EFFECT OF EVOLVING BUBBLES OF A GAS DISSOLVED IN A LIQUID ON THE RESISTANCE IN ITS FLOW THROUGH POROUS METALS. I. MOVEMENT OF DEAERATED WATER

V. A. Maiorov and L. L. Vasil'ev

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The article presents methods and results of the experimental investigation of the hydraulic resistance in the flow of deaerated water through porous metals.

One of the fundamental conditions of reliable operation of various heat- and mass-exchange installations with porous elements is the possibility of accurate and predictable control of the flow rate of a dropping liquid in its flow through a permeable matrix. However, in this process we often find the undesirable effect of nonuniform and nonreproducible decrease of the flow whose main cause is, as was shown in [1], the clogging of the porous structure by evolving bubbles of a gas dissolved in the liquid. Subsequent analytical and experimental investigations [2] revealed that the formation of bubbles and the liberation of dissolved gas in them in steady flow through a permeable matrix occur under conditions that are close to equilibrium saturation.

Below we present the results of the experimental investigation of the effect of various parameters of the process on the intensity of bubble formation of the dissolved gas and on the magnitude of the increase of hydraulic resistance caused thereby when a dropping liquid (water) moves through porous metals.

Experimental Installation. The hydraulic installation illustrated in Fig. 1 ensured thorough cleansing and deaeration of the distilled water, and also its feed in wide ranges of flow rates and temperatures. Deaeration of water was effected by preliminary heating to ≈80°C and its subsequent cooling in vacuum in tank 2 below which it was sucked in without mixing by the batching pump 4. To prevent pulsations of flow rate and pressure, two elastic rubber balloons inflated by air were placed behind the pump and the receiver 5.

Mechanical admixtures were removed from the water by the double combined filter 6. It had two porous disks 5 mm thick and with 50 mm diameter, sintered from spherical bronze powder of fraction 63-100 μm, mounted behind each other in two separate rings; to the inlet surface of each disk a replaceable filter of dense filter paper 0.4 mm thick with mean pore size 3-7 μm was pressed. In addition, preliminary cleansing was carried out by glass filters with replaceable paper filters when water was filled into tank 2 under the effect of the vacuum in it.

Measurement and control of the flow rate of the water were effected with the aid of the measuring stand I from which the water proceeded into the heat exchanger 9 filled with glycerin, and then into the working chamber 10 on the stand II which was mounted directly on the thermostat.

The porous specimen 1 of cylindrical shape with an annular rim on the inlet side (Fig. 2) was hermetically sealed with epoxy resin into the Textolite sleeve 2. Mounted on the supply flange 3 is the protective convective heat exchanger 4 which is heated by glycerin from the thermostat. On both flanges there are outlets for connection to the manometers. The pressure at the outlet of the specimen was controlled by a valve (see Fig. 1).

In the experiments we measured the temperature and pressure of the water inside the porous matrix. The Chromel–Copel thermocouple was hermetically sealed into a radial hole passing through the Textolite sleeve whose depth was ≈0.5 of the radius to the axis of the specimen. The thermoelectrodes were led in between the flanges. As pressure sensor in the stream inside the porous metal we used a hypodermic needle with 1 mm outer diameter, hermetically

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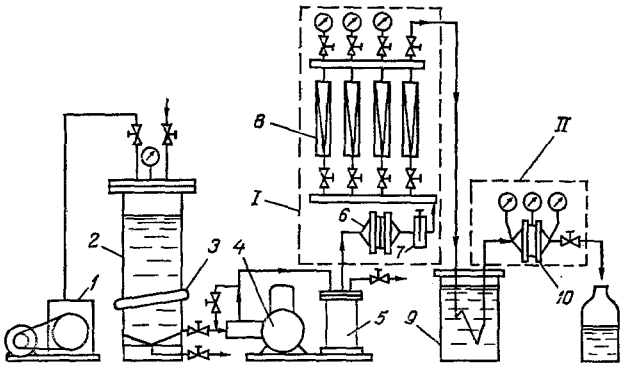

Fig. 1. Diagram of the hydraulic installation: 1) vacuum pump; 2) tank; 3) tubular electric heater; 4) batching pump; 5) receiver; 6) filter; 7) control valve; 8) battery of glass rotameters; 9) thermostat; 10) working chamber; I, II) measuring stands.

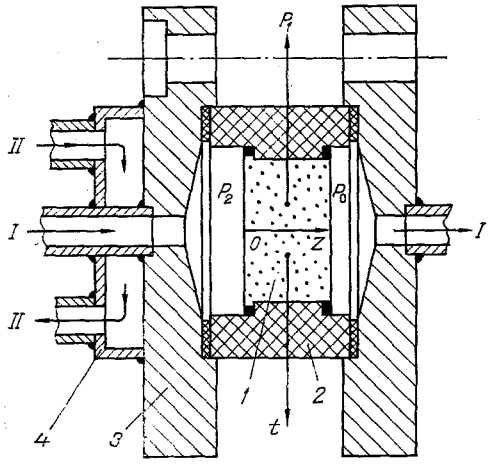

Fig. 2. Diagram of mounting the specimen in the working chamber: 1) porous specimen; 2) Textolite sleeve; 3) supply flange; 4) convective protective heater; t, P_1) output leads from thermocouple and needle, respectively; I) flow of water; II) flow of heating glycerin.

sealed into a radial channel passing through the Textolite sleeve to a depth of ≈0.5 of the radius to the axis. To the needle, and also to the working chamber ahead and behind the specimen, reference manometers were connected.

Experimental Procedure. To determine the effect of the evolving bubbles of air dissolved in water on the increase of resistance when the water moves through porous metals, a program of 3-day tests of each specimen was successively put into effect.

Figure 3 shows two arrangements of carrying out the daily experiments: *a* includes 15 series of measurements. A separate measurement is denoted in the diagram by a point, and with fixed flow rate of the water we determined the pressure P_2 ahead of the specimen and P_1 inside it.

The series 01, 03, 05, 06, 08, 10, 11, 13, and 15 included measurements first at increasing flow rate (9 readings) and then with its gradual decrease through these same 9 values at atmospheric pressure behind the specimen. These flow rates are the same for all specimens, and with the equal diameters of the specimens of 28 mm, they correspond to the following specific mass flow rates of water: 0.915, 1.43, 2.08, 2.70, 4.28, 6.80, 10.0, 13.7, and 17.3 kg/(m²·sec). The object of these series was to establish the effect of the specific water flow rate and of the prehistory of the process (increase or decrease of the flow rate) on the resistance of the specimen.

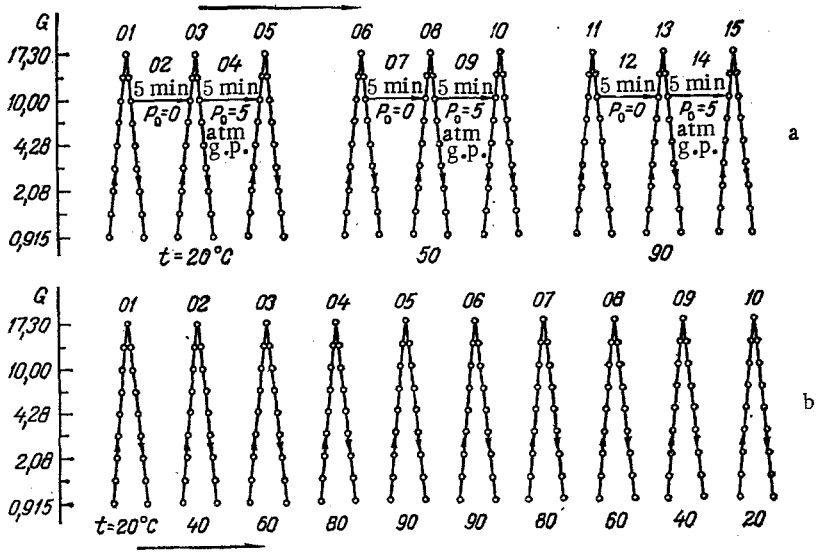

Fig. 3. Diagram of the execution of daily measurements. G, kg/$m^2 \cdot sec$.

When the flow rates were below 4.28 kg/($m^2 \cdot sec$), we did not take the readings of the manometer connected to the needle because when readings of low pressure are taken, the error is excessively large.

The series 02, 07, and 12 include measurements for 1 min in the course of 5 min at constant mass flow rate of 10 kg/($m^2 \cdot sec$) and atmospheric pressure at the outlet of the specimen. Their object was to reveal change of resistance with time at constant flow rate.

In series 04, 09, and 14 the same measurements were carried out as in series 02, 07, and 12, but at constant elevated excess pressure P_0 behind the specimen equal to 5 atm gauge pressure. Their object was to determine in comparison with series 02, 07, and 12 the effect of the pressure behind the specimen on the change of its resistance with time. The groups 01-05, 06-10, and 11-15 differ from each other by the temperature: series 01-05 are carried out at constant water temperature of 20°C; 06-10 at 50°C; 11-15 at 90°C. That way we determined the effect of the temperature on the change of resistance.

On the first day of the 3-day program experiments with deaerated water were carried out only in series 01, 06, and 11 to find the initial characteristics of the specimen. Apart from that we carried out additional measurements in series 01 at reverse flow of the water through the specimen (with its position in the working chamber changed) to verify the correctness of the readings obtained with the needle. After each day the specimens were dried in a drier.

Experiments with arrangement *a* on 15 series were carried out on the 2nd and 3rd days of the program.

On the 2nd day the experiments were carried out with water saturated with air. Saturation was attained by lengthy stirring of the water in glass bottles at atmospheric pressure and at 20°C. After settling, the water was fed by a batching pump directly from the bottle.

On the 3rd day deaerated water was used again.

By comparing the data of the 1st and 3rd days of the program we were able to reveal changes of the characteristics of the specimen with time: whether its resistance increased in consequence of pollution by mechanical admixtures. Comparison of the results of the 2nd day of the program with the results of the 1st and 3rd day makes it possible to evaluate the effect of bubbles of dissolved air on the change of resistance of the specimen.

To investigate the effect of the temperature and of the prehistory of the process (direction of change of temperature), we worked the 3-day program of measurement according to arrangement b. This included the equal series 01-05 of the type of series 01 according to arrangement *a*, carried out at first with successive increase of temperature at the values 20, 40, 60, 80, and 90°C, and then series 06-10 with these same values but in reversed sequence.

TABLE 1. Characteristics of the Investigated Specimens

No. of specimen	Porosity F	Powder fraction, μm	Mean pore size $d_п$, μm	Thickness of specimen δ, mm	Coordinate of needle z_n	Drag coefficient $\alpha \cdot 10^{-12}$, m^{-2}
1	0,335	63—100	26,5	20,1	0,52	0,205
2	0,350	50—63	20,0	19,7	0,47	0,53
3	0,300	50—63	16,0	19,15	0,64	0,59
4	0.285	50—63	14,8	19,0	0,39	0,925

Here it should be pointed out that in the time intervals between series of measurements, when the temperature of the thermostat changed, the pressure in the working chamber was increased to 0.5 MPa to eliminate the possibility of the specimens being saturated with air bubbles.

On the 1st day of the program the experiments were carried out with deaerated water only in series 01-05 (the initial characteristics of the specimens were determined). In addition to that, measurements in series 01 were carried out with reverse flow: this was a check of the correct indications of the needle. On the 2nd day the experiments were carried out by the full program and with water saturated with air. On the 3rd day measurements were carried out with deaerated water and only in series 01-05, to determine the final characteristics of the specimens.

Method of Processing the Results. The data of the hydraulic tests were processed by proceeding from the equation of motion of liquids and gases in porous materials

$$-\frac{dP}{dZ} = \alpha\mu v G + \beta v G^2. \tag{1}$$

First we found the initial hydraulic characteristics of the specimens: the viscous (α) and inertial (β) coefficients of resistance. For that we used the data of the 1st day on the pressure gradient $P_2 - P_0$ on the entire specimen with flow of deaerated water, which had the form

$$(P_2 - P_0)/\delta\mu v G = \alpha + \beta G/\mu. \tag{2}$$

It turned out that for all specimens in the investigated range of flow rates and temperatures the results thus processed lay within an experimental scatter of 5% on the horizontal straight line $(P_2 - P_0)/\delta\mu vG = \alpha = \text{const}$. Then we calculated the normalized magnitude of the pressure gradient on the specimen for all the investigated flow rates, separately for each temperature:

$$(P_2 - P_0)^* = \alpha\mu v\delta G. \tag{3}$$

After the results concerning the pressure gradient $P_2 - P_0$ on the entire specimen of the 2nd and 3rd day of the program were transformed to the dimensionless form

$$\Pi_{2-0} = (P_2 - P_0)/(P_2 - P_0)^*. \tag{4}$$

The advantages of this form of processing the results consist in the following: a) the data are smoothed because the magnitude of α is determined by comparing the results of several series of 17 measurements each at different temperatures; b) the deviation of the value Π_{2-0} from unity for the results of the 2nd and 3rd day of the program makes it possible to evaluate rapidly the resistance of the specimen solely in consequence of external effects: the evolution of bubbles of dissolved air or clogging of the matrix by mechanical pollution.

In an analogous way we processed the data on the pressure gradient at different parts of the specimen: from the entrance to the needle $P_2 - P_1$ and from the needle to the outlet $P_1 - P_0$. Here we found first the distance Z_n between the needle and the inlet surface (Z = 0) in dimensionless form $z_n = Z_n/\delta$. This value was found as the mean of all data of the 1st day for different temperatures from the ratio of the pressure gradient $P_1 - P_0$ at outlet section of the specimen between the needle P_1 and the outlet P_0 to the full pressure gradient $P_2 - P_0$ on the specimen:

$$1 - z_n = \overline{(P_1 - P_0)/(P_2 - P_0)}. \tag{5}$$

After that the results on the pressure gradient on the section between the needle and the outlet from the specimen were transformed to the dimensionless form:

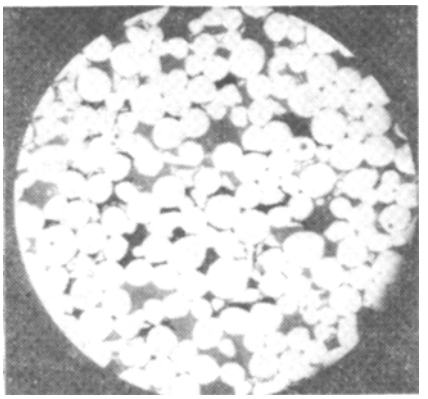

Fig. 4. Microstructure (×100) of bronze with porosity F = 0.34 made by sintering freely filled spherical powder of fraction 50-63 μm.

$$\Pi_{1-0} = (P_1 - P_0)/(1 - z_n)(P_2 - P_0)^* \quad (6)$$

and analogously for the section from the inlet to the needle

$$\Pi_{2-1} = (P_2 - P_1)/z_n(P_2 - P_0)^*. \quad (7)$$

The deviation of the values of Π_{1-0}, Π_{2-1} from unity makes it possible to evaluate the change of resistance on individual sections on the 2nd and 3rd days of the program.

Resistance in Flow of Deaerated Water. The porous cylindrical specimens were made from spherical bronze powder by sintering after free mold filling. The porosity was determined by the volume-weight method; the mean pore size was evaluated in accordance with the recommendations of [3]. The characteristics of the specimens are presented in Table 1, and their microstructure in Fig. 4.

Experiments according to the full 3-day program of arrangement a (see Fig. 3) were carried out with specimens Nos. 1-3; according to the full 3-day program of arrangement b with specimens Nos. 2 and 4. For all specimens qualitatively equal results were obtained.

For identification of the results we adopted a compound numbering system, e.g., 2.11, a. The first figure denotes the number of the day of the 3-day program (2nd); the other two figures denote the number of the series (11); the letter a denotes the arrangement of the experiment according to Fig. 3.

In the investigated range of specific mass flow rates G = 0.915-17.3 kg/(m²·sec) and temperature range 20-90°C, the data of the 1st day transformed to the form (2) lie within the experimental scatter of ∓5% about the horizontal straight line $(P_2 - P_0)/\delta\mu vG = \alpha = \text{const}$. This indicates that under such conditions the inertial component of the resistance βvG^2 is much smaller than the viscous component $\alpha\mu vG$, and we therefore did not manage to determine the value of β. The values of the viscous drag coefficient α are presented in Table 1. A comparison with the analogous characteristics of metals of spherical powder with mean particle size 50 μm, contained in [4], showed that they are close to each other: in [4] for F = 0.30 it was found that $\alpha \approx 1 \cdot 10^{12}$ m^{-2}.

The obtained results confirmed once again the fact that the viscous drag coefficient is a characteristic of a porous matrix and does not change with rising temperature (under the given conditions in the range 20-90°C), whereas the pressure gradient on the specimen in case of flow of dropping liquids greatly decreases on account of reduced viscosity.

A comparison of the data on forward and reverse flow at 20°C on the 1st day of the program showed that the pressure gradient on the specimen is the same, and the sum of the readings of the manometer connected to the needle in forward and reverse flow is equal to the pressure gradient on the specimen: the needle indicates the pressure inside the porous structure correctly. The values of the dimensionless coordinate z_n of positioning the needle are given in Table 1.

An analysis of the results of the 3rd day shows that the values of the dimensionless pressure gradients on the specimen Π_{2-0} and on its individual sections Π_{1-0}, Π_{2-1} within the

limits of experimental scatter do not differ from unity, both at the time of carrying out measurements at a certain temperature for each of the groups of series 01.a-05.a, 0.6a-10.a, 11.a-15.a, and upon change of temperature and in transition from one group to another. No increase of pressure gradient with time was observed in series 02.*a*, 04.*a*, 07.*a*, 09.*a*, 12.*a*, and 14.*a*. Analogous results were also obtained for measurements by arrangement b. On the basis of that it may be concluded that in lengthy flow of deaerated water at different flow rates and temperatures no unpredictable increase of the resistance of the specimen occurs, and it is not polluted by mechanical admixtures when the water is cleaned by filters whose mean pore size is 3-5 times smaller than the analogous characteristic of the investigated specimen.

To this it may be added that during 1 day of measurements according to the full program, up to 50 liters of water passed through the specimen. Toward the end of the 3rd day all in all up to 125 liters flowed through the specimen. The paper filters with pore size of 3-7 μm had to be replaced every day.

NOTATION

G, specific mass flow rate of a liquid; F, porosity, P, pressure; v, specific volume of a liquid; Z, coordinate; α, β, viscous and inertial drag coefficients, respectively, of a porous material; δ, thickness of the specimen; μ, dynamic viscosity of a liquid; Π, relative pressure gradient; subscripts 0, 1, 2, refer to the parameter at the outlet from, inside, and at the inlet to the specimen, respectively.

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