Basic Principles of Lead and Lead-Bismuth Eutectic Application in Blanket of Fusion Reactors

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Abstract. High magnetohydrodynamic pressure drop is an important issue for liquid metal blanket concepts. To decrease magnetohydrodynamic resistance authors propose to form insulating coatings on internal surface of blanket ducts at any moment of fusion reactor exploitation. It may be achieved easily if lead or lead-bismuth eutectic is used and technology of oxidative potential handling is applied. A number of experiments carried out in NNSTU show the availability of the proposed technology. It bases on formation of the insulating coatings that consist of the oxides of components of the structural materials and of the coolant components. In-situ value of the insulating coatings characteristics $\rho\delta$ is ~ 10^{-5} Ohm•m² for steels and $5{,}0\times10^{-6}$ – $5{,}0\times10^{-5}$ Ohm•m² for vanadium alloys. Thermal cycling is possible during exploitation of a blanket. The experimental research of the insulating coatings properties during thermal cycling have shown that the coatings formed into the lead and lead-bismuth coolants save there insulating properties. Experience of many years is an undoubted advantage of the lead-bismuth coolant and less of the lead coolant in comparison with lithium. Russian Federation possesses of experience of exploitation of the research and industrial facilities, of experience of creation of the pumps, steamgenerators and equipment with heavy liquid metal coolants. The unique experience of designing, assembling and exploitation of the fission reactors with lead-bismuth coolant is also available. The problem of technology of lead and lead-bismuth coolants for power high temperature radioactive facilities has been solved. Accidents, emergency situations such as leakage of steamgenerators or depressurization of gas system in facilities with lead and lead-bismuth coolants have been explored and suppressed.

1. Introduction

One of the main requirements of advanced nuclear-power engineering is inherent safety of power installations. It initiates R&D of heavy liquid metals (lead, lead-bismuth eutectic) application in fission reactors as substitute of sodium. The same requirement makes advisable R&D of the lead and lead-bismuth eutectic application in blanket of fusion reactors as substitute of lithium.

2. Comparison of properties of lithium, lead, lead-bismuth eutectic as coolants of fusion reactor

Thermophysical properties of lithium is undoubtedly better then similar properties of lead and lead-bismuth eutectic, corrosion activity of lithium lower. Wide experience of handling with lithium on the research and industrial facilities has been obtained.

An appreciable disadvantage of lithium as a coolant is its fire risk. Fire safety in circuits and systems with lithium so as with sodium is guaranteed by building up complicated security arrangement. It makes power unit complicated, expensive and uneconomical. Chemical interaction between lead (lead-bismuth) and air at high temperatures leads to gradual oxidation of free surface. Oxidation process is slowed down if oxide film is stable.

Interaction between lithium and water, water-steam mixture, steam requires intermediate loop if Rankine cycle is used. Intermediate loop is also required if Brayton cycle is used because of possible interaction between lithium and carbon dioxide. Lead or lead-bismuth eutectic application allows using of simple and economical two-loop cycle. The safety of power installation as a whole is undoubtedly higher in this case.

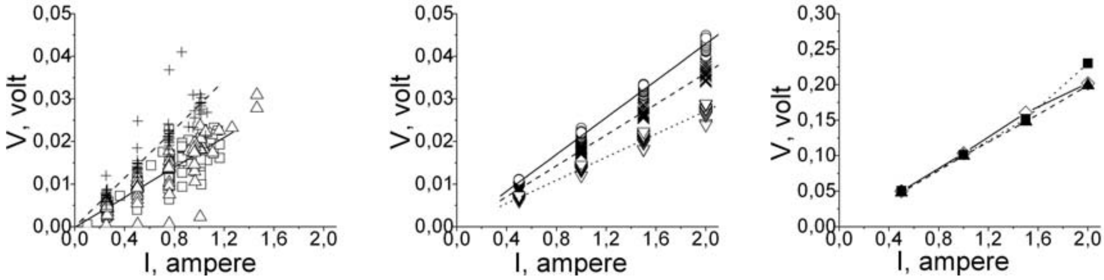
Tritium reproduction provides by nuclear reaction with lithium in modern designs of fusion reactors. But operation, repairing and decommissioning of complicated lithium circuit, which is saturated by tritium, is very difficult and dangerous task. Producing tritium from lithium content ceramics is more safety. That design provides helium as a coolant of container with ceramics. It’s very difficult to maintain necessary temperature conditions by means of gas cooling. Heave liquid metal using provides better conditions of thermostating because of higher thermal lag.

Bismuth (in lead-bismuth eutectic) irradiated by neutrons generates biologically dangerous polonium. But long-term experience of Russian submarines operation developed practical skills of treating with irradiated lead-bismuth coolant in case of different damages.

Lithium so as other alkaline metals is characterized by low corrosion activity related to selected steels up to 600 – 700ºC. In case of lead and lead-bismuth compatibility with steels ensures by protective coatings formed on surface of structural materials during operating up to 620 – 650ºC. Encouraging results of availability are achieved in test with vanadium up to 600ºC. Mentioned above temperatures of steels and heavy liquid metal coolants allows to reach efficiency of power unit up to 40% for Rankine cycle and 44% for Brayton cycle.

3. Insulating coatings on the surface of structural materials

A liquid metal flow in strong magnetic field (5 – 15 tesla) of fusion reactor leads to high magnetohydrodynamic (MHD) resistance. Calculation data shows that pressure drop in such magnetic field will increase up to 20,0 megapascals that is technically senselessly. Authors have offered method of MHD-resistance decreasing in lead and lead-bismuth flow by insulating coatings formation on the inner surface of structural materials [1]. Authors suppose that laying of insulating coating only in initial state (before commissioning, as for lithium provided) is insufficiently effective. Such insulating coating can be destroyed during thermocycling, erosive wear and so on that leads to irreversible increasing of MHD-resistance. Insulating coating should be reproduced at any time of reactor operating that is simply achieved for lead and lead-bismuth by known technology [1]. Numerous experiments [2, 3] have confirmed the efficiency of the insulating coating technology in circuits with heavy liquid metal coolants. Insulating coatings consist of components of structural materials and of coolant components. Insulating coating characteristic $\rho_i\delta_i$ (ρ_i – specific resistance of coatings, δ_i –thickness) is 10^{-5} Ohm·m^2 for steel, $5{,}0\times10^{-6}$ – $5{,}0\times10^{-5}$ Ohm·m^2 for vanadium alloy [2, 3, 4]. Value $\rho_i\delta_i$ depends on oxygen content in coolant and also on other impurities content. It also depends on compound of structural materials, on temperature condition, on streamline condition of surface with the insulating coating. Fig. 1 shows voltage-current characteristic of the insulating coatings formed by different technologies. Fig. 2 shows dependence $\rho_i\delta_i$ of temperature.



a) *b)* *c)*

FIG. 1. Voltage-current characteristic of insulating coatings

a) lead-bismuth coolant in circulating facility;
□ – experiments without purposeful formation of coatings (Fe-18Cr-10Ni);
△ – formation of coatings by oxygen injection in coolant flow (Fe-18Cr-10Ni);
+ – formation of coatings by oxygen feeding into gas volume (V–5Ti–5Cr);

b) lead-bismuth coolant in static facility;
○ – 500ºC, 25C-1Cr, formation of coatings by oxygen feeding into gas volume;
× – 400ºC, 25C-1Cr, formation of coatings by oxygen feeding into gas volume;
▽ – 300ºC, 25C-1Cr, formation of coatings by oxygen feeding into gas volume;

c) lead coolant in static facility;
◇ – Fe-18Cr-10Ni, formation of coatings by oxygen feeding into gas volume;
■ – Be, formation of coatings by oxygen feeding into gas volume;
▲ – 25C-1Cr, formation of coatings by oxygen feeding into gas volume.

Thermocycling of blanket cooling circuits is possible during fusion reactor operating. Thermocycling value is assessed low than 30 – 50ºC per second [3, 5]. Fig. 3 shows that insulating coating characteristic $\rho_i\delta_i$ saves the value [6]. That fact can be explained as possibility of heavy liquid metal coolant to cure by oxidation temporary destroyed part of insulating coating.

Technologies of decreasing of MHD-resistance for ducts with heavy liquid metal coolant are developed in Nizhny Novgorod State Technical University. There are two main methods of oxygen delivery to pipes surfaces: oxygen feeding into gas volume with further diffusion of oxygen into the coolant and injection directly in coolant flow by injector. Fig. 4 shows dependence $\rho_i\delta_i$ of time and oxidation technology.

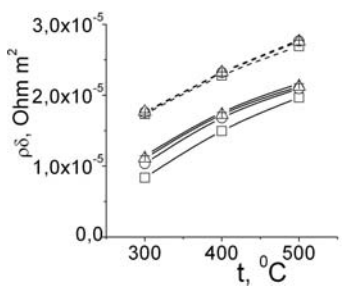


FIG. 2. Dependence $\rho_i\delta_i$ of temperature in lead-bismuth static facility
—— Fe-18Cr-10Ni; - - - 25C-1Cr;
current during measurement of $\rho_i\delta_i$: □ – 0,5amp; ○ – 1amp; △ – 1,5 amp; + – 2 amp.

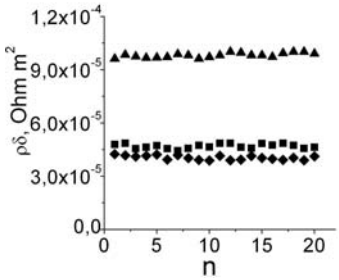


FIG. 3. Dependence $\rho_i\delta_i$ of thermocycle number (n) 20ºC per sec
◆ – Fe-18Cr-10Ni; ■ – Be; ▲ – 25C-1Cr.

4. MHD-resistance of heavy liquid metal coolants in ducts with insulating coating

The effect of conductive liquid flow through the magnetic field has been thoroughly studied. There is experimentally confirmed dependences for round pipe hydraulic resistance in transverse magnetic field. For pipes with nonconductive walls [7]:

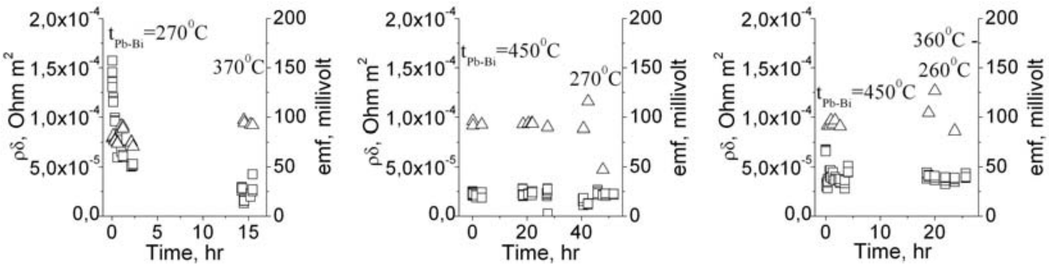
$$\lambda = \frac{3\pi\, Ha}{4\,\mathrm{Re}}\left(1 - \frac{3\pi}{2Ha}\right)^{-1}, \tag{1}$$

λ – coefficient of hydraulic resistance in magnetic field, $Ha = Br\big/\sqrt{\rho\,\mu}$ – Hartmann number, B – induction of magnetic field, r – radius of duct, ρ – specific resistance of coolant, μ – dynamic viscosity, $\mathrm{Re} = \gamma wr/\mu$ – Reynolds number, γ – coolant density, w – coolant mean velocity.

For ducts with conductive walls and contact resistance between liquid metal and structural material [8]:

$$\lambda = \frac{2\,Ha^2}{\mathrm{Re}}\left(1 + \frac{1}{C} + \frac{\rho_i\delta_i}{\rho\, r}\right)^{-1}, \tag{2}$$

$C = \dfrac{\rho\,\delta_w}{\rho_w r}$ – wall conductivity parameter; $\rho_i\delta_i$ – contact resistance parameter; ρ_i – specific resistance of coatings; δ_i – thickness of coatings; δ_w – thickness of the wall; ρ_w – specific resistance of the wall.



a) b) c)

FIG. 4. Changing $\rho_i\delta_i$ during formation
a) Fe-18Cr-10Ni, oxygen feeding into gas volume;
b) Fe-18Cr-10Ni, oxygen injection in coolant flow;
c) V–5Ti–5Cr, oxygen feeding into gas volume.
□ – experimental value $\rho\delta$ (Ohm·m²);
△ – indication of oxygen thermodynamical activity sensor (millivolt) in liquid metal.

Mentioned above ratios (1) and (2) couldn't describe case of lead or lead-bismuth flow though steel or vanadium ducts. Conductivity of wall layer is experimentally defined value. It's expected that pressure drop value of conductive wall is the same order as wall friction value. MHD-resistance can be evaluated by next ratio:

$$\lambda = \lambda_{nc} + \lambda_{cnd} = \frac{3\pi Ha}{4\,\mathrm{Re}}\left(1 - \frac{3\pi}{2Ha}\right)^{-1} + \frac{2Ha^2}{\mathrm{Re}}\left(1 + \frac{1}{C} + \frac{\rho_i \delta_i}{\rho r}\right)^{-1} \quad (3)$$

First component in this ratio reflects Hartman frictional drag for pipes with nonconductive walls. Second component is additional frictional drag caused by electric current closed through the walls. Second component turns into zero if wall conductivity parameter C approaches to zero or $\rho_i\delta_i$ tends to infinity. Ratio (3) is rightly at high Hartman number.

Research on MHD-flow of heavy liquid metal coolants in a transverse magnetic field and methods to decrease MHD-resistance has been carried out at high temperature facilities of the Nizhny Novgorod State Technical University. For each coolant investigations consist of two stages: measurement of MHD-resistance of a test section of duct with as-delivered surface and measurement of MHD-resistance of a test section of duct with insulating coatings formed in the facility. To compare experimental results with a fully insulated duct, experiments with glass pipes were included. Table 1 shows example of used pipes and operating performance of some experiments.

Methods of experiment contained controlled change of oxygen thermodynamic activity in liquid metal, stepwise change of coolant temperature, coolant expenditure and induction of transverse magnetic field. The main measured parameter was pressure drop at the test section. Coefficient of hydrodynamic resistance was defined by next ratio:

$$\lambda = \frac{\Delta p}{\frac{l}{r}\frac{\gamma w^2}{2}}, \quad (4)$$

Δp – pressure drop at the test section, l – length of test section.

Calculation data of MHD-resistance of blanket, measured value $\rho_i\delta_i$ and measured MHD-resistance [9] show the acceptable value of pressure drop. Design of Russian circulation pump overcomes that pressure drop and makes cooling of blanket possible.

TABLE 1: CONDITIONS OF THE EXPERIMENTS

Coolant	**Test section**			***Re***	***Ha***	***t*, °C**
	structural material	**diameter, mm**	**length, mm**			
Pb-Bi	Fe-18Cr-10Ni	10	500	$(50 – 350)\times 10^3$	0 – 160	250 – 450
	V-5Cr-5Ti	14	500	$(90 – 350)\times 10^3$	0 – 220	250 – 450
Pb	Fe-18Cr-10Ni	6	500	$(45 – 200)\times 10^3$	0 – 90	400 – 500
	V-5Cr-5Ti	14	500	$(40 – 120)\times 10^3$	0 – 220	400 – 500

5. Russian experience of handling with system and circuits with heavy liquid metal coolant

Experience of many years is an undoubted advantage of the lead-bismuth coolant and less of the lead coolant in comparison with lithium. Russian Federation possesses of experience of exploitation of the research and industrial facilities, experience of creation of the pumps, steamgenerators and equipment with heavy liquid metal coolants. The unique experience of designing, assembling and exploitation of the fission reactors for submarine with lead-bismuth coolant is available.

Wide experience of design and testing of equipment with lead coolant for fission reactor BREST is also accumulated. There is international experience of R&D for accelerated driven systems with lead-bismuth coolant. The problem of technology of lead and lead-bismuth coolants for power hightemperature radioactive facilities has been solved. Accidents, emergency situations such as leakage of steamgenerators or depressurization of gas system in facilities with lead and lead-bismuth coolants have been explored and suppressed.

6. Conclusions

Requirement of inherent safety for fusion reactor, obtained scientific and technical back-log, experience of designing and exploitation of the fission reactors make promising R&D for lead and lead-bismuth eutectic application in blanket of fusion reactor.

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