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Liquid metal pipe flow hydraulic resistance in a transverse magnetic field

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The results of an experimental study of the effect of a transverse magnetic field on the hydraulic resistance during the flow of mercury in a round pipe with different wall conductivity are considered. The changes in the coefficients of hydraulic resistance at Reynolds numbers in the range $\mathrm{Re} = (10-40) \cdot 10^3$ and magnetic fields providing Hartmann numbers in the range $\mathrm{Ha} = 0-1800$ are investigated. Pipes with different steel wall thicknesses are considered, and the effect of copper plating aimed at improving the electrical contact at the mercury−steel interface is studied.

Keywords: magnetic hydrodynamics, hydraulic resistance, liquid metal, wall conductivity, contact electrical resistance.

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The use of liquid metals for cooling of highly loaded reactor components and producing nuclear fuel is integral to the construction of pure fusion reactors (thermonuclear reactors) and hybrid (fusion−fission) systems [1], but is also associated with various challenges and phenomena that have not yet been studied in sufficient detail [2]. One such effect is an increase in hydraulic resistance of channels during the flow of a conducting medium in strong magnetic fields. Data on the hydraulic resistance during the flow of liquid metal in a transverse magnetic field in channels with different wall conductivities were presented in several studies [3–6].

The results of studies of liquid-metal heat exchange complicated by the influence of a magnetic field indicate that both the hydraulic resistance and the heat exchange (including the emergence of magnetic-convective pulsations) are sensitive to the electrical wall conductivity [2]. The key data were obtained under laboratory conditions with a relatively weak or near-zero wall conductivity [3]. The issue of variation of the electrical wall conductivity throughout the entire experiment was not discussed in detail.

In the present study, the hydraulic resistance in pipes with different wall conductivities is investigated with a detailed examination of the influence of the electrical wall conductivity, the veracity of earlier results reported by other research groups is verified, a method for measuring the hydraulic resistance in liquid metals is tested, and a set of reliable experimental data is produced.

An actual contact between mercury and stainless steel features both thermal [7] and electrical [8] contact resistance. Studies have demonstrated that the characteristics of contact between mercury and stainless steel are governed by layers foreign to liquid metal [8,9]. These layers form in the contact zone due to the chemical interaction of the liquid metal medium with structural materials and due to electrolytic processes in the course of current flow. In view of this, the flow of electric current through the contact zone proceeds through multiple sites of breakdown of the boundary contact layers. Mechanical treatment of the wetted wall (brushing) and the application of intermediate layers with better wettability by liquid metal provide an opportunity to reduce the electrical contact resistance.

A system for pressure drop measurement was used in the studies (Fig. 1). The system features two large-diameter flasks filled with water. Hoses from pressure taps at the working section are connected to these flasks. Measuring hoses (combined with a measuring tape) are brought out from the mating parts of the flasks. Owing to the difference in internal diameters of the flasks ($d_1 = 72$ mm) and the hoses ($d_2 = 6$ mm), an indistinguishable difference in mercury levels translates into a significant difference in water levels, which is sufficient for accurate measurements even at low flow rates. The pressure drop was calculated using the following relation:

$$dP = \rho_W g H \left(\frac{\rho_{\mathrm{Hg}}}{\rho_W} \frac{d_2^2}{d_1^2} + 1 \right), \qquad (1)$$

where ρ_W, ρ_{Hg} are the densities of water and mercury [kg/m^3]; g is the gravitational acceleration [m/s^2]; H is the difference in water levels [m]; and d_1, d_2 are the diameters of the flasks and the hoses, respectively [m].

The hydraulic resistance coefficient was then calculated as

$$\xi = \frac{2DdP}{\rho_{\mathrm{Hg}} U^2 L}, \qquad (2)$$

where D is the internal pipe diameter [m], U is the average flow velocity of liquid metal [m/s], and L is the distance between pressure taps [m].

Four working sections in the form of round pipes with an internal diameter of 40 mm (two with a wall thickness

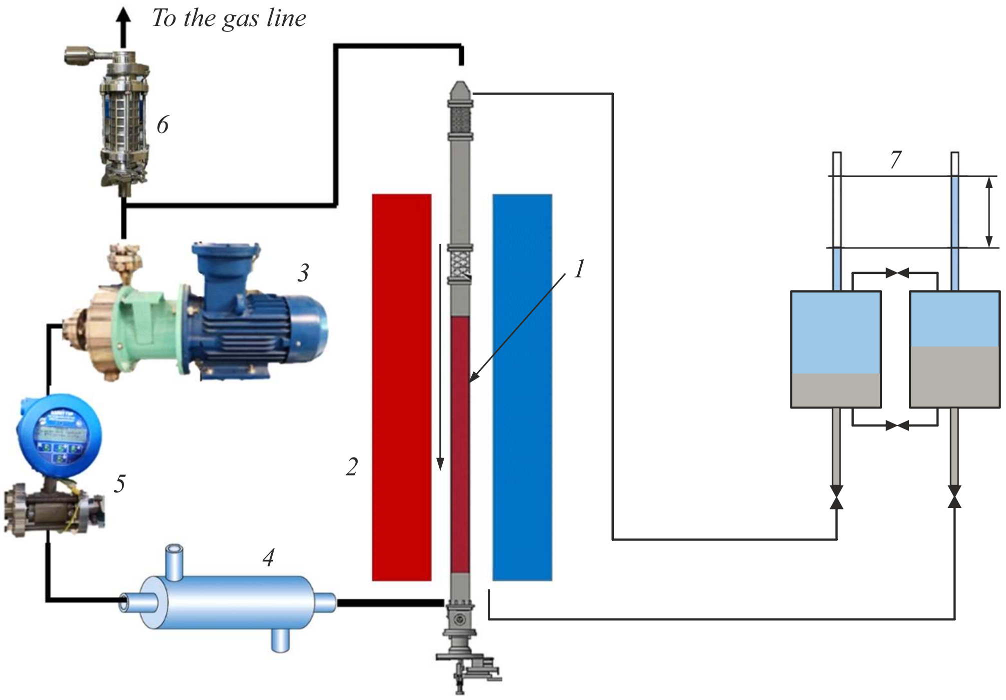

Figure 1. Diagram of the experimental setup. *1* — Experimental working section, *2* — electromagnet, *3* — pump, *4* — heat exchanger, *5* — electromagnetic flow meter, *6* — air-type pulsation damper, and *7* — differential pressure meter.

of 2.5 mm and another two with a wall thickness of 10 mm) were fabricated in order to examine the influence of electrical conductivity of the channel walls on hydraulic resistance. The length of each section was 750 mm. Copper plating of the internal surfaces of a pair of pipes (one thin-walled and one thick-walled) was performed to enhance the mercury–steel contact. The thickness of the applied copper coating was $\sim 100\,\mu$m. Grade R-1 mercury was used in experiments.

A magnetic field affects the flow of liquid metal, suppressing turbulence and making the flow laminar. The obtained experimental data and the asymptotics used correspond to a laminar flow in a strong transverse magnetic field [4]. It is known that the hydraulic resistance coefficient of a conducting channel depends not on two independent parameters (Reynolds and Hartmann numbers), but on their combination (Stuart number) [4].

The measurement results are presented in the form of dependences of the hydraulic resistance coefficient on dimensionless parameter $\mathrm{N} = \mathrm{Ha}^2/\mathrm{Re}$ (Stuart number), where the Reynolds (Re) and Hartmann (Ha) numbers are defined as

$$\mathrm{Re} = \frac{UD}{\nu}, \qquad \mathrm{Ha} = BD\sqrt{\frac{\sigma}{\eta}}, \tag{3}$$

where ν is the kinematic viscosity of mercury [m^2/s], B is the magnetic field induction [T], σ is the electrical conductivity of mercury [Ω^{-1}], and η is the dynamic viscosity of mercury [$\mathrm{Pa}\cdot\mathrm{s}$].

Thin-walled sections (40×2.5 mm) with and without copper plating were examined first (Fig. 2, *a*). The experimental points for the copper-plated pipe are positioned above the values for the non-copper-plated pipe, suggesting that the mercury–steel contact is enhanced. The calculated dependences of the hydraulic resistance coefficient for channels with perfectly conducting and completely insulated walls are also shown for comparison [3]. The experimental points are located between these curves and are characterized well by the dependence for walls with a finite conductivity [4]. The properties of stainless steel 12Kh18N10T and mercury were taken from [10] and handbook [11], respectively. The theoretical dependence for a thin-walled non-copper-plated pipe with relative conductivity $C_w = 0.044$ provides a fine fit to the experimental data for the copper-plated pipe only. The results without copper plating follow the dependence with a conductivity reduced by a factor of 2.6 ($C_w = 0.017$). This is indicative of poor electrical contact between mercury and steel due to insufficient wetting of the channel walls by mercury.

At the second stage, measurements for a pair of thick-walled pipes (40×10 mm) with and without copper plating were carried out (Fig. 2, *b*). The values of hydraulic resistance in thick-walled pipes are higher than those for thin-walled pipes. Copper plating has a pronounced positive effect on the contact of liquid with the wall. The theoretical dependence with calculated value $C_w = 0.176$ is close to the obtained results in the case of a copper-plated pipe. Without copper plating, the dependence becomes close to the experimental points only when the relative wall conductivity decreases by a factor of 6.5 (C_w drops to 0.027), which is indicative of poor contact of liquid with the pipe wall.

The loss of wettability of the copper-plated wall over time was also examined in the present study (Fig. 3). With this aim in view, mercury was kept in the copper-plated pipe for a long time, and hydraulic resistance measurements were performed periodically within this interval. Their results revealed that the deviation of subsequent measurements from the first one reaches a constant level of $\sim$ 15%.

Thus, experimental hydraulic resistance measurements were carried out during the flow of liquid metal in a transverse magnetic field in round pipes with different thicknesses of walls with and without copper plating of the internal surface. Experiments revealed the influence of wall thickness and copper plating of the internal surface on the liquid–wall contact and the hydraulic resistance. Semi-empirical dependences characterize well the results obtained for copper-plated pipes. In the case of non-copper-plated walls, the results are underestimated by a factor of 3–7, and an experimentally determined correction to the relative conductivity coefficient is needed in order to obtain a correct description of conductivity. The obtained data provide an opportunity to make an allowance for the effect of poor wall wettability on the hydraulic resistance of liquid metal in a magnetic field both in completed experimental studies and in those that are at the planning stage.

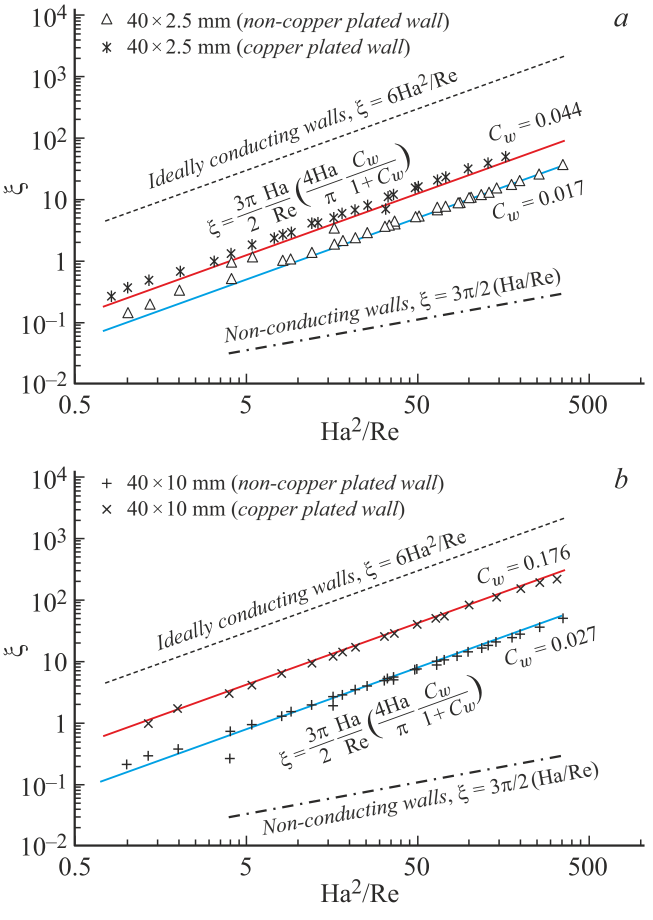

Figure 2. Hydraulic resistance during the flow of liquid metal in a transverse magnetic field. *a* — Thin-walled round pipe (40 × 2.5 mm); *b* — thick-walled round pipe (40 × 10 mm). $\mathrm{Re} = (10{-}40)\cdot 10^3$, $\mathrm{Ha} = 0{-}1800$.

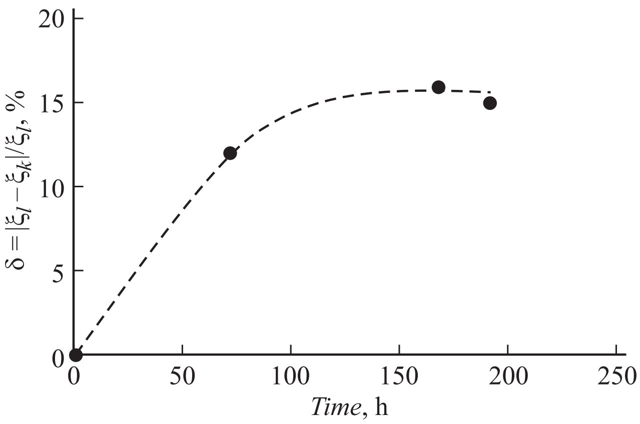

Figure 3. Deviation of the hydraulic resistance coefficient from the initial measured value as a function of duration of the experiment with liquid metal in the circuit.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] S. Smolentsev, Fusion Sci. Technol., **79** (3), 251 (2023). DOI: 10.1080/15361055.2022.2116905

[2] O. Zikanov, I. Belyaev, Y. Listratov, P. Frick, N. Razuvanov, V. Sviridov, Appl. Mech. Rev., **73** (1), 010801 (2021). DOI: 10.1115/1.4049833

[3] S. Smolentsev, Fluids, **6** (3), 110 (2021). DOI: 10.3390/fluids6030110

[4] L.G. Genin, V.G. Sviridov, *Gidrodinamika i teploobmen MGD-techenii v kanalakh* (MEI, M., 2001) (in Russian).

[5] J.A. Shercliff, J. Fluid Mech., **1** (6), 644 (1956). DOI: 10.1017/S0022112056000421

[6] V.A. Glukhikh, A.V. Tananaev, I.R. Kirillov. *Magnitnaya gidrodinamika v yadernoi energetike* (Energoatomizdat, M., 1987) (in Russian).

[7] T. Mizushina, S. Iuchi, T. Sasano, H. Tamura, Int. J. Heat Mass Transfer, **1** (2-3), 139 (1960). DOI: 10.1016/0017-9310(60)90017-X

[8] L.A. Sukhanov, *Elektricheskie unipolyarnye mashiny* (VNIIEM, M., 1964) (in Russian).
[9] P. Klaudy, Elektrotechnik und Maschinenbau, **78** (3), 128 (1961).
[10] E.A. Protasov, V.N. Petrovskii, V.D. Mironov, Tech. Phys., **64** (2), 171 (2019). DOI: 10.1134/S1063784219020166.
[11] P.L. Kirillov, M.I. Terent'eva, N.B. Deniskina, *Teplofizicheskie svoistva materialov yadernoi tekhniki* (IzdAT, M., 2007) (in Russian).

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