CAPILLARY IMPREGNATION OF POROUS METAL GAUZES WITH LIQUID

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UDC 532.685

The article presents a method of calculating the height of capillary rise of a liquid in porous metal gauzes; calculated and experimental results are being compared.

The use of porous metals in the transfer of liquid media, e.g., in heat pipes, requires that methods be worked out for calculating the parameters of the transfer process such as height and rate of rise of the liquid,

In recent years porous woven and braided metal gauzes have come into widespread use in engineering [1, 2]. A porous metal gauze (PMG) has a complex internal structure characterized by a certain size and distribution density of the pores according to dimensions, different shape of the pores, etc. [3].

In a precise description of the process of impregnation of a PMG with liquid it is necessary to take into account all the features of its structure, but this is impossible at present. Therefore, models of the porous body are often used for calculating the parameters of the process of impregnation. With the aid of these models the process of impregnation of ideal porous media [4] is described, and also of porous media consisting of axisymmetric beaded capillaries [5] on the assumption that impregnation proceeds in two mutually perpendicular directions with the ratio of the liquid masses 2:1.

For solving the problem of the rate of capillary rise of liquid in a PMG we used the model of a porous body consisting of a set of cylindrical capillaries of different diameter, communicating over the height of the porous body. The equation of motion of the liquid front in the pores during their filling under the effect of the capillary forces in the field of the forces of gravity (not taking into account forces of small order of magnitude) for each of the channels can be written in accordance with the equation of motion of a meniscus of liquid in a single cylindrical capillary [4] in the form

$$\frac{dl}{dt}=\frac{r\sigma\cos\theta}{4\mu l}-\frac{r^2 g\rho}{8\mu}\sin\alpha. \tag{1}$$

If we consider only l as a function of time t as variable in Eq. (1), we find the solution in the form

TABLE 1. Characteristics of Porous Plates and Parameters of the Process of Impregnation

No.	Plate dimensions, mm			Porosity	Mean pore size $d_{\pi av}$, μm	Maximum pore size $d_{\pi max}$, μm	Specific surface of PMG S_0, cm^2/cm^3	Max. calc. height of liquid rise $(h_p)_{max}$, mm	Max. expl. height of liquid rise $(h_e)_{max}$, mm
	length	width	thickness						
1	404	49,0	3,60	0,400	48,3	70,7	798	570	190
2	401	43,0	2,90	0,767	165	530	310	115	160
3	388	46,0	2,70	0,726	148	540	363	143	155
4	391	49,0	2,94	0,458	49	75	721	450	180
5	378	50,5	2,98	0,478	50	80	694	415	180
6	390	52,0	7,31	0,425	39	56	765	514	225
7	405	49,0	5,10	0,453	45	66	728	459	218
8	402	52,0	3,50	0,360	40	61	851	676	271

N. É. Bauman Moscow Technical University. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 43, No. 1, pp. 91-95, July, 1982. Original article submitted April 13, 1981.

0022-0841/82/4301-0774$07.50

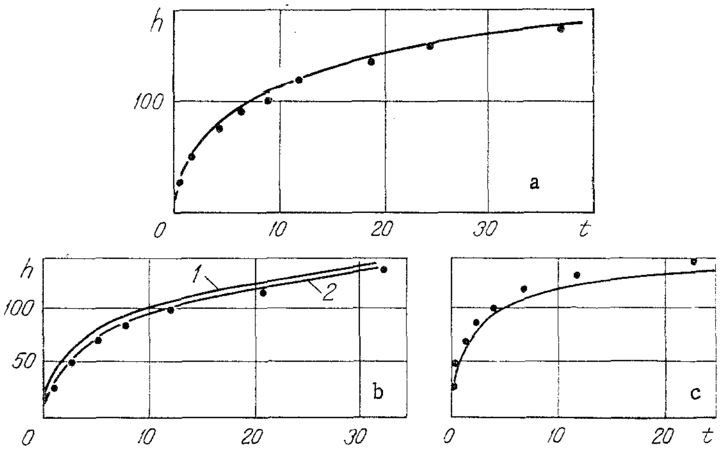

Fig. 1. Dependences of height h (mm) of capillary liquid rise in pores of PMG on time t (min) in the process of impregnating specimens No. 7 (a), 8 (b), 3 (c). Dots: experiment; curves: calculation by Eq. (2).

$$A\frac{l}{r^2} + \frac{B}{r^3}\ln(1 + Crl) = t, \tag{2}$$

where

$$A = -\frac{8\mu}{g\rho\sin\alpha};\quad B = -\frac{16\mu\sigma\cos\theta}{\rho^2 g^2\sin^2\alpha};\quad C = -\frac{g\rho\sin\alpha}{2\sigma\cos\theta}.$$

With $t\to\infty$ we obtain the condition of attaining the maximum rise of the liquid

$$h_{\max} = l\sin\alpha = \frac{2\sigma\cos\theta}{rg\rho}, \tag{3}$$

and the expression in parentheses in Eq. (2) tends to zero.

For the adopted calculation model at the instant t_1, the liquid, under the effect of the capillary forces, passes through capillaries of different sizes $r_1, r_2, \ldots, r_i, \ldots, r_n$ and traverses the paths $l_1, l_2, \ldots, l_i, \ldots, l_n$, respectively. Simultaneously with the rise of the liquid there occurs its redistribution between capillaries of different sizes in such a way that in the larger capillaries (r_1) the liquid settles at the level l_{x1}, which is lower than the calculated value of l_1, and for small capillaries (r_i, $i > 1$) the level l_{xi} is higher than the calculated value l_i.

Thus, at the end of the time interval t_1 the liquid settles at the level l_{x1}, and at the subsequent instant t_2 the rise of the liquid will proceed from this level to the level l_{x2}, etc. When the rise of the liquid has attained the height $h_{x1} = l_{x1}\sin\alpha$, corresponding to the maximum rise of the liquid in the capillaries with the largest size r_1, these capillaries are disengaged from the process of capillary rise and spread of the liquid. This reduces the volume of the pores that are filled with liquid in impregnation. An analogous disengagement of the pores occurs with increasing rise and spread of the liquid in the examined model until the liquid reaches the maximum height of its rise in the pores with the smallest size r_n.

Thus, when a liquid rises in a model of capillaries with different diameters on condition of redistribution of the liquid among capillaries of different size, the rate of rise is actually reduced in capillaries with large diameter, and increased in capillaries with small cross section.

The process of capillary rise of a liquid can be calculated on a computer for the range of pore sizes from $r_1 = d_{\pi\max}/2$ to $r_n = d_{\pi\min}/2$ of the porous body, where $d_{\pi\max}$ and $d_{\pi\min}$ are the maximum and minimum pore size, respectively, with specified pore distribution according to size or the regularity of change of the relative volume of the pores occupied by pores with each size r_i.

Experimental verification of the calculated parameters of the process of impregnation was carried out with plates of PMG made by pressing and subsequent sintering of braided gauzes "Lastic" made of wire 12Kh18N9T with 30 μm diameter with 20 wires in a braid [1]. Table 1 presents the structural and geometric characteristics of the investigated specimens of PMG.

Porosities were determined according to the density of the material, and the mean and maximum pore size by the method of expelling the liquid from the pores in a direction perpendicular to the motion of the liquid front in impregnation [3].

In experiments with impregnation with $\alpha = 90°$, the specimen was lowered with its bottom end face into 96% aqueous solution of ethyl alcohol at 293°K. For each specimen of PMG the dependences $h_e = f(t)$ were obtained, and the maximum height of liquid rise in them $(h_e)_{max}$ was ascertained (see Table 1).

For calculating the parameters of the impregnation process by Eq. (2), it is necessary first to find the values of $d_{\pi min}$, which entails certain difficulties. Therefore, the greatest possible heights of liquid rise $(h_p)_{max}$ in specimens of PMG were calculated by the method of [6] based on the use of the values of the specific surface S_0 of a porous body. In that case $(h_p)_{max}$ is determined by the formula

$$(h_p)_{max} = \frac{S_0 \sigma \cos\theta}{\rho g \Pi}. \qquad (4)$$

In calculating $(h_p)_{max}$, $\cos\theta$ was taken equal to unity. A special case of Eq. (4) is Eq. (3) which is correct for cylindrical capillaries when $d_\pi = 4\Pi/S_0$.

The specific surface of the specimens of PMG was calculated according to the known length and diameter ($d_{wi} = 30$ μm) of the wire on the assumption that the area of contact between individual fibers is negligibly small in comparison with the total surface of the pores. In that case the formula for determining the specific surface of the PMG has the form

$$S_0 = \frac{4}{d_{wi}}(1 - \Pi). \qquad (5)$$

The calculated values of S_0 are given in Table 1.

A comparison of the values of $(h_e)_{max}$ and $(h_p)_{max}$ shows that for most of the investigated specimens coincidence of these values can be attained by putting $\theta \approx 65°$. An exception were the results of the experiments with specimens with great porosity (specimens 2, 3) for which $(h_e)_{max}$ was found to be larger than $(h_p)_{max}$. Similar values for the angle θ (60-70°) were obtained in impregnating quartz sand with water [7].

The minimum size of the pores $d_{\pi min}$ in PMG was evaluated according to the limit value of the height of liquid rise in specimens of PMG taking formula (3) into account. After determination of the parameters $d_{\pi min}$ and θ by Eq. (2) we found the theoretical dependence $h_p = f(t)$ for the investigated specimens of PMG.

Figure 1a shows the results of the calculation (curve) and the experimental values (dots) of the height of capillary liquid rise in specimen 7 in dependence on the time of the impregnation process. The calculation was carried out separately for four pore sizes $d_{\pi 1} = 66$, $d_{\pi 2} = 48$, $d_{\pi 3} = 40$, $d_{\pi 4} = 12$ μm, the volume of the pores of each size $V_{\pi i}$ was taken equal to 0.25 of the total pore volume V_π, i.e., $V_{\pi i}/V_\pi = 0.25$. The difference between the calculated and experimental data is less than 10%.

Figure 1b shows the analogous dependences for specimen 8 of PMG with the following conditions of calculation: $d_{\pi 1} = 61$, $d_{\pi 2} = 47.5$, $d_{\pi 3} = 34$, $d_{\pi 4} = 20.4$, $d_{\pi 5} = 7$ μm with uniform distribution of the pores over the volumes $V_{\pi i}/V_\pi = 0.2$ (curve 1) and with nonuniform distribution $V_{\pi 1}/V_\pi = 0.1$, $V_{\pi 2}/V_\pi = V_{\pi 3}/V_\pi = V_{\pi 4}/V_\pi = 0.2$, $V_{\pi 5}/V_\pi = 0.3$ (curve 2).

Nonuniform distribution of the pores according to their volumes with increasing proportion of small pores, a characteristic trait of specimens of PMG with small porosity, yields better coincidence of the calculated data (curve 2) with the experimental results (dots).

Figure 1c shows the calculated dependence $h_p = f(t)$ for specimen 3 of high porosity and the experimental data (dots). Calculations by Eq. (2) were carried out for $d_{\pi 1} = 540$, $d_{\pi 2} = 413$, $d_{\pi 3} = 286$, $d_{\pi 4} = 158$, $d_{\pi 5} = 31$ μm and $V_{\pi i}/V_\pi = 0.2$. It can be seen from Fig. 1c that the theoretical dependence runs below the experimental data. The coincidence of the calculated and the experimental data can be improved by increasing the proportion of large pores, which is a regularity for specimens of PMG with great porosity.

A comparison of the calculated and the experimental values of the function $h = f(t)$ showed that the suggested model of a porous body satisfactorily describes the process of capillary impregnation of pores of PMG with liquid. For calculating the parameters of the process of impregnating PMG with a liquid it is indispensable to know, in addition to the properties of the liquid, the pore sizes, and also the distribution density of the pores according to sizes.

On the other hand, satisfactory agreement between the calculated and the experimental data over the height of liquid rise in porous metals makes it possible by conversion to determine the pore size distribution in porous metals according to the experimental function $h = f(t)$, the minimum and maximum pore sizes.

NOTATION

l, distance along the axis of the capillary from its beginning to the meniscus of liquid, m; t, time, sec; r, radius of the capillary, m; σ, capillary tension, N/m; μ, dynamic viscosity, $N \cdot sec/m^2$; ρ, density, kg/m^3; θ, contact wetting angle, deg; g, acceleration of gravity, m/sec^2; α, slope of the capillary to the horizontal, deg; h, height of liquid rise in the capillary, m; S_0, specific surface of a porous body, m^2/m^3; d_π, pore diameter, m; d_{wi}, wire diameter, m; Π, porosity; V_π, volume of pores, m^3.

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