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Optimization of insulating coating formation technology on the structural materials for heavy liquid metal coolants

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Abstract

Development of liquid metals as coolants for blankets and diverters of tokamaks can lead us to choose coolant with higher safety standards than lithium. Heavy liquid metal coolants ensure higher safety of energy installations. Heavy liquid metal coolants facilitate formation of oxygen based electroinsulating coatings and maintain their stability. Conclusions of the most effective methods of electroinsulating coating formation are based on results of direct measure of magnetohydrodynamic resistance of different heavy liquid metal coolants. It has been proven experimentally that value of magnetohydrodynamic resistance to heavy liquid metal flow in round steel ducts with electroinsulating coatings in a transverse magnetic field is between the theoretical values for electroconductive walls and fully nonconducting walls. Electroinsulating coatings created in heavy liquid metal coolants are able to decrease the value of magnetohydrodynamic resistance by more than 5–10 times (depending on the coolant).

1. Introduction

The current design of ITER provides a water coolant blanket [1]. Probably a single experimental module with lithium coolant will be constructed. Further development of liquid metal application as the coolant for the blanket and diverter of tokamaks can lead us to choose coolants that provide higher safety standards than lithium. Heavy liquid metal coolants such as lead, gallium, eutectic lead–bismuth and eutectic lead–lithium ensure higher safety because they do not burn in the air and do not react with water and steam like alkaline metals. For cooling diverter channels a possible choice is gallium [2]; lead based coolants are candidates for blankets [3].

The flow of a conductive liquid through a strong magnetic field leads to considerable MHD-resistance. Engineering solutions (arrangement of circulation ducts along the force line of magnetic field, duct form selection) can minimize the resistance, but there are sections of pipes that inevitably cannot be optimized.

Electroinsulating coatings formation on the internal surface of ducts is an effective solution to the high MHD-resistance problem. Heavy liquid metal coolants facilitate formation of oxygen based electroinsulating coatings and help maintain their stability.

The effect of conductive liquid flow through the magnetic field has been thoroughly studied. There are experimentally confirmed dependences for round pipe hydraulic resistance in transverse magnetic field [4]:

$$\frac{\lambda}{\lambda_0} = \frac{3\pi Ha}{64}\left(1 - \frac{3\pi}{2Ha}\right)^{-1}$$

for pipes with nonconductive walls;

$$\frac{\lambda}{\lambda_0} = \frac{\pi Ha}{1+2a}\left(\frac{\pi}{\alpha Ha} - \frac{1}{(\alpha Ha)^2} + \frac{\pi}{8(\alpha Ha)^3} - \frac{\ln\left(4\alpha Ha + \sqrt{16(\alpha Ha)^2 - 1}\right)}{4(\alpha Ha)^3\sqrt{16(\alpha Ha)^2 - 1}}\right)$$

with conductive walls.

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These equations cannot be used for the case of an electroconductivity coating layer between the liquid metal coolant and the wall structural material because of feature of the physicochemical interaction of heavy liquid metal coolants (lead, gallium, lead–bismuth and lead–lithium eutectics) and structural materials (stainless steel, vanadium alloys). It is necessary to investigate the influence of operating characteristics, physicochemical composition and impurity contents for each combination of liquid metal coolant – structural material.

Research on MHD-flow of heavy liquid metal coolants in a transverse magnetic field and methods to decrease MHD-resistance by the formation of oxide electroinsulating coatings on the internal surface of ducts has been carried out by the department of 'Nuclear and Thermal Power Stations' of the Nizhny Novgorod State Technical University for more than 10 years. The experimental results of last years are presented in this paper.

2. Experimental basis and investigation technique

Investigations of MHD-resistance and methods of decreasing the resistance were carried out at the experimental facilities of Nizhny Novgorod State Technical University. For those experiments circulation test benches with gallium and lead coolant were created and a circulation test bench with lead–bismuth coolant was modified. A simplified schematic diagram of test bench is presented in Fig. 1.

For each coolant investigations consists of two stages:

- measurement of MHD-resistance of a test section of duct with as-delivered surface;
- measurement of MHD-resistance of a test section of duct with electroinsulating coatings formed in the test bench.

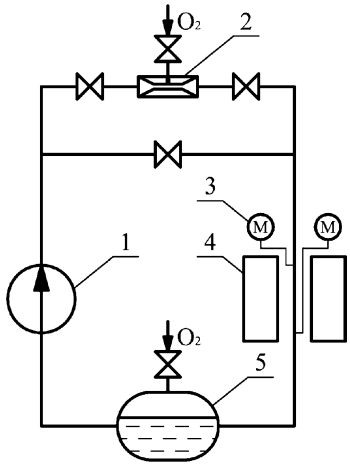

Fig. 1. Schematic diagram of the test bench. 1 – circulation pump (max pump capacity: Ga – 1.5 ton/h; Pb – 7.5 ton/h; Pb–Bi – 100 ton/h); 2 – injector; 3 – manometer; 4 – electromagnet (up to 0.8 T); 5 – expansion vessel.

The insulating oxide coating is formed on the internal surface of the structural pipes during manufacturing and technological treatments. The first stage is dedicated to determination of this coating state. Forming of oxide electroinsulating coatings in test bench conditions was done by two main methods of oxygen delivery to pipes surfaces:

- injection of oxygen gas mixture by injector 2 (Fig. 1);
- feeding of oxygen gas mixture over the free surface of the coolant in the expansion vessel 5 (Fig. 1), with further diffusion of oxygen into the coolant.

Test sections were made of round pipes of austenitic steel and round pipes of vanadium alloy (conditions of experiments are shown in Table 1). To compare experimental results with a fully electroinsulated duct, experiments with glass pipes were included.

During experiments hydrodynamic resistance of test sections that were placed in the air-gap core of an electromagnet 4 (Fig. 1), was measured by manometer 3 and by the level of liquid metal. The coefficient of hydrodynamic resistance λ was calculated by equation [5]:

$$\lambda = \frac{\Delta P}{\frac{l}{d} \cdot \frac{\gamma \cdot w^2}{2}}, \qquad (1)$$

where ΔP – pressure drop at the test section, l – length of test section, d – diameter of test section, γ – coolant density, w – coolant mean velocity.

To represent experimental results in dimensionless form the next equation was used [4]:

$$\lambda = \lambda_0(1 + \psi Ha^2/Re), \qquad (2)$$

$Ha = Bd\sqrt{\frac{1}{\rho\gamma\nu}}$ – Hartmann number, $Re = \frac{wd}{\nu}$ – Reynolds number, B – induction of magnetic field, ρ – specific resistance of coolant, ν – kinematic viscosity, Ha^2/Re – parameter of MHD-interaction (Stewart number), λ_0 – coefficient of hydrodynamic resistance without magnetic field ($Ha = 0$), ψ – numerical coefficient, that depends on rough edges [4]. This coefficient defines the state of the wall layer, and the electroinsulating state of the test section is characterized by that parameter.

3. Experimental results

Experimental results of MHD-resistance in a duct of austenitic steel are shown at Fig. 2. According to Eq. (2)

Table 1
Conditions of the experiments

Coolant	Test section			Re	Ha^2/Re	t, °C
	Material	Diameter, mm	Length, mm			
Pb–Bi	Fe–18Cr–10Ni	10	500	$(50–350)\times10^3$	0–0.10	250–450
	V–5Cr–5Ti	14	500	$(90–350)\times10^3$	0–0.20	250–450
Pb	Fe–18Cr–10Ni	6	500	$(45–200)\times10^3$	0–0.09	400–500
	V–5Cr–5Ti	14	500	$(40–120)\times10^3$	0–0.90	400–500
Ga	Fe–18Cr–10Ni	6	500	$(8–70)\times10^3$	0–1.2	100–300
	V–5Cr–5Ti	14	500	$(8–40)\times10^3$	0–30	100–300

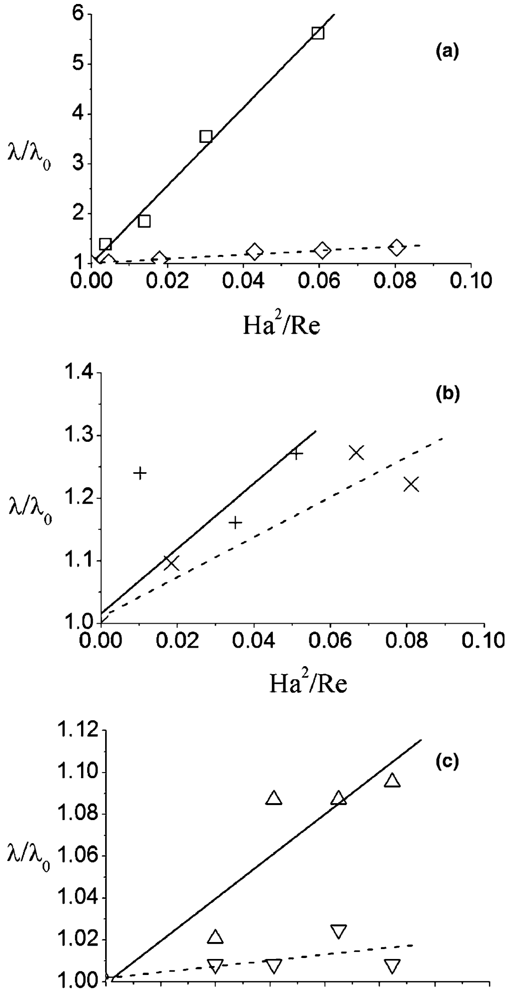

Fig. 2. MHD-resistance of test section of austenitic steel: (a) lead–bismuth coolant; (b) lead coolant; (c) gallium coolant. (—) Test section in as-delivered state; (- - -) test section with formed electroinsulating coatings.

dimensionless dependence $\lambda/\lambda_0 = f(Ha^2/Re)$ is linear. Thus numerical coefficient ψ in Eq. (2) could be represented as tangent of the slope angle of a line that fits the experimental points. It is convenient to define the effectiveness of the electroinsulating coatings by value of the coefficient ψ in different electroinsulating coatings states.

Fig. 2 shows that the best electroinsulating coatings were formed in lead–bismuth coolant (Fig. 2(a)): where the coefficient ψ decreased by a factor of 19 (from 78.2 to 4.1). Feeding of gaseous oxygen over the free surface of coolant was the best method in case of the lead–bismuth coolant.

During experiments with lead coolant (Fig. 2(b)) the coefficient ψ decreased by a factor of 1.6 (from 5.19 to 3.20). Gaseous oxygen was injected in this experiment.

During experiments with gallium coolant (Fig. 2(c)) after forming electroinsulating coatings the coefficient ψ decreased by a factor of 10 (from 0.10 to 0.01). In this case the most effective method of forming electroinsulating coatings was by the method of oxygen introduction from gallium oxide.

The effectiveness of electroinsulating coating formation technology was defined by the specific of each experimental test bench.

Also experiments with test sections of vanadium alloy were carried out. Decreasing of value of coefficient ψ was achieved in experiments with lead coolant, but in experiments with gallium and lead–bismuth coolants decreasing the effect of the influence of magnetic field was not achieved. Results obtained in experiments with test section of vanadium alloy require further experimental verification.

As mentioned above, due to the specific of physicochemical interaction of heavy liquid metal coolants and structural materials, the electroconductivity of the wall could not be described fully for neither the electroinsulated case nor the conductive case. Diagrams of dependencies of hydraulic resistance of Hartmann number that was calculated theoretically and obtained experimentally are shown at the Fig. 3.

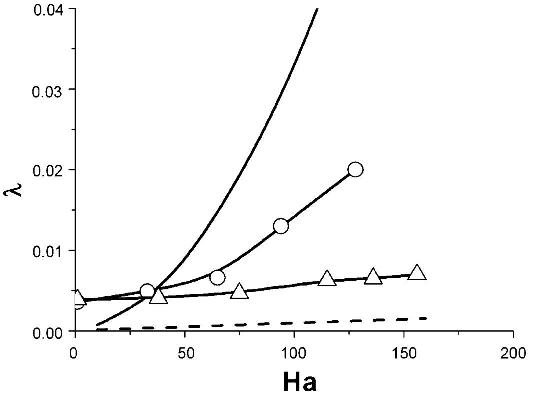

Fig. 3. Theoretical and experimental data of hydraulic resistance in magnetic field: (—) conductive walls (theory); (– – –) electroinsulated walls (theory); (–○–) surface in as-delivered state (exp.); (–△–) formed coatings on surface (exp.).

The fully electroinsulated wall case defines by the next equation [6]:

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

An equation convenient to use for hydraulic resistance calculation of duct of austenitic steel that was used in experiments is [7]:

$$\lambda \approx \frac{3\pi}{4}\frac{Ha^2}{Re}\left(\frac{1}{Ha} + \frac{C}{1+C}\right)\left(1 - \frac{3\pi}{2Ha}\right)^{-1}. \tag{3}$$

$C = \frac{\rho_i\delta_i}{\rho a}$ – relative walls electroconductivity, $\rho_i\delta_i$ – electroinsulating coatings characteristics (ρ_i – specific conductance of coatings, δ_i – thickness); ρ – specific conductance of structural material (08X18H10T); a – thickness of pipe wall.

Shown in Fig. 3 are experimental data taken with lead–bismuth coolant and test section of austenitic steel (like Fig. 2(a)).

It is expected that experimental points should be placed between values that was calculated theoretically. However at low Hartmann numbers experimental curves are above the theoretical curves. Experimental data do not come to zero at $Ha = 0$ because of usual turbulent friction, but at higher Hartmann numbers experimental points do fall between the theoretical curves.

Experiments with direct measurement of electrical resistance of oxide insulating coatings $\rho_i\delta_i$ were completed earlier for static and circulation test benches for a wide temperature range and with different coolants [8–13]. Also value $\rho_i\delta_i$ can be defined from Eq. (3) using results of MHD-resistance experiments. Results of such reverse calculation are shown at Fig. 4. Initial data were taken from experiments with lead–bismuth coolant and test section of austenitic steel (like Fig. 2(a)).

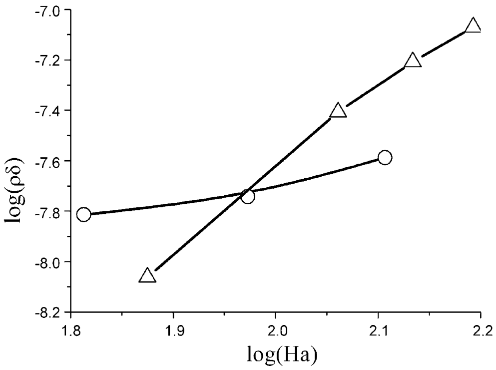

Fig. 4. $\rho_i\delta_i$ value, from MHD-resistance experiments: (–○–) surface in as-delivered state; (–△–) formed coatings on surface.

It is evident from Fig. 4 that $\rho_i\delta_i$ increases with Ha increasing and its value is substantively lower than one defined in experiments with direct measurement of electrical resistivity ($\rho_i\delta_i \sim 10^{-5}\ \Omega\,\mathrm{m}^2$). It means that experimental data refer to a transition range from the usual hydraulic friction to MHD-resistance, because Eq. (3) is not correct at low Hartmann number. It may be estimated that in experiments with higher Hartmann numbers $\rho_i\delta_i$ will increase and stabilize at asymptotic level where hydraulic friction becomes negligible in comparison with MHD-resistance and Eq. (3) becomes practically correct.

4. Conclusions

Experiments have shown that formation of oxide insulating coatings that effectively decrease MHD-resistance on austenitic steel is possible. The possibility of oxide insulating coating formation on ducts of vanadium alloy requires further experimental verification and adjustment of insulating coating formation technology for those alloys.

The decrease in MHD-resistance achieved in experiments with heavy liquid metal coolants is substantial but is not complete. Theoretical calculations show the possibility of major MHD-resistance decreases that requires further precise evaluation both of experimental and calculation methods.

Investigations of liquid heavy metal coolant flow in magnetic field are expanding in the direction of carrying out heat transfer in magnetic field. Heat transfer and MHD-resistance in such liquid metal coolants like lead, gallium, lead–bismuth and lead–lithium eutectics are defined by the wall layer state, including all components of that state. So MHD-resistance is defined both by the state of proper electroinsulating coatings on the surface of structural material and the state of the wall layer of liquid metal that is saturated in all kinds of impurities. Continuing investigations will evaluate the role of each of these factors in decreasing MHD-resistance.

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