EXPERIMENTAL STUDY OF FLOW AND HEAT EXCHANGE IN HIGHLY POROUS STRUCTURES

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Permeable porous metals are widely used in various fields of modern technology as construction materials for cooling channels in thermally loaded elements. Design for reliable operation of such constructions is impossible without data on the thermophysical characteristics of the porous material. The literature offers a large number of studies dedicated to investigations of such characteristics, but the overwhelming majority have been performed on porous metals prepared by sintering in the porosity range $\varepsilon = 0.3$–0.5. At the present time the technology has been developed [1, 2] for production of porous metals using a porous structure-forming matrix washed by a suspension of metallic powder with subsequent drying, heating in a reducing medium to eliminate nonmetallic components, and final sintering. The spatial structure of such a material consists of a three-dimensional cellular grid with pore dimensions from tens of microns to tens of millimeters, with open porosity up to 99%. Such materials have high homogeneity of characteristics over their volume.

The results presented in the present study were obtained on highly porous ($\varepsilon = 0.87$–0.97) materials with pore dimensions $d_p = 0.62$–2.17 mm, prepared from N36 invar, copper, and molybdenum.

The quantities α and β were determined by passing air through the specimens. Experiments were performed on cylindrical specimens 15 and 40 mm in diameter, with lengths from 9.5 to 18 mm, at pressure drops across the specimens of from 2 to $0.95 \cdot 10^5$ Pa, with flow rates of 0.05–14 g/sec. The experiments were arranged to eliminate air passage through the outside of the cylindrical surface and insure motion along the specimen axis. The data obtained were represented in the form of functions $A = A(j)$, where $A = (P^2_{out})/2R\bar{T}j\ell$ (Fig. 1).

It is evident from the figure that the function $A = A(j)$ has three characteristic segments: linear horizontal I, curvolinear II, and linear inclined III [3]. Segment I corresponds to laminar flow in the pores "linear filtration", while III is a turbulent flow regime. The transition from laminar to turbulent flow occurs smoothly without the clearly expressed boundaries characteristic of liquid flow in channels of proper form [4].

On the basis of the above, the viscosity coefficient α, characterizing the laminar flow regime, was determined from the expression $\alpha = A_0/\mu$, where A_0 is the segment on the A axis spanned by the horizontal portion of the curve $A = A(j)$ (segment I). The inertial coefficient β, characterizing the turbulent flow regime, was determined from the tangent of the curve $A = A(j)$ in segment III. Results for α and β are presented in Table 1.

Analysis reveals that the principle of decrease in α and β with increase in porosity noted in many studies is maintained at high porosity values. However, in the latter case the effect of mean pore diameter on α and β also manifests itself, especially in the case of the viscosity coefficient, in contrast to data obtained for mean porosity where this effect is often neglected [4]. As a result, the generalized expressions for the viscous and inertial coefficients in highly porous structures obtained by use of multiple correlation analysis have the following form:

$$\alpha = 6{,}61 \cdot 10^7 \bar{d}_p^{-1{,}98} \varepsilon^{-4{,}75}, \quad (1)$$

$$\beta = 5{,}16 \cdot 10^2 \bar{d}_p^{-1{,}07} \varepsilon^{-11{,}16}, \quad (2)$$

where $\bar{d}_p$ is the relative pore diameter, normalized to $d_0 = 1$ mm. The mean pore diameter for such structures was determined by multiple microscopic studies.

The mean square error in calculations by Eqs. (1), (2) as compared to experimental results does not exceed 15% at a confidence level of 95%.

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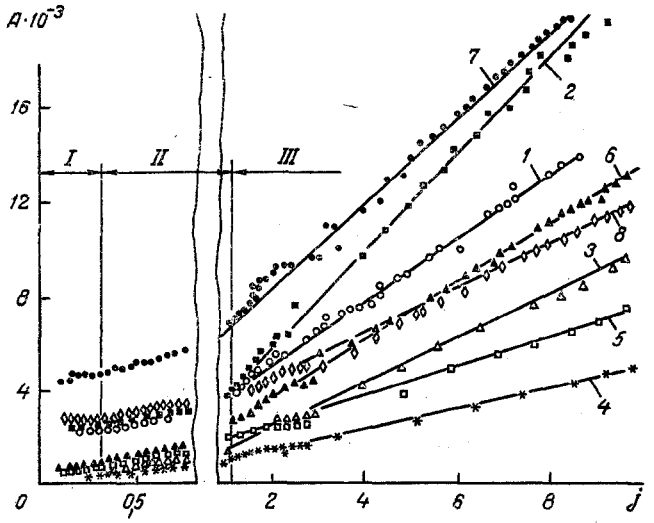

Fig. 1. Experimental data obtained for draft through porous specimens. Notation explained in Table 1.

Internal heat transfer in the highly porous structures was studied by using volume heating, for which purpose cylindrical specimens of the sizes described above with impermeable outer walls were clamped on their end faces between permeable current leads. The electrical system used for heating the specimens allowed varying the current passing through the specimens from 0 to 700 A. A coolant, well purified water, was pumped through the current leads and specimens. The supply system provided coolant at the required temperature and pressure. Flow rate was varied from 2 to 31 g/sec, as monitored by a floating rotameter. During the experiments coolant temperature was measured at the input and output of the specimen, as was the specimen temperature at its ends, using Chromel–Copel thermocouples. The thermocouples measuring specimen temperature were spot welded to the metal body, while those for the coolant were located in adjacent pores not touching the body. To determine the effect of the temperature of the surrounding liquid on the indication of the thermocouple attached to the body test experiments were performed in which the mounted thermocouple was coated by a layer of thermal insulation (epoxy resin). Temperatures indicated by coated and uncoated thermocouples proved practically identical, so that in the future the thermocouples without coatings were used. The effect of electrical voltage on thermocouple indication was analyzed experimentally. Because of use of ac voltage and the small dimensions of the thermocouple crown the voltage drop has practically no effect on indications. During experiments the voltage drop across the specimen and strength of the current passing through were also measured.

The measurement results were used to determine the amount of heat absorbed by the coolant and the temperature head between specimen and coolant, which were then used to determine the value of the internal heat transfer coefficient.

In the past [4-6] experimental data on internal heat exchange in porous media have been presented in the form $Nu_V = f(Re, Pr, \varepsilon)$. A large number of studies using various coolants (air, nitrogen, ethanol, transformer oil, argon, helium) have shown that the effect of thermophysical properties on internal heat exchange in porous structures of low and moderate porosity ($\varepsilon < 0.6$) can be considered by the number Pr, which appears in the similarity equation to the same power as the number Re. Test experiments with water and air revealed that this relation between numbers Pr and Re is maintained for the high porosity structures studied herein.

With consideration of this, in Fig. 2 the symbols show experimental data on internal heat exchange in the form of the dependence $Nu_V = f(Pe)$, while the hatched region illustrates similar results from the literature for low and moderate porosity structures (taken from [5]). In the similarity equations proposed in the literature the exponent of Pe varies over quite wide limits (n = 0.65-1.84); however, in the majority of cases it takes on values from 0.9 to 1.3. For high porosity structures, as is evident from the figure, this exponent is smaller, having a value of 0.56. It can also be concluded from the figure that the experimental data on internal heat exchange are layered for various values of the porosity ε.

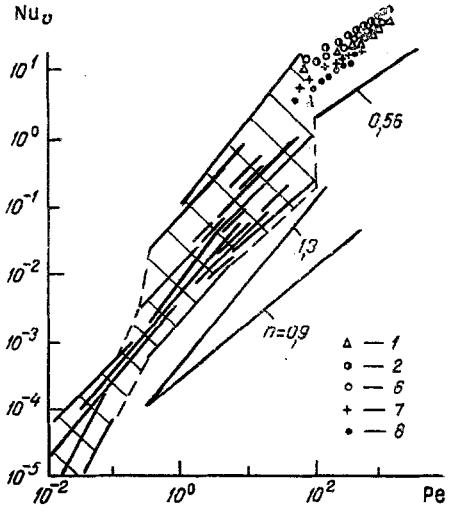

Fig. 2. Comparison of experimental function $Nu_V = f(Pe)$ with data from literature [5]. Notation described in Table 1.

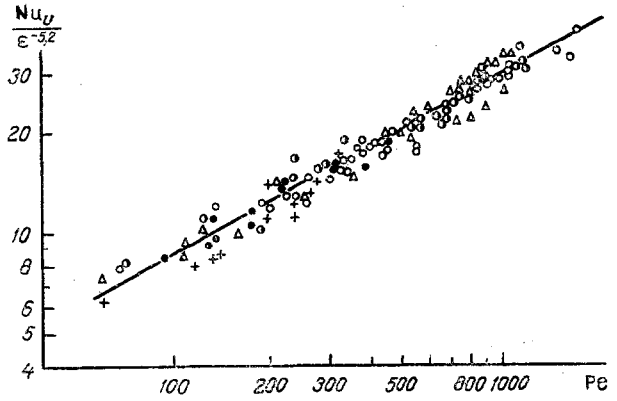

Fig. 3. Generalized internal heat exchange. Notation as in Fig. 2.

TABLE 1. Results of α and β Determination

No.	Material	Specimen thickness, mm	d_p, mm	ε	α, m^{-2}	$\beta \cdot 10^{-3}$, m^{-1}
1	Invar	10,7	0,81	0,92	$1,43 \cdot 10^8$	1,8
2	Invar	9,9	0,93	0,87	$1,65 \cdot 10^8$	2,1
3	Invar	11,5	1,66	0,91	$3,08 \cdot 10^7$	0,96
4	Invar	10,3	2,17	0,92	$2,64 \cdot 10^7$	0,48
5	Molybdenum + nickel (3%)	13,7	1,69	0,92	$3,52 \cdot 10^7$	0,72
6	Copper	18,1	1,72	0,87	$3,21 \cdot 10^7$	1,3
7	Copper	16,3	0,62	0,94	$2,47 \cdot 10^8$	1,92
8	Copper	17,5	0,7	0,97	$1,51 \cdot 10^8$	0,96

Consideration of the effect of porosity permitted all experimental data on internal heat exchange (Fig. 3) to be expressed with a mean square error $\delta Nu_V = 0.12$ by a similarity equation

$$Nu_v = 0{,}606\, Pe^{0{,}56}\, \varepsilon^{-5{,}2}, \tag{3}$$

where for the characteristic dimension we take the mean pore diameter d_p, defined by the method described above, and for the defining velocity, the coolant filtration rate.

The experimental data obtained and the relation which generalizes them, Eq. (3), indicate that at high porosity values with increase in ε, values of α_V decrease, in contrast to

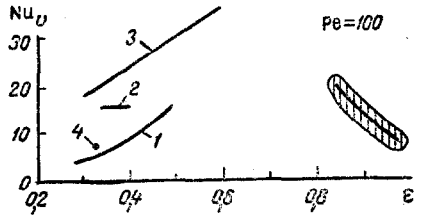

Fig. 4. Function $Nu_v = f(\varepsilon)$; hatched region is field of experimental data; solid curves, results of following authors: 1) Belov (for unit thickness plate); 2) Grotenhus et al.,; 3) Timofeev; 4) Boiko, Eroshenko, et al.

the effect of ε on α_v for low porosity values, in which case with increase in ε, values of α_v increase. These effects of porosity in various ranges are shown in Fig. 4. It is evident that there exists some porosity value (ε = 0.5-0.7) which corresponds to maximum internal heat transfer in porous structures.

NOTATION

ε, porosity; α, β, viscous and inertial coefficients of porous medium; α_v, internal heat transfer coefficient; P_{in}, P_{out}, coolant pressures at specimen input and output; $\overline{T}$, mean coolant temperature within specimen; l, specimen length; $Nu_v = \alpha_v d^2_p/\lambda$, Nusselt number; $Re = jd_p/\mu$, Reynolds number; $Pr = \mu c_p/\lambda$, Prandtl number; $Pe = RePr$, Peclet number; λ, p, c_p, ρ, thermal conductivity, viscosity, heat capacity and density of coolant; v, coolant viscosity; $j = \rho v$, reduced flow rate.

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