MODELING OF OVERLAP AREA OF POWDER FILTER MATERIALS

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Abstract: *A model for calculating the permeability of two-layer powder filter materials (PFMs) is proposed taking into account the overlap area. Examples of calculating the permeability of PFMs on real powder structures are given.*

KEYWORDS: TWO-LAYER POWDER FILTER MATERIALS, CALCULATION MODEL, PERMEABILITY, OVERLAP AREA.

1. Introduction

Despite the widespread use of polymeric, paper, and ceramic materials in engineering, powder filter materials compete worthy with them, especially in cases where it is necessary to realize the physico-chemical properties typical for metals and alloys from which PFMs consist. PFMs are successfully used to solve various problems: for aeration of the air flow in order to saturate the air-culture fluid with oxygen when growing aerobic microorganisms in bioreactors; for dispergation of the ozone-containing air mixture flow in order to decontaminate the fish habitat (including young fish) in recirculating aquaculture systems (RAS) and uniform distribution of vapor flow over the volume of coolant (water) to control the temperature in working tanks during heat treatment of milk, milk mixtures and technological media used in milk treatment; air, water vapor, and oil purification, as well as for other purposes [1–5].

In practice, two-layer materials are widely used to increase the operational properties of PFM. One layer is formed by fine particles and provides the necessary fineness of cleaning. The second layer if formed by coarse particles and provides sufficient strength and high permeability of PFM [6, 7]. The problem in this case is the appearance of the intermediate layer at the boundary of the layers, the so-called “overlap area”, in which smaller particles fill the pore space formed by coarse particles [8]. One of the effective ways to improve the properties of two-layer PFMs is to reduce the thickness of the fine layer [8]. In this regard, the calculation of the influence of the overlap area on the properties of two-layer PFMs is of great interest.

The purpose of this work is modeling of PFM “overlap area” and calculation of the permeability of this area.

2. Results and discussion

When two-layer materials are produced by co-molding powders of different fractions in the area of the layer boundary, smaller powder particles partially fill the pore space formed by larger particles, making, as noted above, an intermediate layer (overlap area). Figures 1 and 2 illustrate examples of the formation of such structures in the production of two-layer materials based on titanium and copper powders. We determine the effect of the overlap area on the permeability of two-layer PFMs.

To calculate the permeability taking into account the overlap area, we consider the case when the porous material consists of two layers and the overlap area. The first and second layers are respectively formed from powder particles with sizes D_1 and D_2, with $D_1 > D_2$. The overlap area (conditionally it can be considered as the third layer), located between the first and second layers. It consists of particles of these two sizes. Small particles with sizes D_2 are located between large particles with size D_1. We denote the thicknesses of the first layer (substrate), the intermediate layer (overlap area) and the second layer (fine powder) by h_1, h_{12} and h_2, and the flow rate of the filtered medium through the PFM per unit time by Q.

Fig. 1 The structure of a two-layer PFM made of titanium powders with a particle size of (minus 1000 + 400) and (minus 100 + 40) μm

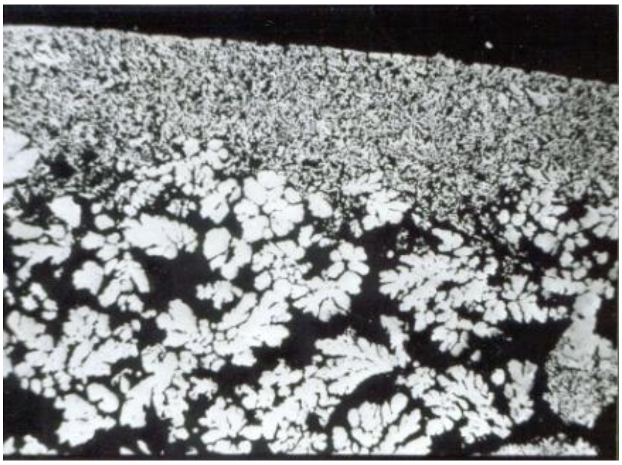

Fig. 2 The structure of a two-layer PFM made of copper powders with particle sizes (minus 315 + 200) and (minus 80 + 40) μm

Considering the flow of a liquid or gas through the whole material, it is possible to write the following according to Darcy’s law [9]:

$$Q = \frac{k \Delta p}{\mu h} S , \qquad (1)$$

where k – coefficient of permeability; Δp – differential pressure on PFM; S – filtration area; μ – viscosity of filtered medium; h – thickness of PFM.

For each layer separately, equation (1) can be written as follows:

$$Q_1 = \frac{k_1 \Delta p_1}{\mu h_1} S, \qquad (2)$$

$$Q_{12} = \frac{k_{12} \Delta p_{12}}{\mu h_{12}} S, \qquad (3)$$

$$Q_2 = \frac{k_2 \Delta p_2}{\mu h_2} S, \qquad (4)$$

where Δp_1, Δp_{12}, Δp_2, - respectively, differential pressure on each of the layers with thicknesses h_1, h_{12}, h_2;

S – the filtration area of all layers (the first layer is the substrate; the intermediate layer is the overlap area and the second layer is fine powder).

Obviously, the flows of the filtered medium passing through the whole material Q and through each layer separately Q_1, Q_{12}, Q_2, are equal to each other:

$$Q = Q_1 = Q_{12} = Q_2, \qquad (5)$$

and differential pressure on PFM and its thickness are:

$$\Delta p = \Delta p_1 + \Delta p_{12} + \Delta p_2, \qquad (6)$$

$$h = h_1 + h_{12} + h_2. \qquad (7)$$

Based on (1–4), taking into account (5–7), it is possible to obtain the following equations:

$$\frac{\Delta p_1}{\Delta p} = \frac{k h_1}{k_1 h}, \qquad (8)$$

$$\frac{\Delta p_{12}}{\Delta p} = \frac{k h_{12}}{k_{12} h}, \qquad (9)$$

$$\frac{\Delta p_2}{\Delta p} = \frac{k h_2}{k_2 h}. \qquad (10)$$

Summing up the left and right sides of equations (8–10), we obtain the equation for calculating k:

$$1 = \frac{k h_1}{k_1 h} + \frac{k h_{12}}{k_{12} h} + \frac{k h_2}{k_2 h}, \qquad (11)$$

from which:

$$k = \frac{h}{\dfrac{h_1}{k_1} + \dfrac{h_{12}}{k_{12}} + \dfrac{h_2}{k_2}}. \qquad (12)$$

To determine the coefficient of permeability in the overlap area, we have the following considerations. Surface sections blocked by large particles with sizes D_1 are excluded from the filtering process of this layer, and therefore its throughput capacity is determined by the pore space areas of the substrate filled with fine powder with an area of $S_{12} < S$. Accordingly, the coefficient of permeability of these areas can be taken equal to k_2.

Then, on the basis of the continuity condition of the flow (5), the value of Q_{12} can be represented as:

$$Q_{12} = \frac{k_2 \Delta p_{12}}{\mu h_{12}} S_{12}. \qquad (13)$$

Equating the right sides of equations (3) and (13) to each other, we obtain:

$$k_{12} = k_2 \frac{S_{12}}{S}. \qquad (14)$$

To calculate S/S_{12} value, we use the elementary cell model, according to which the properties of each PFM element are determined by the elementary cell parameters in the form of a parallelepiped selected from the regular laying of 8 powder particles joined by interparticle contacts [9]. Then the value of S_{12} within such a cell varies from a minimum value equal to:

$$S_{12\min} = D_1^2 - \frac{\pi}{4} D_1^2, \qquad (15)$$

to the maximum value:

$$S_{12\max} = D_1^2. \qquad (16)$$

To calculate S_{12}, we take the average value of this quantity:

$$S_{12cp} = D_1^2 - \frac{\pi}{8} D_1^2. \qquad (17)$$

Given that:

$$S = D_1^2, \qquad (18)$$

then:

$$\frac{S}{S_{12}} = \frac{1}{1 - \dfrac{\pi}{8}}. \qquad (19)$$

The resulted equations (11), (14) and (15) make it possible to calculate the coefficient of permeability of a two-layer PFM taking into account the overlap area between layers, knowing the values of the coefficients of permeability of the substrate and the fine layer.

Table 1 shows the results of calculations of the PFM permeability coefficients for two-layer materials, the structures of which are shown in Figures 1 and 2, and their experimental values. The values of the permeability coefficients of the substrate and the fine layer, as well as the thickness of the overlap layer are determined experimentally.

Table 1

The calculated and experimental values of the permeability coefficients of two-layer PFMs

Initial material	Powder particle size, μm		Thickness, mm			Coefficient of permeability, m², ×10^{13}				
	Sub-strates	of fine layer	Sub-strates	of overlap area	of fine layer	Experimental values			The calculated value of two-layer PFM	
						Sub-strates	of fine layer	of two-layer PFM	with over-lap area	without overlap area
Titanium powder	minus 1000 +400	minus 100 +40	3	1,0	1,5	180,0	7,0	14,2	11,8	23,3
Copper powder	minus 315 +200	minus 80 +40	1,7	0,3	1,0	70,0	2,16	4,17	4,19	6,1

The analysis of the data presented in the table shows, firstly, a satisfactory coincidence of the calculated and experimental data and, secondly, a significant negative effect of the overlap area on the permeability of two-layer PFMs: its presence reduces the permeability by 1.46 – 1.98 times when comparing the resulted calculations and by 1.46 – 1.64 times when comparing the results of calculations with experimental values. This effect can be reduced by reducing the thickness of the fine layer.

Figure 3 shows the calculated dependences of the permeability coefficients of two-layer PFMs based on titanium (1) and copper (2) powders on the layer thickness of fine powder at a constant total thickness of the porous material, which, when compared with the calculated data presented in the table, indicate that, for example, a three-fold decrease in the thickness of the fine layer leads to an increase in the permeability of PFM based on titanium by 1.4 times, and based on copper – by 1.8 times. In the second case, the permeability coefficient of the material is higher than the value of the permeability coefficient of PFM with the initial thickness of the fine layer, calculated without taking into account the overlap area.

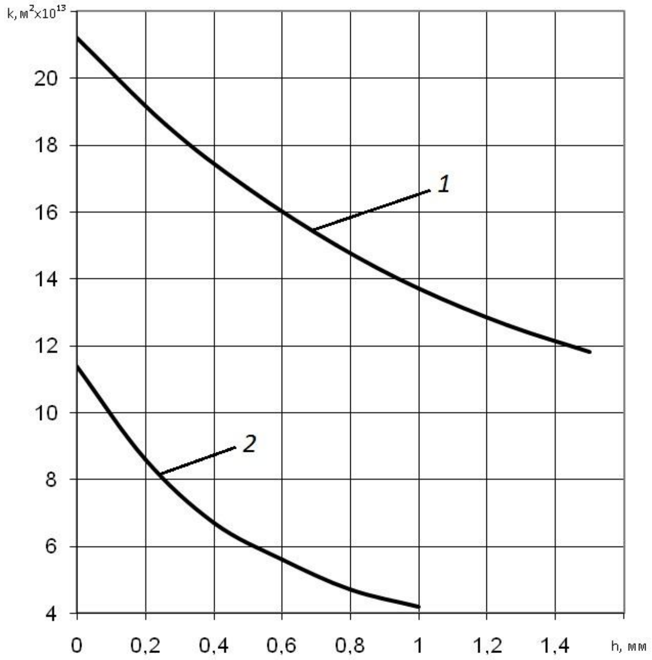

Fig. 3 The dependence of the permeability coefficient of two-layer PFM on the thickness of the fine layer:
1 – titanium-based PFM, 2 – copper-based PFM

4. Conclusion

With reference to the abovementioned, it is possible to state that the quotation obtained for calculating the permeability coefficient of two-layer PFMs with the overlap area satisfactorily agrees with experimental data. The negative effect of this area on the permeability coefficient of the porous material is shown, which, due to its presence, decreases by more than 1.46 times. It was found that this effect can be compensated by a decrease in the fine powder layer.

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