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INFLUENCE OF SURFACE ROUGHNESS OF CHANNEL ON FRICTION COEFFICIENT OF ELECTRICALLY CONDUCTING FLUIDS

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ABSTRACT

In this article we elucidate method for estimating the effect of surface roughness for a case in which conductive liquid flows in the channel. In case of using conductive and electrically insulating silicon-organic coatings with the purpose of tracking their effect on the coefficient of friction and pressure loss in the channel with availability of a transverse magnetic field are considered. For general case of fluid flow in the channel are used equations which show determination of the pressure drop and the coefficient of resistance. In case of a stabilized flow task can be solved by solving a simplified equation of motion.

INTRODUCTION

It is fact (McKeon, B.J. et al., 2004, 2005) [1,2], (McGovern, J., 2011) [3], for pipe flow, as long as entrance effects, roughness, and temperature variations are small, dimensional analysis indicates that the friction factor λ is only a function of the Reynolds number Re.

When the values of the aforesaid factors that have an effect on friction factor increase, they should not be neglected. It is true for both common and current conductive liquids. The use of a magnetic field that may have an effect on the characteristics of the electrically conducting liquid flow is a special case. Issues of magnetic field generation in electrically conducting fluids are considered in (Moffatt, H.K., 1978) [4]. Issues of the channel surface roughness effect on the friction factor of electrically conducting fluids need detailed analysis.

EXPOSITION

Works [5], [6] are dedicated to the study of viscous and extra-viscous fluid flows in a transverse magnetic field. The experiments demonstrated that the magnetic field appreciably affects the hydraulic friction factor in channels with a certain grade of finish. Experiments on mercury flow in a magnetic field performed by Dukure R.K. evidence that, in general case, the hydraulic friction factor is determined as

$$\lambda = \frac{2r\Delta p_i}{\rho \upsilon^2 L} \quad (1)$$

here Δp_i is a pressure drop over the segment;

r is a hydraulic radius which equals the ratio of the sectional area and the wetted perimeter for the smooth conduit of the same cross-section;

ρ is a density of the fluid;

υ is a speed of the fluid flow.

This quantity is a function of both Reynolds criterion and Hartmann criterion; moreover, it also characterizes the effect of the magnetic field on forces of friction. The experiments [6] demonstrate that in the presence of the magnetic field λ may be represented as

$$\lambda_{магн} = \lambda_0 (1 + const \frac{Ha}{Re}) \quad (2)$$

here λ_0 is a hydraulic resistance in the absence of the magnetic field.

Given the fixed Reynolds numbers, the effect of the Hartmann criterion may be explained by increase in pressure drop due to the effect of the transverse magnetic field. Our experimental study of the flow of electrically conducting fluids in a transverse magnetic field demonstrated a significant “deceleration” of the flow due to the magnetic field effect. However, the above formulae do not give a comprehensive idea of wall effects associated with the surface roughness in the field of mass forces. Viscous-plastic electrically conducting fluids were used that are subject to Shvedov-Bingham rheological law. Channels with various values of surface roughness were analyzed. In order to elucidate the effect of the magnetic field on the hydraulic resistance, various surface coatings were used that possess either dialectic or electric conductivity properties. Silicon-organic coatings were utilized. It is known [7] that silicon-organic coatings on the

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basis of mica-muscovite, chrysotile asbestos, Al_2O_3, Fe, Zn, SiC possess a series of peculiarities. The presence of the aforesaid elements in the surface layer improves the adhesive properties in the zone of contact with a fluid and assures the increased corrosion resistance. Moreover, depending on proportion of the components, these coatings demonstrate different values of their electric conductivity and magnetic permeability.

A distinctive feature of silicon-organic coatings is their capacity to demonstrate either insulating or electric conducting properties. The effect of the coating composition on insulating properties is revealed in [7]. Application of such coatings in channels exposed to the permanent magnetic field actually affects the hydrodynamic parameters of the flow, hence, permits to calculate the hydraulic resistance with account of roughness (or degree of the applied coating adhesion).

Adhesive properties of the coating have a significant effect on a friction factor. They may be determined in accordance with recommendations given in [7] and depend on a number of factors.

When solving problems on viscous fluid flowing in a magnetic field, the condition at the liquid and solid body interface plays a key role.

In the simplest case (for the Hartmann flow) the condition of liquid adherence to the solid surface is accepted, and the flow velocity is determined on the basis of the equation [5]

$$\frac{\partial \rho}{\partial x} = \eta \frac{\partial^2 u}{\partial y^2} + j_z B_y \tag{3}$$

In this case the velocity profile is described as

$$u(x,y) = -\frac{\partial \rho}{\partial x} \cdot \frac{Ha}{\sigma B_y^2} \cdot \frac{ch(Ha) - ch(Ha\frac{y}{a})}{sh(Ha)} \tag{4}$$

and the friction factor equals

$$\lambda = \frac{2}{Re} \cdot \frac{Ha^2 \cdot th(Ha)}{Ha - th(Ha)} \tag{5}$$

The comparison of this formula with the experimental formula (2) permits to evaluate the error of calculations caused by walls effect on the flow.

It should be noted that for a non-Newtonian fluid (for example, Bingham plastic), the solution of the similar problem of Hartmann flow permits to determine velocity profile for the given conditions as follows:

$$u = A\left[1 - \frac{ch\left(Ha\left(\frac{y - y_0}{a}\right)\right)}{ch\left(Ha\left(1 - \frac{y_0}{a}\right)\right)}\right] \text{ при } y_0 \le y \le a \tag{6}$$

$$u = A\left[1 - \frac{1}{ch\left(Ha\left(1 - \frac{y_0}{a}\right)\right)}\right] \text{ при } a \le y \le y_0 \tag{7}$$

here

$$A = -\frac{\partial \rho}{\partial x} \cdot \frac{1}{\sigma B_y^2} + E_z j B_y . \tag{8)}$$

After all, the pressure drop over the length for the channels with silicon-organic coating may be determined on the basis of the obtained experimental diagrams (Fig. 1).

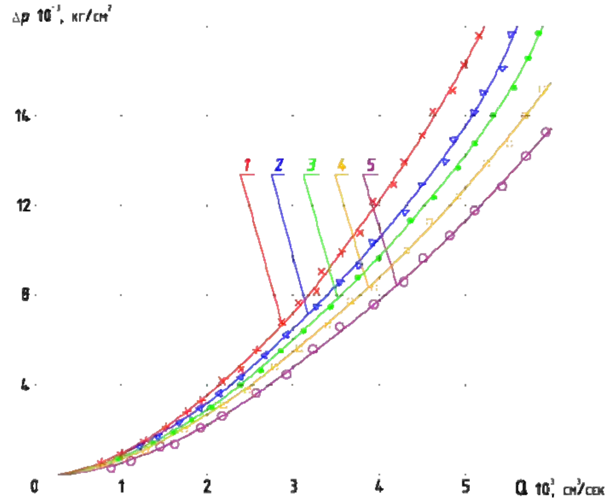

Fig. 1. $\Delta p = f(Q)$ diagrams: 1 – channel without coating; 2 – channel with KNN – 130; 3 – channel with KNN – 128; 4 – channel with KNN – 121; 5 –channel with KNN – 126
Vertical axis: kg/cm2 Horizontal axis: cm3/s

A disadvantage of diagrams (Fig. 1) consists in ignoring peculiarities of interaction of the fluid with the solid surface, i.e., the wall effects are not taken into account in these Hartmann flows.

It is shown [5] that current and eddy layers may exist on the surface of interaction of the electrically conducting fluid and solid surface, and their intensities correlate. Moreover, tangential viscous shears exist in the limit of vanishing viscosity, that balance magnetic force acting on the current sheet. Unfortunately, a clear idea about this process is possible on the basis of experimental studies, especially in the case when the surface also possesses specific rheological and electro-conducting properties. In this context, the necessity to determine the velocity diagram and tangential viscous shears for profiled silicon-organic surfaces arises at the first stage of studies.

As is shown in studies presented in [5], the important part in description of magnetic field effect on a fluid flow belongs to conditions existing in the zone of contact of electrically conducting fluid and solid surface of the channel. The presence of silicon-organic coatings that possess either electric conducting or dielectric properties on such surface may exert significant influence on hydraulic resistance in a near-wall region. Presumably, it is the liquid and solid surface interface that may serve as a "screen" from the solid surface. However, in case of silicon-organic coatings the said statements need serious proofs. Nevertheless, the said coatings do not possess perfect electric conductivity which is proved by their composition (Table 1).

Table 1. Electric resistance of KNN coatings after their thermal processing, MOhm

Coating thickness, mm	Substrate material	Temperature, °C							
		150	200	250	300	350	400	450	500
KNN-13									
0.02	Alloy D16	500	400	400	180	140	100	50	20
KNN-15									
0.04	Stainless steel	1000	500	500	100	60	30	20	0
	Nickel	2000	1000	200	150	100	50	30	10
KNN-21									
0.002	Alloy D16	1	0	0	0	0	0	0	0
0.002	Stainless steel	0	0	0	0	0	0	0	0
0.11	Nickel	-	400	400	1000	500	500	500	40
KNN-46									
0.1	Alloy D16	200	160	400	200	100	6	5	1

Application of the said coatings may cause formation of different roughness of the surface. The grade of finish was determines by using the profilograph – profilometer, model 201. The System of Profile Transformation СПП–1 [8] was used in order to quickly calculate the surface roughness parameters. As a result of roughness measurements for various types of silicon - organic coatings the profilograms were obtained (Fig. 2).

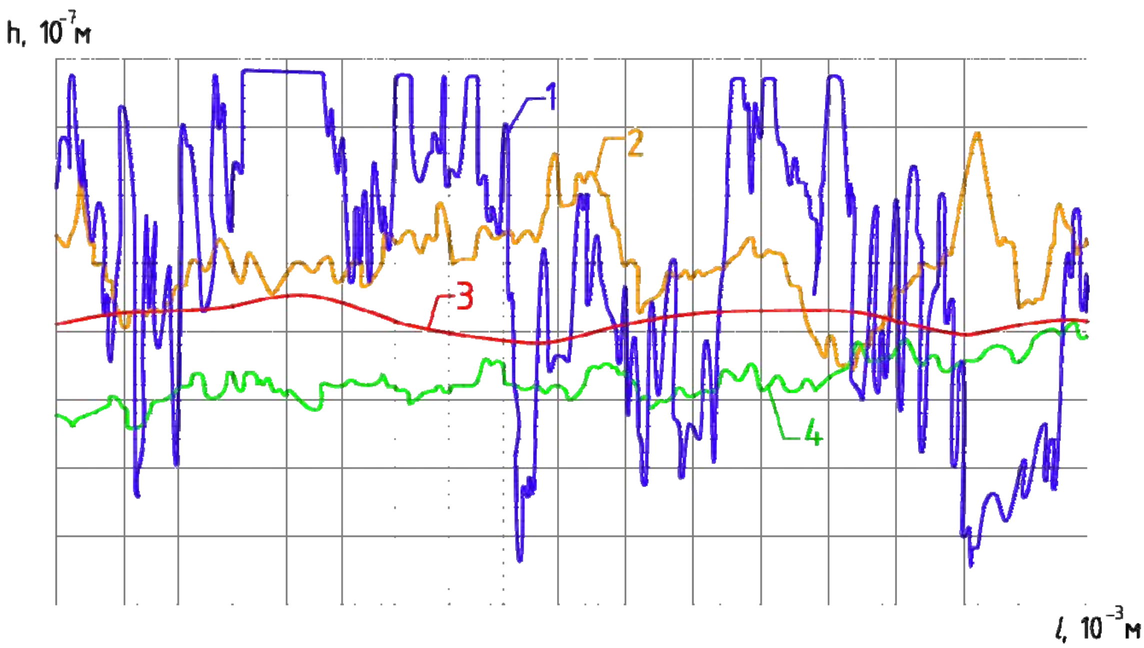

Fig. 2. Profilograms of : 1 – the internal surface of a new steel tube; 2 – the surface of organic glass with silicon-organic coating No. 121; 3 – the surface of sheet organic glass; 4 – the surface of organic glass with silicon-organic coating No. 126

If a function that characterizes the profile of a rough surface, F(x), is known, then the equation that describes the similar flow of the viscous-plastic fluid may be written as

$$(u\nabla)u = F(x) - \frac{1}{\rho}grad(p) + \frac{1}{\rho}\left(\mu_b + \frac{\tau_0}{H_m}\right)\left(\nabla^2 u + \frac{1}{\zeta}\nabla v\right) - \frac{2\tau_0 l}{\rho H_m^2}grad(H_m) - \frac{2\tau_0}{3\rho H_m^2}grad(u) + \frac{\sigma E^*(x)B(x)}{c} + \frac{\sigma B^2(x)}{c}u(x,y) \quad (9)$$

here u is a velocity vector, H_m is a square invariant of the strain rate tensor; $F(x)$ is an acceleration function that accounts for surface roughness; p, ρ are pressure and density, respectively; μ_b is Bingham viscosity; τ_0 is a yield point.

These equations are much simpler for a Newtonian fluid and stabilized flow. When using the dimension theory for Hartmann flow of viscose-plastic fluids one can establish that the pressure drop and, consequently, the hydraulic friction factor are functions of Reynolds (Re), Hartmann (Ha), Hedstrom (He) criteria:

$$\lambda = f(Re, Ha, He) \quad (10)$$

here $Ha = BL\sqrt{\frac{\zeta}{\eta}}$, $He = \frac{\rho \tau_{cm} D^2}{\mu_b^2}$

Hence, in case of a stabilized flow the problem of pressure drop, as well as resistance factor determination reduces to the solution of the simplified equation of motion (3). The friction factor may be represented as a sum of two summands, as it is shown in [6], one of them characterizes the absence of the magnetic field effect, and the other one – its presence. In the absence of the magnetic field the components of the velocity vector near the surface with profile coating may be represented as and the tangential viscous shear shall be written as

$$\begin{aligned} u_x &= \frac{1}{\mu}\left[\frac{u_0}{u_{cp}} \cdot \frac{\partial^3 f(x)}{\partial x^3} + \frac{\partial p}{\partial x}\alpha\right] \cdot \\ &\cdot \{[0{,}27y^3 f^{-1}(x) - 0{,}5y^2 + 0{,}2yf(x)] + \nu Re[-0{,}2y^2 f^{-4}(x) + 0{,}6yf^2(x)]\} \\ u_y &= \frac{1}{\mu}\left[\frac{\partial^4 f(x)}{\partial x^4}\right] \cdot [-0{,}07y^4 f^{-1}(x) - 0{,}17y^3 - 0{,}1y^2 f(x)] + \\ &+ \frac{1}{\mu}\left[\frac{u_0}{u_{cp}} \cdot \frac{\partial^3 f(x)}{\partial x^3} + \frac{\partial p}{\partial x}\alpha\right] \cdot [-0{,}07y^4 f^{-2}(x) - 0{,}1y^2]\delta_1 + \\ &+ \nu Re[-0{,}2y^4 \delta_1^{-5} + 0{,}6y^2 \delta_1^{-3}]\delta_0 + u_x \frac{\partial f(x)}{\partial x}, \end{aligned} \tag{11}$$

$$\tau_{xy} = \tau_{cm} - \left(\rho g + \frac{\partial p}{\partial x}\right)\left[\left(\frac{3\mu^2\, Re}{4\rho^3\left[\frac{u_0}{\rho} a \frac{\partial^3 f(x)}{\partial x^3} + g\right]}\right) - ya\right] \tag{12}$$

CONCLUSION

Therefore, being guided by formulae (11) and (12), and basing on the results of the experiment we can evaluate the effect of rheological properties of Bingham plastic and the grade of finish of the surface with silicon-organic coating on the friction factor and pressure losses.

As a final comment it should be noted that the absence of electric conductivity in certain silicon-organic coatings may be used with the aim to solve the problem of the magnetic field strength change. An example of an applied problem where the results of the study may be used, is a problem of fluid flow blockage due to magnetic field change in case of a sharp increase of electric current in electrically conducting fluid flow. This opportunity is practical in case of fluid fire extinguishment of installations that possibly carry voltage.

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