

Model of interaction of a steam-water cavity with a molten metal near a solid wall

O I Melikhov^{1*}, *V I Melikhov*¹, and *D V Finoshkina*¹

¹National Research University Moscow Power Engineering Institute, Moscow, 111250, Russia

Abstract. To evaluate the consequences of an accidental rupture of a steam generator heat exchange tube in a reactor with a heavy liquid metal coolant, a mathematical model of the interaction of a steam-water cavity with molten metal near a solid wall was developed. The melt flow is considered as a potential flow of an incompressible fluid. The heat exchange between the melt and the steam-water mixture is not taken into account. The steam-water mixture is modeled by an equilibrium two-phase model. It is believed that the evolution of the steam-water cavity is an isentropic process. The numerical implementation of the mathematical model was performed using the boundary element method. Verification of the developed model using a numerical solution of a spherically symmetric problem of the interaction of a spherical steam-water cavity with a melt in infinite space, obtained using the Rayleigh-Plesset equation, showed good agreement between the solutions obtained by different methods. Using the developed model, a test calculation of the interaction of a steam-water cavity with the surrounding molten metal near a solid wall was performed. Analysis of the calculation revealed several stages of this interaction

1 Introduction

In fast reactors with a heavy liquid metal coolant (lead or eutectic lead-bismuth mixture), steam generators are designed as follows. Feed water is supplied to the heat exchange tubes under high pressure (approximately 20 MPa), which receives heat from the coolant, boils, and the generated steam goes to the turbine. The hot coolant entering the steam generator from the reactor is under low pressure, the value of which is determined by the pressure in the gas space above the coolant level (0.1 MPa) and the hydrostatic pressure of the coolant column in the steam generator (about 1 MPa).

In the designs of these reactors, an accident with a rupture of the heat exchange tube of the steam generator is allowed. This means that the reactor design must ensure its safety in the case of this accident. Several system computer codes have been developed to assess the safety of reactors with liquid metal coolants: SIMMER-III [1], FEMAXI-FBR [2], EUCLID/V1 [3] and others. These system codes make it possible to reproduce the progress of an accident on the scale of the entire reactor installation and predict its response to various emergency events. But at the same time, some fine phenomena and processes may

* Corresponding author: oleg.melikhov311@yandex.ru

not be taken into account. Therefore, it is necessary to deepen the analysis of emergency situations and look for new possible effects that can lead to negative consequences.

The initial stage of an accident with a rupture of the heat exchange tube of a steam generator was studied in sufficient detail in [4]. In this study, the force effects on adjacent intact heat exchange tubes of a steam generator from the following effects that occur during an emergency rupture of one of the tubes were estimated: 1) a shock wave propagating through the liquid lead coolant, 2) the impact of the lead coolant flow due to the expansion of the steam-water cavity around the rupture site, 3) the impact of a steam-water jet flowing from the rupture.

However, the effect of a steam-water cavity action on internal structures after the heat exchange tube rupture has not been previously considered. (This cavity has essential potential for construction destruction.) The hydrodynamics of this effect cannot be described in a one-dimensional spherically symmetric approximation, but requires at least two-dimensional axisymmetric analysis. If for the spherically symmetric case the Rayleigh-Plesset equation was obtained [5, 6], which significantly simplifies the technique of analyzing hydrodynamics, then for the two-dimensional case there is no analogue of this equation. But to solve two-dimensional axisymmetric problems, you can use the boundary element method (BEM) [7]. This method allows you to effectively track the movement of the interface between two media, taking into account the presence of solid boundaries and a free surface.

Our paper proposes a mathematical model of the interaction of a high-energy steam-water cavity with the surrounding molten metal in the presence of a solid wall near the cavity. The numerical implementation of the model is based on the boundary element method.

2 Materials and methods

The model describes the compatible flow of a steam-water mixture and the surrounding molten metal. It is assumed that the steam-water mixture is in an equilibrium state. This means that the temperatures of steam and water are equal to the saturation temperature, which corresponds to the pressure of the steam-water mixture. In the steam-water cavity, all parameters (pressure, temperature, void fraction) are distributed uniformly.

We will neglect the heat exchange of the steam-water cavity with the surrounding molten metal, since short time intervals are considered. Therefore, the cavity dynamics will be an isentropic process. The development of this process is described by the integral law of conservation of mass of the steam-water cavity, the equation of state of the steam-water mixture and the pressure of the molten metal at the boundary of the steam-water cavity.

We will consider the flow of molten metal as a potential flow of incompressible fluid, which is limited by a flat solid infinite wall, and in which there is a steam-water cavity. The pressure in the cavity is equal to the pressure of the molten metal at the boundary with the cavity. We will neglect the effect of the gravity force because we are considering small time intervals.

At the initial moment of time, the steam-water cavity has a spherical shape. Let us draw a straight line from the center of the sphere, perpendicular to the solid wall. The problem under consideration will have cylindrical symmetry with respect to this line. The problem is formulated in cylindrical coordinates, the solution of the problem does not depend on the angular variable.

In [7], it was proven that the solution that describes the flow of molten metal can be found from the integral equation for the velocity potential on the surface of the steam-water cavity. The numerical solution of this integral equation is determined on a set of boundary elements that approximate the surface of the cavity. As a result, solving the integral

equation is reduced to solving a system of linear equations with respect to the velocity potential and the normal derivative of the velocity potential, defined in the boundary elements. Details of the numerical implementation of this method are given in [8-10].

3 Results

In order to verify the proposed model, it was used to calculate the dynamics of the steam-water cavity in the case when the solid wall was far from the cavity and did not affect the process, which ensured the spherical symmetry of the numerical solution. A comparison was made with the spherically symmetric case of the dynamics of a steam-water cavity in an infinite space filled with molten metal. In this case, the same equilibrium model of a steam-water cavity was used as in this work. The dynamics of molten metal was described by a one-dimensional, spherically symmetric model of an incompressible fluid. As is known, in this case, the description of the hydrodynamics of the molten metal is reduced to solving the Rayleigh-Plesset equation [5, 6], which relates the change in the radius of the steam-water cavity with the difference between the pressure in the cavity and the pressure in the molten metal far from the cavity (“at infinity”).

Numerical solutions of the problem of the dynamics of a spherical steam-water cavity in molten metal using the method proposed in this work and using the method using the Rayleigh-Plesset equations [5-6] were obtained for typical parameter values, which are given in Table 1.

Table 1. Parameters for a spherically symmetric problem.

Parameter	Value
Initial cavity pressure, MPa	18
Initial void fraction	0
Initial cavity radius, mm	13
Initial pressure of molten metal, MPa	0.8
Density of molten metal, kg/m ³	10417

To approximate the cavity contour in calculations using the BEM method, 60 boundary elements were used, the time step was chosen from the condition proposed in [8].

A comparison of the dynamics of transients of the cavity radius and the cavity pressure, calculated using the BEM method, with the results obtained using 1D model is shown in Figure 1.

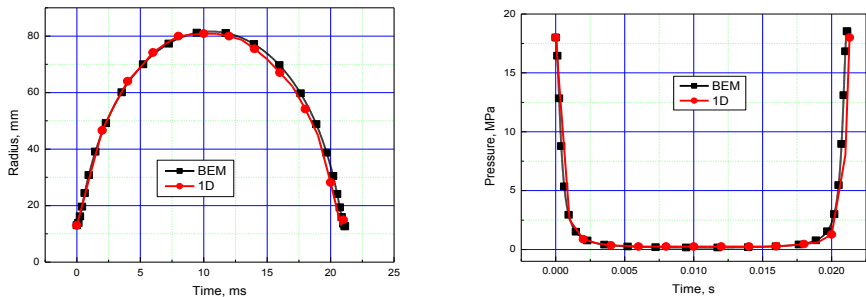


Fig. 1. Transients of the cavity radius (left) and cavity pressure (right).

As follows from Fig. 1, there is a good agreement between the results obtained by different methods. It can be noted that in the BEM case, the compression stage of a steam-water cavity is modelled slightly slower compared to the one-dimensional case. Using the BEM method, it is possible to obtain only one period of oscillation of a spherical steam-water cavity, after which the calculation becomes unstable. Variation of the numerical parameters (number of boundary elements, time step, smoothing parameters) did not eliminate this problem. Using a simpler one-dimensional model, an unlimited number of oscillations of a steam-water spherical cavity can be obtained.

Figure 2 shows the results of our calculations of pressure distributions in the molten metal at times when the radius of the expanding spherical steam-water cavity was 20 mm, 30 mm, 40 mm and 60 mm, appropriately. Calculations using the BEM method and a one-dimensional model are presented. In general, there is consistency in the results obtained using different methods. However, it should be noted that near the cavity surface, the BEM method gives slightly underestimated pressure values compared to the results of the one-dimensional model.

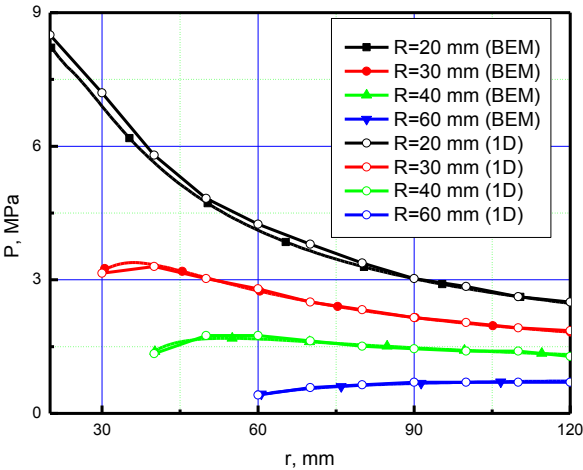


Fig. 2. Pressure distributions in the melt. The moments at which the distributions are shown correspond to the moments when the cavity diameter was 20, 30, 40 and 60 mm, appropriately.

Let us consider the dynamics of a steam-water cavity in a half-space filled with a melt and bounded by a solid wall. We will consider a short period of time when the process is not affected by gravity. At the initial moment, the cavity is a drop of saturated water. The initial pressure of water in a drop is much greater than the initial pressure of liquid lead. The lead pressure far from the cavity (“at infinity”) retains its initial value throughout the process under study.

Using the developed model based on the BEM method, a test calculation of the further evolution of such a cavity was performed with the calculated parameters presented in Table 1. The initial distance of the cavity center from the solid wall was equal to three initial radii of the cavity. Figure 3 shows the pressure fields in the considered region at successive moments in time. First of all, it should be noted that the central area, painted in the same color, shows the contour of the cavity itself, in which there is a uniform pressure, the value of which is calculated during the integration of the governing equations. Analysis of the evolution of pressure fields in molten metal will help to determine the main patterns of the dynamics of a steam-water cavity and its effect on the solid wall.

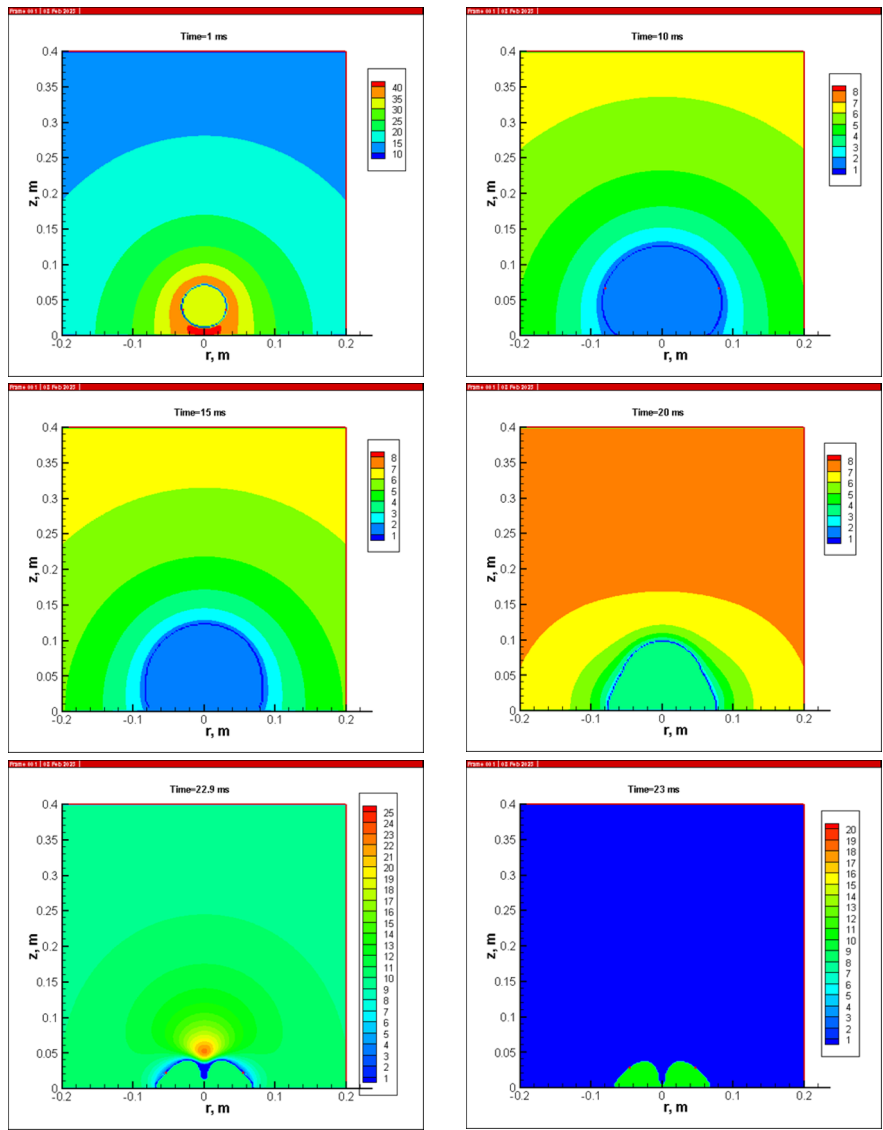


Fig. 3. Evolution of the pressure field.

4 Discussion

Unlike the cases considered in [8-9], in our case the process develops as follows. Under the action of high pressure, the cavity begins to expand, while the pressure in the cavity drops, water begins to boil, and a steam-water mixture forms in the cavity. Under the influence of the expanding cavity, liquid metal begins to move towards the periphery of the region. Quite quickly, the pressure in the cavity becomes less than the pressure in the layers of liquid metal adjacent to the cavity. However, despite this, the cavity continues to expand due to the inertia of the melt which started to move. To slow down the melt and force it to move towards the center of the cavity, a long-term force is required, resulting from the difference between the pressure of the melt away from the cavity and the pressure in the cavity itself.

After the flow of molten metal towards the periphery of the region is stopped under the influence of melt pressure far from the cavity, a return flow of melt begins towards the center of the cavity. It leads to the destruction of the cavity and the melt action on the solid wall. This process is similar to the collapse of a vapor bubble near the wall [10]. The pressure fields before the collapse of the steam-water cavity are shown in Fig. 3 at times 22.5 ms and 23 ms. A local area of increased pressure is formed above the cavity, which forms a high-speed jet of molten metal. This jet breaks through the cavity and reaches the solid wall, acting on the wall at the moment of braking.

5 Conclusions

A model of the interaction of a steam-water cavity with a molten metal near a solid wall was developed. An integral equilibrium model is used to describe the steam-water mixture. The heat exchange of the steam-water cavity with the surrounding melt is neglected, which allows us to consider the dynamics of the cavity as an isentropic process. The flow of a liquid melt is considered as a potential flow of an incompressible fluid. The numerical implementation of the model is based on the boundary element method.

The model was successfully verified using a numerical solution of a spherically symmetric problem, which was obtained using the Rayleigh-Plesset equation.

A test calculation of the interaction of a steam-water cavity with molten metal revealed the following stages of this process: cavity expansion, cavity compression, formation of a high-speed melt jet above the cavity, penetration of the melt jet into the cavity, and the impact of this jet on the solid wall.

To realistically evaluate the impact of the resulting melt jet on the wall, detailed information about the initial state of the steam-water cavity is required.

Acknowledgement

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

References

1. Y. Tobita, Sa. Kondo, H. Yamano, K. Morita, W. Maschek, P. Coste, T. Cadiou, *Nucl. Technol.*, **153**, 245 (2006)
2. T. Okawa, I. Tatewaki, T. Ishizu, H. Endo, Y. Tsuboi, H. Saitou, *Progr. Nucl. Energy.*, **82**, 80 (2015)
3. V.M. Alipchenkov, A.V. Boldyrev, D.P. Veprev, Yu.A. Zeigarnik, P.V. Kolobaeva, E.V. Moiseenko, N.A. Mosunova, E.F. Seleznev, V.F. Strizhov, E.V. Usov, S.L. Osipov, V.S. Gorbunov, D.A. Afremov, *Thermal Eng.*, **65**, 627 (2018)
4. A.S. Iskhakov, V.I. Melikhov, O.I. Melikhov, S.E. Yakush, *Nucl. Eng. Des.*, **341**, 198 (2019)
5. L. Rayleigh, *Phil. Mag.*, **34**, 94 (1917)
6. M.S. Plesset, *J. Appl. Mech.* **16**, 228 (1949)
7. C.A. Brebbia, J.C.F. Telles, L.C. Wrobel, *Boundary element techniques* (Springer-Verlag, Berlin, 1984)
8. D.C. Gibson, J.R. Blake, *Appl. Scientific Research.*, **38**, 215 (1982)
9. A. Pearson, J.R. Blake, S.R. Otto, *J. Eng. Mathematics.*, **48**, 391 (2004)
10. E. Klaseboer, B.C. Khoo, *Comp. Mech.*, **33**, 129 (2004)