# EFFECT OF PARTICLE SIZE ON THE AVERAGE HEAT-TRANSFER RATE FROM A CYLINDER IN A LIQUID-PENETRATED GRANULAR BED

**V. V. Baluev and A. I. Rzaev**

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*Experimental results on the average heat transfer from a cylinder in a liquid-penetrated granular bed are presented and the dependence of the heat-transfer rate on the particle size in the bed is found.*

Data on heat transfer of bodies submerged in a fixed liquid-penetrated granular bed are important for the development of efficient catalytic and helium reactors and hydrogen accumulators based on porous intermetallics. At present there are few reports on the problem. The number of theoretical papers [1-3] on heat transfer in a flow around cylindrical bodies whose dimensions essentially exceed the particle size and experimental publications on local heat-transfer rate from cylindrical heat-transfer elements in a granular bed [4, 5] are scanty. There are almost no reports on the average heat transfer of a cylinder in a granular bed, although such information is important too.

The paper presents experimental results on the effect of the particle size in a granular bed on the average heat-transfer rate from a cylinder submerged in a liquid-penetrated granular bed.

Distilled water circulating, with the aid of a pump, through a closed loop, consisting of a rectangular working section, 0.3 × 0.3 m area and 0.4 m length, filled with a fixed granular bed of glass spheres, 3 and 8 mm in diameter, or river sand with a mean particle size of 0.5 mm was used as a penetrating liquid.

The granular bed was fixed by metal grids with a controlled vertical position. The flow rate through the section was controlled by valves and measured by a specially graduated orifice plate. The water temperature at the working section inlet was maintained at 30-35°C and measured by a copper–constantan thermocouple. The longitudinal pressure drop in the working section was measured by an inclined-tube micromanometer.

In the center of the granular filling a cylindrical probe, $D = 49$ mm, was installed. It consisted of a central part made of copper, 100 mm long, which simulated an isothermal cylinder in a transverse flow of penetrating water and two lateral pieces made of fabric-based laminate, which served as thermal and electrical insulators and were packed in pipes with glands mounted on the side surfaces of the working section.

The average peripheral heat-transfer coefficients of the cylinder were measured as follows. Along the cylindrical probe axis a through hole was drilled, 20 mm in diameter, where a Ni–Cr alloy electric heater enclosed in a quartz tube was installed and over the cylindrical surface grooves were made with copper–constantan thermocouples placed in them, which were caulked in flush with the cylindrical surface of the probe. The grooves were filled with Wood alloy, and the copper probe surface was finished. Six thermocouples were used in the measurements. All the thermocouple readings were checked with a vacuum tube millivoltmeter.

The heater output was controlled by a laboratory transformer, the current through the heater and pressure drop were measured by an ammeter and a mirror scale voltmeter, 0.5 accuracy class.

The input power of the heater varied depending on the water flow rate to provide a temperature difference of about 10-15°C between the cylinder and the bed in order to exclude the free convection effect and to maintain a nearly constant temperature of the cylinder surface.

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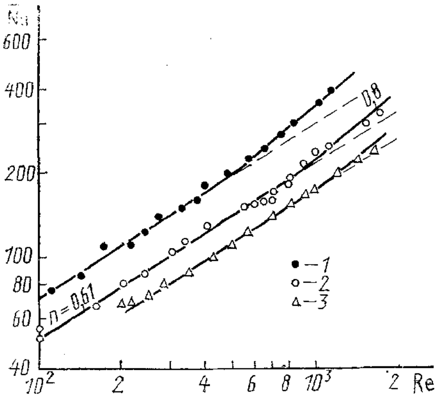

Fig. 1. Average heat transfer from the cylinder versus the Reynolds number for different particle diameters: 1) d = 0.5 mm; 2) 3.0 mm; 3) 8.0 mm.

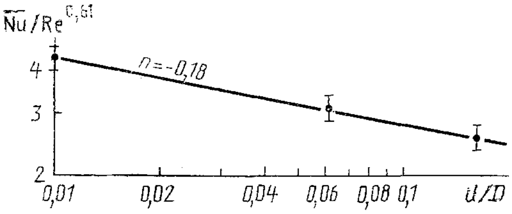

Fig. 2. Dependence of the average heat transfer from a cylinder on d/D.

The experimental method included a preliminary determination of the domain of validity of Darcy's quadratic filtration law with different filling particle sizes. To do this, the pressure drop was measured in the water-penetrated bed, and from the water volume flow rate and the cross-sectional area of the working section the flow velocity $U_\infty$ was determined and the relation $\Delta P = f(U_\infty)$ was plotted for three diameters of spherical filling. For a bed with d = 0.5 mm the curve was linear up to a velocity of 0.07 m/sec and up to 0.08 and 0.13 m/sec for beds with d = 3.0 mm and 8.0 mm. The respective Reynolds numbers, calculated with the probe diameter, amounted to 500-800 [6].

The average heat-transfer coefficients from the cylinder were found as follows:

$$\bar{\alpha} = \frac{V_h I_h}{S_c(\bar{t}_{cs} - t_\infty)}, \quad W/(m^2\cdot K) \qquad (1)$$

where $S_c = \pi D l$; $\bar{t}_{cs} = \Sigma^n t_{cs}/n$ is the average temperature of the cylinder surface determined from the readings of six thermocouples, °C.

The experimental data on average heat transfer are given in Fig. 1 as a plot of Nu = f(Re). The graph shows that, depending on the filling particle diameter at Re < 500-800 the experimental data lie along the generalizing curves $Nu = cRe^m$, where m = 0.61. However, at large Re all three curves have a distinct bend and the degree of the Re number effect is m = 0.8, which approximately corresponds to the boundary of validity of Darcy's linear filtration law found earlier for each particle size of the granular bed. A more rapid increase of the average heat-transfer rate at high Reynolds numbers may probably be ascribed to the vortex flow structure at the front point of the cylinder and corresponds to a flow with a local maximum at that point [3].

One can also see from Fig. 1 that the experimental Nu values scatter with different sphere sizes, and as the particle diameter increases the average heat-transfer rate diminishes over the whole Re range. This may be explained by the fact that with different particle sizes the heat conduction of the solid skeleton of the bed decreases in different ways, especially near the cylinder wall. It should be also noted that for internal heat transfer (heat transfer from a cylindrical tube to a granular bed packed in it) investigated in [7], the dependence of Nu on the parameter D/d, i.e., on the particle size, was inverse.

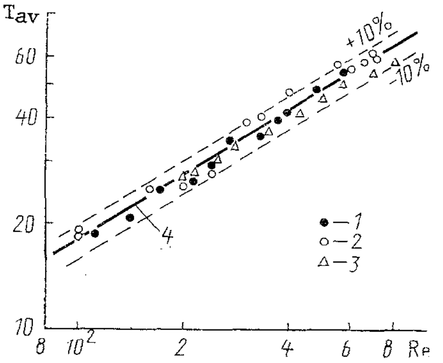

Fig. 3. Generalization of experimental average heat transfer in liquid-penetrated granular beds: 1-3) (see Fig. 10; 4) Eq. (2). $T_{av} = [Nu] \times [Pr_{liq}{}^{0.33}(Pr_{liq}/Pr_w)^{0.25}(d/D)^{-0.18}]^{-1}$.

Further analysis in this study was performed for the data following the linear filtration law as the relation Nu = (Re, d/D, Pr). The plot of $Nu/Re^{0.61} = f(d/D)$ is presented in Fig. 2. It can be seen that with a scatter within ±10% $Nu \sim (d/D)^n$ for all the experimental findings, and the degree of the effect of d/D on the average heat-transfer intensity is $n = -0.18$. The effect of physical properties on convective heat transfer in the range of Re = 100-800 was included by the 0.33th power of Pr [8].

Thus, the data on the average heat transfer from a cylinder submerged in a fixed liquid-penetrated granular bed in the range of Reynolds numbers studied with a scatter within ±10%, shown in Fig. 3, are located near the averaging line which can be described by the following dimensionless equation:

$$\overline{Nu} = 1{,}08\,(d/D)^{0,18}\,Re^{0,61}\,Pr^{0,33}\,(Pr_{liq}/Pr_w)^{0,25}. \tag{2}$$

The present results are important for practical estimation and design of catalytic reactors.

## NOTATION

d, particle diameter in a granular bed; D, cylindrical diameter; $V_h$, heater voltage; $I_h$, heater current; $S_c$, cylindrical surface area; $t_{cs}$, $t_\infty$, cylindrical surface and penetrating liquid temperatures; $U_\infty$, penetrating liquid velocity; $\Delta P$, pressure drop in the granular bed; $\bar{\alpha}$, average heat-transfer coefficient: $Nu = \bar{\alpha}D/\lambda$, average Nusselt number; $Re = U_\infty D/\nu$, Reynolds number for penetrating liquid; $\lambda$, $\nu$, thermal conductivity and viscosity of the penetrating liquid; $Pr_w$, $Pr_{liq}$, Prandtl number determined from the cylindrical surface and liquid flow temperatures.

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