Conceptual aspects of melting unit vessel cooling by heavy liquid metal coolant

A.Yu. Legkikh*, R.Sh. Askhadullin, P.N. Martynov, V.P. Melnikov, A.N. Storozhenko

JSC "SSC RF-IPPE", 1 Bondarenko Square, Obninsk, Kaluga Region 249033, Russia

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Abstract

The article presents a conceptual analysis of the feasibility of lead–bismuth coolant application for cooling the melting unit steel vessel designed for implementation of a new efficient radwaste reprocessing technique. In support of the lead–bismuth coolant feasibility, the main advantages and specific features of its application are presented, taking into account significant experience acquired in Russia in handling this coolant (nuclear submarines reactor units and circulation loops), availability of job-proved methods and equipment for the coolant quality control, coolant properties ensuring fire and explosion safety and heat removal capability under high temperature and low pressure conditions. Preliminary calculated estimates were made as for temperature distributions during lead–bismuth cooling of the melting unit steel vessel. Calculations were made for the melting unit normal operation, in the presence of refractory coating and slag lining of a certain thickness formed on the vessel inner surface.

Based on the results of the calculated temperature distribution estimates, it can be concluded that lead–bismuth cooling of the melting unit steel vessel in normal operation (i.e. in the presence of refractory coating and slag lining on the vessel inner surface) provides an opportunity to maintain steel surface temperatures which do not exceed the limits at an acceptable flow rate. Data presented in this article have been obtained for the first time and may be useful in designing melting units for radwaste reprocessing.

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Introduction

Currently, new and more efficient technological schemes for radwaste reprocessing are under development in Russia. One of the trends in this respect is the creation of melting units for low and medium metal radwaste reprocessing [1,2]. The melting unit is supposed to use the melting chamber steel vessel with liquid metal cooling. The authors examine the conceptual aspects of the feasibility of lead–bismuth coolant application for the melting unit steel vessel cooling.

The lead–bismuth coolant is efficient in removing heat at high temperatures and low pressures. Due to a high boiling temperature (∼1670°C), its application practically eliminates the heat removal crisis and hazards associated with steam explosions. This coolant is flame-explosion-proof because of its chemical inertness with respect to water and air, and has a relatively low melting point (∼125°C).

As of today, the lead–bismuth coolant management technique has been mastered which is confirmed by a significant experience acquired in Russia in safe operation of submarine lead–bismuth cooled reactor units and their on-shore test facilities [3,4], long-term operation of research non-isothermal circulation loops, and application of this coolant for new generation fast breeder reactors [5,6].

Based on the existing experience in using the lead–bismuth coolant as well as methods and equipment of its quality
control, the authors think it highly advisable to consider lead–bismuth cooling of the melting chamber steel vessel for the projects of advanced melting units.

**Lead–bismuth coolant usage specifics**

One of the main advantages of the lead–bismuth coolant is a lack of energy release during its chemical interaction with air and water. It is well known that heavy liquid metal coolants, including lead–bismuth, have the lowest stored potential energy in comparison with other coolants [7]. Other things being equal, the higher the value of the coolant stored potential energy, the greater the likelihood of a severe accident and the harder its consequences are. Thus, when the lead–bismuth coolant is used, it ensures safety of the facility by eliminating the very causes of coolant-related severe accidents.

The specifics of the lead–bismuth coolant usage in circulation loops include the following:

1. Maintaining the specified oxygen potential in the coolant to prevent erosion-corrosion damage to structural steel at a long-term operational lifetime (thousands of hours).
2. Ensuring cleanliness of the coolant and circulation loop surfaces in order to maintain the design thermal-hydraulic characteristics throughout the operating period.

Up to date, the operating temperatures for the lead–bismuth coolant are within 650°C, at which the long-term experimental studies have proved the possibility of ensuring the corrosion resistance of steels exposed to the coolant [8].

The specialists of the JSC “SSC RF-IPPE” developed a technology providing corrosion protection of steels and produced equipment for its implementation in various circulation loops including those of nuclear reactors [9,10]. This technology provides conditions in the coolant for forming protective coatings on the structural steel surfaces and ensures their integrity in operation. This is achieved by maintaining the specified oxygen potential in the coolant.

If the lead–bismuth coolant contains dissolved oxygen, protective oxide films are formed on the steel surfaces of the liquid metal circuit and equipment due to lower lead oxygen affinity as compared with the main components of steel (iron and chrome). The oxide films have the following structure: MeOx, where Me denotes Fe, Cr and other components of steel.

Due to its inertness to the coolant, good adherence to the steel surface, and the ability to ‘heal’ defects if the coolant contains dissolved oxygen, the protective oxide film prevents the structural steel surface from direct contact with the liquid metal coolant, ensuring the corrosion resistance of steel at a long-term operational lifetime. In this regard, today the ‘oxygen’ technology developed at the JSC “SSC RF-IPPE” is the main method for structural steel corrosion protection in the heavy liquid metal coolant environment, including the projects of advanced fast breeder reactors with heavy liquid metal coolants.

To control the oxygen dissolved in the coolant, the specialists of the JSC “SSC RF-IPPE” developed sensors based on solid oxide electrolyte [11] which are characterized by rapid response, high sensitivity, the ability to work for a long time at high temperatures and thermal shocks, reliability and stability of conductive and mechanical properties in a wide range of temperatures and oxygen partial pressures.

The best method for controlling the oxygen TDA in the coolant is a so-called solid-phase control method, which was also developed at the JSC “SSC RF-IPPE” [10]. Technical implementation of the solid-phase control method is carried out by means of special devices, i.e. mass-transfer devices with a solid oxygen source. Up to date, a considerable experience has been acquired in long-term operation of different mass-transfer devices at the test facilities with lead–bismuth and lead coolants which attests to their reliability, possibility of fine tuning the oxygen insertion rate and absence of negative effects on the loop as a whole [12].

The lead–bismuth coolant properties are such that its direct contact with ambient oxygen (during gas system filling or leakage or equipment repair) may result in solid-phase deposits based on the coolant oxides.

To eliminate the coolant oxide-based deposits, a special technological procedure is used, i.e. hydrogen purification [13] which results in the removal of eutectic components from the deposits. In this case, the deposits are destroyed whereas lead and bismuth are returned to the coolant. Hydrogen purification is carried out using the gas mixtures ‘hydrogen - water steam - inert gas (argon or helium)’. When hydrogen purification is carried out, the hydrogen-containing gas mixture is entered into the coolant flow, whereas slag recovery occurs simultaneously with a mechanical action of the two-component coolant flow, which completely solves the problem of effective cleaning of the circulation loop surfaces. The hydrogen purification method for circulation loops with heavy liquid metal coolants and equipment for its implementation was developed at the JSC “SSC RF-IPPE”.

The efficiency of removing deposits from the coolant and loop surfaces using hydrogen-containing gas mixtures has been repeatedly proven at submarine reactors and various research circulation loops with lead–bismuth and lead coolants. By now, several types of devices have been developed for gas mixture insertion into the heavy liquid metal coolant flow using which it becomes possible to provide efficient purification of circulation loops of various structures and coolant circulation patterns.

It should be noted that hydrogen purification is a rare procedure which is only required when a circulation loop has been polluted with solid-phase deposits. In cases where a circulation loop is operated with a full-pressure gas system, the coolant is not drained or the equipment is repaired, hydrogen purification is not needed.
Fig. 1. Lead-bismuth cooling of steel melting unit vessel.

Calculated estimates of temperature distribution in lead–bismuth cooling of melting unit steel vessel

To assess the temperature level of the melting unit vessel during lead–bismuth cooling, the authors performed preliminary calculations using a simple one-dimensional heat-transfer model.

In making calculated estimates, the melting unit vessel cooling circuit was considered as shown in Fig. 1. The coolant circulation was assumed to be forced and carried out by a pump as follows: pump → melting unit vessel → heat exchanger → pump.

Assumptions. The following assumptions were made in the calculations:

- The coolant movement in the melting unit vessel is carried out through the gap between the inner and outer walls from top to bottom;
- The lead–bismuth coolant flow is evenly distributed across the gap;
- The heat flow to the unit wall is constant;
- The coolant has no solid-phase impurities that can affect the heat transfer (the lead–bismuth coolant technology is observed);
- The intercase space thickness is 10 mm;
- The outer wall is insulated from the outside (one-sided heating);
- All heat transferred to the liquid metal coolant is removed in the heat exchanger (without specifying the method) and the coolant constant temperature at the entrance to the intercase space is 300 °C;
- The gas filling temperature in the burning chamber was assumed to be 1850 °C;
- The slag-skin temperature was assumed to be 1650 °C;
- On the unit wall inner surface (the burning chamber-side) there is a slag lining layer (according to the melting unit parameters presented in [1,14]) and refractory coating;
- The average heat conductivity of the slag lining and refractory coating are 5 W/(m °C) and 3.5 W/(m °C), respectively;
- The thicknesses of steel, slag lining and refractory coating were assumed as shown in Fig. 2.

For the calculations, the authors used the properties of lead–bismuth coolant [15] and gas filling as well as the technique of thermal radiation flux estimates [16].

Calculation method principles. The method was based on the following equations:

- heat balance
  \[ N = G \cdot C_p \cdot \Delta t \]  (1)
where \( G \) is the coolant mass flow rate, kg/s; \( C_p \) is heat capacitance, J/(kg·grad); \( \Delta t \) is the coolant heat up, °C;

- heat transfer

\[
q_{\text{heat}} = k \cdot \Delta t, \tag{2}
\]

where \( q_{\text{heat}} \) is the heat flux, W/m²; \( k \) is the heat transfer coefficient, W/(m²·grad); \( \Delta t \) is the coolant heat up, °C;

- Stefan–Boltzmann’s law

\[
q_{\text{rad}} = \varepsilon \cdot \sigma_0 \cdot T^4 \tag{3}
\]

where \( \sigma_0 \) is the Stefan–Boltzmann constant, W/(m²·K⁴); \( q_{\text{rad}} \) is the thermal radiation flux density, W/m²; \( T \) is the temperature, K; \( \varepsilon \) is the total emissivity.

In the calculations it was assumed that the gas in the burning chamber is a selectively black medium and the inner wall is a black surface. Under this assumption, the heat flux transmitted from the gas filling to the vessel inner wall can be defined using the formula:

\[
q_{\text{rad}} = \sigma_0 \cdot (\varepsilon_g \cdot T_g^4 - \varepsilon_g,w \cdot T_w^4) \tag{4}
\]

where \( \varepsilon_g \) and \( \varepsilon_g,w \) is the gas emissivity factor at the gas and wall temperatures, respectively; \( T_g \) is the gas temperature, K; \( T_w \) is the vessel inner wall temperature (the burning chamber-side), K.

In calculating the gas emissivity factor, a correction was considered for mutual interference of CO₂ and water vapor absorption bands. The flow from the slag surface to the slag lining surface was calculated in a similar way (Fig. 1).

The equivalent channel length \( L \) was calculated by the formula:

\[
L = \frac{F}{\pi \cdot R_1} \tag{5}
\]

where \( F \) is the vessel inner wall surface cooled with liquid metal, m²; \( R_1 \) is the vessel inner wall radius, m.

Based on the melting unit geometry developed at the “Tekhnologiya metallov” manufacturing company, it was assumed in the calculations that \( F = 24 \, \text{m}^2; R_1 = 1.5 \, \text{m} \).

The heat transfer coefficient \( \alpha \) to the liquid metal coolant was calculated from the ratio:

\[
a = \frac{Nu \cdot \lambda_{\text{heat}}}{d_h}, \tag{6}
\]

where \( \lambda_{\text{heat}} \) is the lead–bismuth coolant thermal conductivity coefficient, W/(m·K); \( d_h \) is the hydraulic diameter, m; \( Nu \) is the Nusselt criterion.

The Nusselt criterion was calculated using the formula:

\[
Nu = A + 0.008 \times Pe^{0.87} \times [1 + B \times \exp(-4/Re)] \tag{7}
\]

where \( A = [6.4 - 3/\lg(Re)] \times R^{0.24}; B = 0.5; R = R_2/R_1 \) is the vessel outer-to-inner wall radius ratio.

The average liquid metal coolant flow velocity in the melting unit intercase gap was estimated from the ratio:

\[
w = \frac{G}{(2S \rho)} \tag{8}
\]

where \( G \) is the coolant mass flow rate, kg/s; \( S \) is the intercase gap cross-sectional area, m²; \( \rho \) is the coolant density, kg/m³.

The temperatures of the vessel walls and other components were estimated using the heat transfer equation:

\[
\Delta t_w = q/a, \tag{9}
\]

\[
\Delta t_s = q \cdot \delta_s/\lambda_s, \tag{10}
\]

where \( \Delta t_w \) is the temperature difference between the wall and liquid metal coolant flow; \( \Delta t_s \) is the temperature difference in the layer with a thickness of \( \delta_s \) and heat conductivity of \( \lambda_s \) (Fig. 2).

The temperature of the slag lining inner surface (the burning chamber-side) was calculated by the method of successive approximations under the condition of heat flux equality:

\[q_{\text{heat}} \approx q_{\text{heat}}\]

Results of calculated estimates. The calculated temperatures of the steel vessel surfaces and average heat fluxes per wall under given parameters and different coolant flow rates within the range of 25–50 m³/h, as the most appropriate in terms of technical implementation, are presented in Table 1. Fig. 3 shows the temperature distribution among the melting unit vessel layers at the coolant outlet from the vessel at extreme values of the considered coolant flow range. The calculations were made for the melting unit normal operation mode: in the presence of refractory coating and slag lining on the vessel inner surface.

Based on these estimates, it can be concluded that the lead–bismuth coolant in the presence of refractory coating and slag lining on the inner surface can potentially provide an average coolant-side temperature on the steel surface up to 600°C within the considered coolant flow range.

Moreover, in the presence of refractory coating and slag lining on the vessel inner surface, a decrease in the coolant flow rate in two and a half times (from 50 to 20 m³/h) leads to an increase in the coolant heating up to ∼133°C, whereas the vessel inner wall temperature (i.e. the burning chamber-side slag lining) increases only a little, up to ∼5°C.

At the coolant flow rate of 50 m³/h, the calculated coolant-side temperature of the steel surface does not exceed 450°C. As mentioned above, the lead–bismuth coolant temperatures
applicable to austenite steels do not exceed 650°C, therefore, the question of steel corrosion resistance is not problematic.

Considering the fact that nonuniform temperature distribution can be observed in a real melting unit system, it seems advisable to carry out three-dimensional thermo-hydraulic calculations using the calculated estimates of heat fluxes presented in this paper as benchmark data.

**Conclusion**

1. The lead–bismuth coolant is an efficient flame-/explosion-proof coolant which can remove heat at high temperatures and low pressures.

2. As of today, the lead–bismuth coolant management technique has been mastered. As a result of long-term operation of research non-isothermal circulation loops and submarine reactor facilities, methods were elaborated for steel corrosion protection and cleaning of the coolant from solid-phase slags and equipment was developed for their implementation in circulation loops.

3. For the first time calculated estimates were made as for temperature distributions during the melting unit steel vessel cooling with the lead–bismuth coolant. The calculations were carried out using a one-dimensional heat transfer model.

4. Based on the results of the calculated temperature distribution estimates, it can be concluded that lead–bismuth cooling of the melting unit steel vessel in normal operation (in the presence of refractory coating and slag lining on the vessel inner surface) provides an opportunity to maintain a coolant-side temperature on the steel surface which does not exceed the temperatures applicable for this coolant. Therefore, the question of steel corrosion resistance is not problematic.

5. The data presented in this paper may be useful for carrying out three-dimensional thermo-hydraulic calculations of the melting unit steel vessel which are essential for determining non-uniform temperature distribution across the vessel during lead–bismuth cooling.

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