Thermal contact resistance of a liquid lead and structural steel

A B Kruglov, V B Kruglov, V S Kharitonov, P G Struchalin and D P Shornikov
National Research Nuclear University “Moscow Engineering Physics Institute”,
Moscow, Russia
E-mail: PGStruchalin@mephi.ru

Abstract. The paper presents numerical investigation of the thermal resistance of the contact surface of heat exchange and melt of lead. Using a geometric model of the contact area, developed on the basis of image analysis of the contact surfaces of steel and lead, the calculation of the contact resistance between molten lead and the surface of steel EP-823. The results of the calculations are compared with experimental data on thermal resistance of contact of the lead with steels EP-823 and 312 steel.

1. Introduction
The future of nuclear energy is associated with the development of reactor installations on fast neutrons with sodium (BN) and lead (BREST) coolants. The use of such installations nitride nuclear fuels will improve the fuel efficiency and move to a closed fuel cycle.

The fast reactors are characterized by high heat flows and temperatures in the core reactor. At temperatures above 1000 °C nitride fuel begins to rapidly swell due to the increase of fission gas release. Achieving deep burnup of the fuel in such conditions is possible when you use fusible heat-conducting layers between the fuel and sheath, in particular, layers of lead and its alloys. The use of thermally conductive layers reduces the temperature of the fuel, it’s the swelling and gas release increases the radiation resistance of fuel rods. High chemical activity of lead, leading to significant corrosion of its interaction with the shell, can be reduced by introducing some additives lead [1].

The calculations showed that in the fuel elements, when the gap between fuel and shell of 0.1 mm, the thermal resistance of liquid metal thermal interface layer is comparable to the thermal resistance of the boundaries of contact of the melt with fuel and shell. With increasing burnup, the thermal conductivity of the fuel will decrease and the thermal resistance will increase in connection with the accumulation on the surfaces of the fuel and shell of gaseous fission products and corrosion products of the interaction of the liquid metal, the shell and fuel. As a result, the temperature in the center of the fuel will increase.

The above factors should be taken into account in the calculations of the thermal regime of the fuel rods and the reactor installation as a whole, and the thermal resistance of the contact boundary layer of liquid metal fuel and the cladding shall be experimentally investigated.

2. The content of this work
Earlier, in [2, 3] conducted the experimental study of thermal contact resistance of molten lead, and steel EP-823 (figure 1).
Figure 1. Thermal resistance of the boundaries of contact "steel – liquid lead”

The data shows that the thermal contact resistance $r_t$ "liquid lead - steel" is comparable to the thermal resistance of the layer of lead with a thermal conductivity $\lambda$ and thickness $\delta$: $r_{Pb} = \delta / \lambda$. When $\lambda = 20 \text{ W/(m-K)}$ and $\delta = 0.1 \text{ mm}$ (this value of the gap assumed in the fuel rods with nitride fuel) we obtain the value of $r_{Pb} \approx 0.5 \times 10^{-5} \text{ (m}^2 \text{-K})/\text{W}$.

In the present work for the analysis of the measurement results of thermal resistance, a study was conducted of the structure of surfaces of lead and steel in the contact area with electronic and optical microscope. The contact area was formed in an argon atmosphere on a steel substrate during melting at $T = 350 \degree C$, soaking at a temperature of $650 – 900 \degree C$ for $0.5 – 1.5$ hours and cooling to room temperature. Then a drop of lead was separated from the substrate and carried out the study of the contact surfaces of lead and steel, optical and electronic (Jeol 6610 LV) microscopes. Figures 2 and 3 show examples of the obtained images. Analysis of the images revealed many areas of local wetting of the surface of steel by lead. The proportion of the wetted surface is small and the greater part of the surface of contact with lead, such as lead was separated from the surface by layer of gas.

Figure 2. Contact surfaces of steel (a) and lead (b) (Pictures on optical microscope)

Figure 3. Contact boundary of steel (Pictures on electronic microscope)

On a substrate made of steel EP-823 by the method of lying drop studied the change in wetting angle by liquid lead at the temperature of crystallization of $T_k = 327.5 \degree C$ depending on
temperature and exposure time of the melt on the steel surface. In argon atmosphere was studied wetting of the two surfaces: brushed (No. 1); polished, then oxidized (No. 2). By results of measurements it is established that the wetting angle $\alpha_k(T_k)$ steel EP-823 by lead decreases with increasing temperature and the total exposure time and stabilized on level $\alpha_k(T_k) \approx 100^\circ$ (figure 4).

After analyzing the images of the contact surfaces we created the model of contact of the molten lead and the steel surface (figure 5). According to this model, the contact consists of areas of the snug lead to the steel through the oxide film and areas with a gas layer between the liquid lead and steel. In the model, the heat flux transmitted through the boundary between steel and molten lead, encounters the thermal resistance of a single oxide layer, or together with the resistance of the gas layer. Thermal resistance of the oxide layer in its thickness $\delta_{ox} \approx 1$ mkm and $\lambda_{ox} \approx 1$ W/(m·K) estimated to be $r_{ox} = \delta_{ox}/\lambda_{ox} \approx 10^6$ (m²·K)/W. The thermal resistance of the gas layer with thickness comparable to the mean free path of the gas molecules, determined by the accommodation of gas molecules to the surfaces of lead and steel [4]. In the conditions of the experiments the calculation of the thermal resistance of the gas layer leads to the values $r_g \approx 10^4$ (m²·K)/W. Since the thermal resistance of the gas layer is several orders of magnitude more thermal resistance of the oxide layer, the latter can be neglected in places of contact of lead and steel through the gas layer. In this case, the total thermal resistance of a boundary of contact of steel and lead can be recorded with the help of the interpolating formula (1):

$$r_t = \frac{r_{ox} r_g}{(1 - \varepsilon_g) r_g + \varepsilon_g r_{ox}}$$

where $r_{ox}$ – thermal resistance of oxide layer with thickness $\delta_{ox}$ and thermal conductivity $\lambda_{ox}$, $r_g$ – thermal resistance of gas layer, $\varepsilon_g$ – the percentage of the surface covered with a gas layer.

The results of the calculation of the thermal resistance $r_t$ of the proportion of the surface covered with gas $\varepsilon_g$, shown in figure 6.
From figure 5 it is seen that the thermal resistance $r_t \approx 0.5 \times 10^{-5}$ (m$^2$K)/W, observed in experiments, corresponds to the fraction of the gas interlayer $\varepsilon_g \approx 0.8$. Analysis of the obtained images of the surfaces of contact of steel and lead is consistent with this value $\varepsilon_g$.

3. Conclusion
The study of the structure of the contact liquid lead and structural steel developed a model of contact geometry on the basis of which the calculations of the thermal resistance of the contact. The obtained results agree with experimental data.

The developed model can be used to predict changes in thermal resistance due to the accumulation of gaseous fission products in the thermal interface layer between the fuel and shell in the fuel element during operation in the reactor.

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References
[1] Orlova E A, Kruglov A B, Chuvaev D V, Struchalin P G, Zagrebayev S A, Zhmurin V G, 2016 VANT. Series: nuclear reactor constants 4 95–8 (In Russian)
[2] Kruglov A B, Kruglov V B, Struchalin P G, Kharitonov V S, Orlova E A, Zagrebayev S A, Zhmurin V G, 2016 Bulletin of the Lebedev Physics Institute 43 302-5
[3] Kruglov A B, Kruglov V B, Struchalin P G, Kharitonov V S, 2015 Abstracts of reports at scientific conference (Obninsk: SSC RF-IPPE) 274 (In Russian)
[4] Kirillov P L, Bobkov V P, Zhukov A V, Yuryev Yu S Reference book on thermohydraulic calculations in nuclear power (vol 1) ed P Kirillov (Moscow, Izdat) p 776 (In Russian)