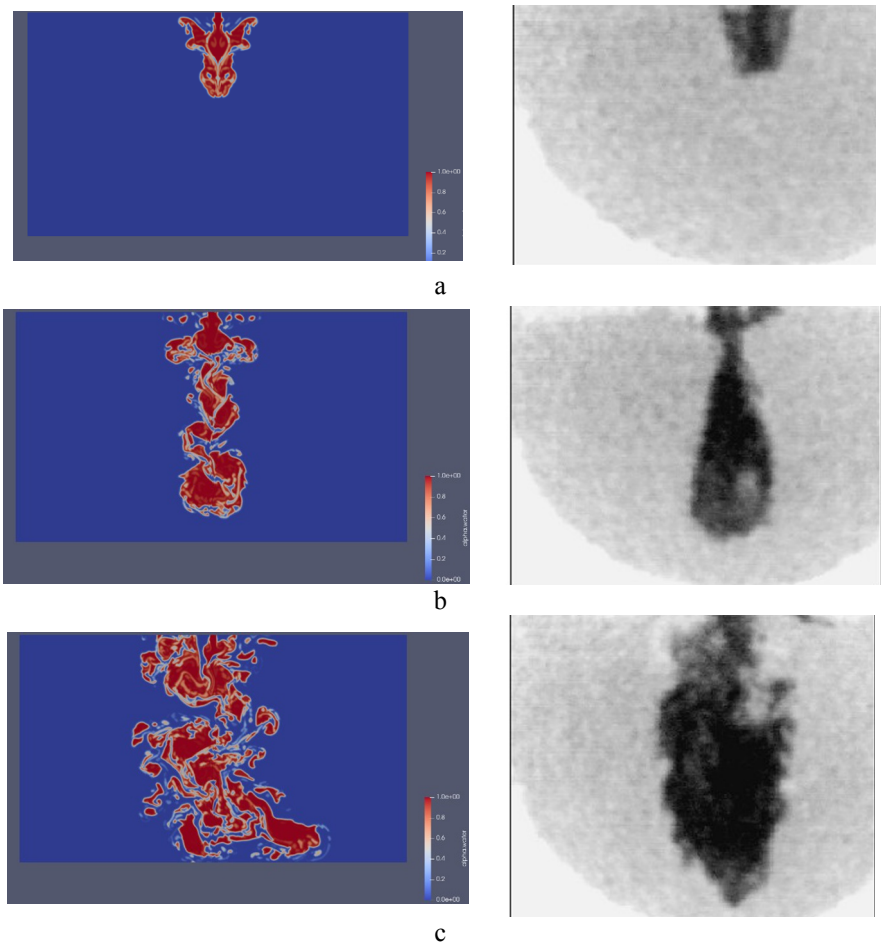

Fig. 2. Evolution of a water jet in the melt at V_j = 7.5 m/s. On the left is the calculation, on the right is the experiment. t^* = 33 (a), 89 (b), 189 (c).

4 Discussion

As follows from a comparison of the calculated and experimental results presented in Figures 1 and 2, the evolution and breakup of the water jet when it penetrates into a heavy melt do not significantly depend on the jet velocity before the melt surface. In both cases, fragmentation of the jet occurs when it reaches the bottom of the vessel. However, as can be clearly seen in Figure 2, at a higher input velocity of the water jet there is a difference in the propagation speed of the water jet in the melt between calculation and experiment. In the calculation the jet moves faster than in the experiment. Apparently, this is due to the fact that when the jet speed increases, the heat exchange between the melt and water

increases, which is why the water around the jet begins to boil. The generating vapor rises upward under the influence of buoyancy force and slows down the propagation of the water jet. The mathematical model currently does not take into account the boiling of water. This leads to the fact that in the calculation the water jet moves to the bottom of the vessel faster than in the experiment.

5 Conclusions

The validation of the model of interaction of a water jet with a molten heavy metal (eutectic alloy of lead and bismuth) located in a vessel into which the water jet is injected, carried out in this work, showed a qualitative agreement of the hydrodynamic processes observed in the calculations with experimental data. A quantitative comparison of calculated results and experimental data on the propagation speed of the water jet gave good agreement for the relatively low entry speed of the water jet. However, in the case of a high entry velocity of the water jet, the results obtained from the model, overestimate the speed of the water jet propagation relative to the experiment. Apparently, this is due to the fact that the model does not take into account the boiling of water on a hot melt. Future improvement of the model should include a description of heat transfer processes and phase transitions.

Acknowledgement

This research was funded by Russian Science Foundation (RSF) under Grant 21-19-00709.

References

1. T.N. Dinh, *Multiphase flow phenomena of steam generator tube rupture in a lead-cooled reactor system: a scoping analysis*, in Proceedings of the International Congress on Advances in Nuclear Power Plants, ICAPP, 13-18 May 2007, Nice, France (2007)
2. A.V. Beznosov, S.S. Pinaev, D.V. Davydov A. A. Molodtsov, T. A. Bokova, P. N. Martynov,V. I. Rachkov, Atomic Energy, **98**, 170 (2005)
3. D.F. Fletcher, Int. J. Heat Mass Transfer, **34**, 2435 (1991)
4. T. Ginsberg, *Liquid jet breakup characterization with application to melt-water mixing*, in ANS Proceedings. National Heat Transfer Conference, 4-7August 4-7 1985, Denver, Colorado (1985)
5. V.I. Melikhov, O.I. Melikhov, G.Yu. Volkov, S.E. Yakush, B. Saleh, Thermal Eng., **70**, 62 (2023)
6. C.W. Hirt, B.D. Nichols, J. Comp. Phys., **39**, 201 (1981)
7. Y. Sibamoto, Y. Kukita, H. Nakamura, *Simultaneous measurement of fluid temperature and phase during water jet injection into high temperature melt*, in 11th Int. Top. Meet. Nucl. Therm. NURETH-11, 2-6 October 2005, Avignon, France, (2005)
8. Y. Sibamoto, Y. Kukita, H. Nakamura, J. Nucl. Sci. Technol., **44**, 1059 (2007)
9. J. Brackbill, D. Kothe, C. Zemach, J. Comp. Phys., **100**, 335 (1992)
10. OpenFOAM: The open source CFD toolbox, https://www.openfoam.com/