# STRUCTURE AND HYDRAULIC RESISTANCE OF A PACKED LAYER IN ANNULAR CHANNELS

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*Sphere packings in annular channels with a structure typical for a packed layer and minimum hydraulic resistances are investigated. Relations are obtained to calculate the resistance coefficient of annular packings in longitudinal flows.*

Packed-layer apparatuses are used as catalytic reactors, adsorbers, filters, and high-temperature heat exchangers in power engineering [1, 2]. When used in heat exchangers, the effectiveness of infinite packings of spheres ($D >> d$) is limited by the radial nonuniformity of the velocity field, and in the case of an axial heat-carrier flow, by high hydraulic resistance [1, 3].

One of the trends in development of heat exchangers in which the advantages of a packed layer are retained and the influence of the above adverse factors is reduced to minimum is their construction in the form of a few annular channels packed with spheres and with axial filtration of the heat carrier through the packing [4, 5]. It is established experimentally [5] that in annual channels with a width commensurable with the sphere diameter, packings of a specific structure are formed, which leads to different dependences of the resistance coefficient and porosity of the packing on geometric parameters. The range of the channel width-to-sphere diameter ratio in which the specific features of the structure and hydrodynamics of thin annular packings [5] are considerably manifested is a concern of the present study.

Here, we provide experimentally obtained dependences of the porosity and hydraulic resistance of a packed layer on the geometric parameters of annular channels.

The structure of the sphere packings was investigated by the method of section treatment. Annular channels made of acrylic plastic and packed with lead spheres were filled with epoxy adhesive, and the hardened packing was cut in different, with respect to its height, sections for the purpose of its structure investigation. The porosity of the packings was measured by the volumetric-weight method. Hydrodynamics investigations were accomplished on a water stand at Reynolds numbers of from 1000 to 12,000 with an isothermal heat-carrier flow. The water flow rate was measured by a vortex-type flow transducer, and the pressure differential across the packing, by differential pressure gauges. The results of the experimental studies were processed in terms of a capillary flow model for a packed layer [1].

The experimental sections in which porosity and hydraulic resistance were measured represented annular channels formed by two coaxial cylindrical walls and filled with a monodisperse sphere packing. In the experiments, use was made of spheres with a diameter $d$ of 3, 4, 4.763, and 6 mm. Investigations were carried out on five experimental sections with different outer diameters: $D = 25$, 32, 36, 42, and 46 mm ($z = 4.17-15.3$). Detachable inner displacers in combination with the sphere diameters of the packing provided a channel width-to-sphere diameter ratio of $k = 1.03-3$. Holes for pressure taps were made at a distance of no less than $10d$ from the packing ends and were arranged uniformly over the circumference. To avoid overlapping of the holes by packing spheres and to average the static pressure with respect to the layer section, they were paired and integrated into a common collector. The height of sphere packing at which the pressure differential was measured was greater than $100d$.

Geometric similarity of annular channels packed with spheres is determined by the parameters $k = (D - D_{\text{in}})/2d$ and $z = D/d$. The influence of the parameter $z$ on the structure of the annular packing of spheres is

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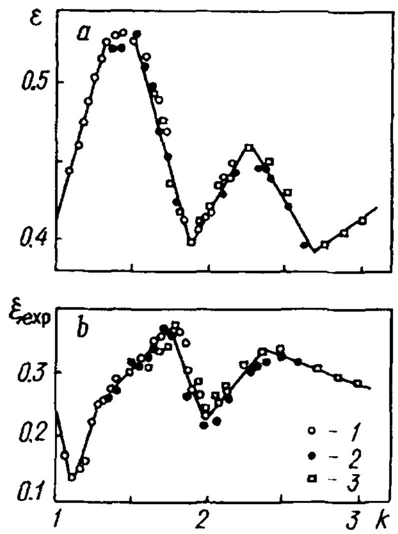


Fig. 1. Porosity of packed layer (a) and hydraulic resistance coefficient of sphere packings (Re = 8000) (b) as functions of annular channel width: 1) $z$ = 6.83; 2) 8.61; 3) 10.25.

most pronounced at $k = 1$, which is manifested in nonuniform distribution of the free flow section at the inner and outer walls of the annular channel. The latter will exert an influence on heat transfer in the layer, in particular, on the local coefficient of heat transfer from a sphere. The difference between the diameters of the outer and inner enclosing walls of annular packings is responsible for the characteristic structural features of the packed layer. In channels whose width is commensurable with the sphere diameter, regular packings are formed with an annular sphere layer being located only near the outer channel wall, while at the inner wall a flow area in the form of straight-through channels with the cross-section periodically changing relative to the packing height and not blocked by spheres is observed. An increase in the annular channel width ($k > 1.15$) leads to destruction of the regular packing and formation of local structural inhomogeneities of the sphere layer. In this case, the porosity of the sphere packing increases and reaches its maximum at $k \approx 1.43$. The maximum value $\varepsilon \approx 0.53$ is retained in a small range of $k = 1.43-1.5$ (Fig. 1a). Next, the layer porosities decrease due to regularization up to formation of a two-row packing of spheres arranged over the channel width at $k \approx 1.88$. Destruction of the two-row packing at $k > 1.9$ causes an increase in the sphere layer porosity, and for packings with $k > 2.25$, the layer again undergoes regularization reduction of porosity. In annular channels with $k \approx 2.7$ there is observed a regular three-row packing of spheres. Here, the sphere layer porosity decreases and reaches a value close to that in the case of infinite packings. Porosity fluctuations of the sphere layer attenuate with increasing width of the annular channel, since the influence of the enclosing walls on the structure of the packing decreases with increasing $k$ (Fig. 1a). Proceeding from the behavior of the $\varepsilon$ versus $k$ graph, for the investigated annular packings in the range $1 < k \leq 3$ five dependences of porosity on $k$ can be written in the form:

$$\varepsilon = ak^{f}. \tag{1}$$

The coefficients (a) and (f) in expression (1) for the indicated ranges of $k$ are given in Table 1. As in the case of single-row annular packings [5], no pronounced influence of $z$ on the hydrodynamics and porosity of the sphere layer is found in the investigated ranges of $k$ and $z$; therefore, in the present work we have not generalized the experimental data on $z$.

In generalizing the experimental data, the hydraulic resistance coefficient and Reynolds number were determined by the formulas

$$\xi = \frac{\varepsilon^3}{3(1-\varepsilon)} \frac{d}{H} \frac{\Delta P}{\rho v^2}, \quad \mathrm{Re} = \frac{2}{3(1-\varepsilon)} \frac{vd}{\nu}. \tag{2}$$

TABLE 1. Values of the Constants in Correlation (1)

| $k$ | $a$ | $f$ |
|---|---|---|
| $1 < k < 1.40$ | 0.424 | 0.716 |
| $1.50 < k \le 1.88$ | 0.859 | −1.181 |
| $1.88 \le k \le 2.25$ | 0.248 | 0.763 |
| $2.25 \le k \le 2.70$ | 0.934 | −0.862 |
| $2.70 \le k \le 3$ | 0.245 | 0.482 |

TABLE 2. Values of the Constants in Correlation (3)

| $k$ | c | $m$ | $n$ |
|---|---|---|---|
| $1 < k \le 1.15$ | 1.425 | −0.19 | −5.236 |
| $1.15 \le k \le 1.29$ | 0.290 | −0.19 | 6.126 |
| $1.29 \le k \le 1.82$ | 1.006 | −0.19 | 1.233 |
| $1.82 \le k \le 2.0$ | 32.11 | −0.19 | −4.566 |
| $2.0 \le k \le 2.5$ | 0.436 | −0.19 | 1.619 |
| $2.5 \le k \le 3$ | 3.751 | −0.19 | −0.753 |

The thermophysical parameters $\rho$ and $\nu$ entering expression (2) were chosen according to the temperature of the incident heat-carrier flow.

The behavior of the dependence of the resistance coefficient of the sphere packing at Re = 8000 on the width of the annular channel (Fig. 1b) obtained by processing of experimental data using Eqs. (2) can be interpreted as follows. An abrupt decrease in hydraulic resistance in the interval $1 < k < 1.15$ is caused by the formation of one-row packing with a free flow area near the inner wall of the annular channel, which increases with $k$. Destruction of the regular packing at $k > 1.15$ leads to an increase in hydraulic resistance despite the abrupt increase of porosity (Fig. 1a), since the flow area of annular channels is more completely screened by spheres. At $k > 1.43$, the behavior of the $\xi$ versus $k$ curve changes due to regularization of the sphere layer in annular channels and the formation of two-row packing at $k \approx 1.8$. The decrease in hydraulic resistance in the range $k = 1.82-2.0$ is explained by an increased free flow area near the annular channel walls without failure of the two-row packing. Screening of the flow area by spheres upon the failure of two-row packing at $k > 2$ results in an increase of the hydraulic resistance of annular packings in the interval $k = 2.0-2.5$. A further increase in the width of annular channels ($k > 2.5$) causes a decrease in the resistance coefficient. Similarly to porosity, $\xi$ fluctuations attenuate with increasing width of the annular channel; however, the form of the dependence and the $k$ ranges for minimum and maximum $\varepsilon$ and $\xi$ do not coincide.

Annular packings of spheres in the range $1 < k \le 3$ show the same behavior of the resistance coefficient as a function of the Reynolds number: in Eqs. (3) the exponent for Re is $m = -0.19$ (Table 2), as in the case of the one-row packings in annular channels [5]. For the all investigated packings ($k \le 3$) similarity is reached at Re $\ge 8000$, which testifies to a steady-state turbulent flow in the layer and is also consistent with results from [5]. Variation of the parameter $z$ only insiginificantly changes the hydraulic resistance of annular packings in the investigated $k$ and Re ranges. It is impossible to correlate experimental data on $\xi$ by a single relation, since small changes in $k$ entail an abrupt change both in the value and in the behavior of the hydraulic resistance coefficient (Fig. 1b). In generalizing the results to qualitatively represent $\xi$ as a function of $k$, six ranges of the parameter $k$ have been adopted in which the hydraulic resistance coefficient, geometric parameter $k$, and Reynolds number are related by power-law dependences of the type:

$$\xi = c\,\mathrm{Re}^{m} k^{n} . \tag{3}$$

The values of $c$, $m$, $n$ for the indicated ranges of $k$ in Eq. (3) are given in Table 2. Experimental data on $\xi$ and porosity are correlated by expressions (1) and (3) with an accuracy of 5%.

The experiments conducted have revealed that different packing structures can be formed in annular channels, depending on the ratio of the annular channel width-to-sphere diameter: regular sphere packings near the outer wall with a free flow area at the inner wall of an annular channel and irregular packings. The ranges of $k$ are experimentally determined within which sphere packings in annular channels have minimum hydraulic resistance. Depending on the $k$ values in the indicated intervals, the hydraulic resistance coefficient of annular packings decreases by a factor of 1.5–3.0. The revealed structures of annular packings with minimum hydraulic resistance can be used in developing new high-efficiency heat and mass exchangers.

## NOTATON

$d$, sphere diameter, m; $D$, $D_{\mathrm{in}}$, outer and inner diameter of the annular channel, respectively, m; $k$ and $z$, geometric parameters; $H$, height of the sphere packing, m; $\Delta P$, pressure differential across the packing, Pa; $v$, flow velocity, m/sec; $\xi$, hydraulic resistance coefficient; $\varepsilon$, packing porosity; $\rho$, heat-carrier density, kg/m$^3$; Re, Reynolds number; $\nu$, kinematic viscosity, m$^2$/sec.

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