STATISTICAL CHARACTERISTICS OF CONVECTIVE EXCHANGE IN A STATIONARY GRANULAR BED

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A statistical investigation of local coefficients of convective exchange in a stationary granular bed is made in the range of Re_e = 30-800.

The main peculiarity of flows in porous media is their statistical character [1]. The hydrodynamic environment in the free volume of a stationary granular bed (SGB) was investigated earlier [2] using methods of stream visualization. Flow-through and nonflow-through zones of free volume having a continuously deforming, pulsating boundary between them, were revealed at the scales of a grain.

In a disorderly charge, the nonflow-through zones located in the vicinity of points of contact between particles are oriented in different ways relative to the flow-through zones, and, as a consequence, in them the convective exchange between the stream and the solid surface can differ unpredictably from the mean value, especially in the region of transitional Reynolds numbers Re = 30-800. The data on the measurement of local velocities in an SGB presented in [3] also indicate random velocity fluctuations over a cross-section of a charge, determined by the structure of the medium. The combination of these hydrodynamic effects must result in random fluctuations of the coefficient of exchange between the stream and individual particles of the SGB. Also rather obvious is the fact that the influence of these effects will not be additive, so that it does not seem possible to predict the behavior of the exchange coefficients on the basis of the available information [2, 3]. We also note that both the first and the second mechanisms are random not in themselves, but as a consequence of the randomness of the SGB structure, i.e., they are determined by the deviations of porosity in it.

The present paper is devoted to an experimental investigation of the distribution of local coefficients of convective exchange in an SGB in the range of Reynolds numbers Re_e = 30-800, averaged at a scale on the order of the diameter of a ball. The number Re_e is connected with the number Re by the relation $Re_e = 2Re/3(1 - \varepsilon)$.

To run the experiments we used the mass-exchange method, enabling us to isolate the convective component of exchange in pure form. For correctness of the averaging, we chose a cylindrical fragment of a ball charge with a diameter of 13.3 ball diameters and a height of 10 diameters. The procedure is based on the physical absorption of a radioactive marker (UF_6), introduced into the carrier-gas (argon) stream, on the surface of metal balls. A diagram of the apparatus is presented in Fig. 1.

An argon stream, into the central part of which the radioactive marker was ejected along the main stream, was pumped vertically downward through a bed of steel balls 3 located on a brass screen 4 with a mesh of $1\cdot10^{-3}$ m (wire diameter $0.2\cdot10^{-3}$ m). The mixture passed through the ball bed, part of the marker was absorbed on its surface, and then it left the experimental channel. Equalizing grids and a special nozzle were used to assume a uniform argon-velocity profile at the entrance to the bed. The uniformity of the UF_6 distribution at the entrance to the bed was monitored by measuring the α activity over the radius of the entrance screen 2, and its uniformity was demonstrated. The argon and UF_6 flow rates were measured with diaphragms 1 and 6. The boiling temperature of uranium hexafloride, a tank of which was placed in the water bath 9, is 56.4°C. The entire channel for supplying the marker to the experimental channel was built of Teflon and preventilated with hot (70-90°) argon. The ejection time was chosen with allowance for the sensitivity of the method of measuring the absorbed mass and assured constancy of the precipitation rate, while the concentration of marker in the stream was chosen with allowance for the least disturbance of the stream. After the blow-through ended, the bed was taken apart, the coordinates of the individual

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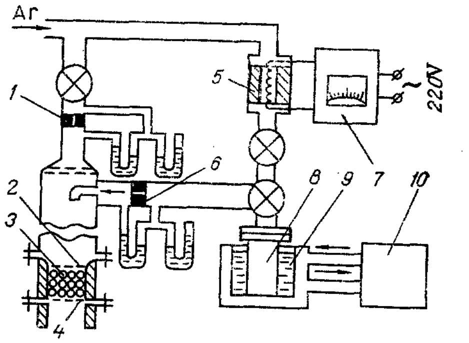

Fig. 1

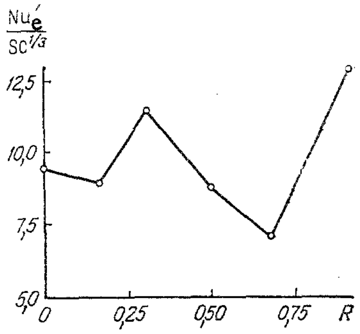

Fig. 2

Fig. 1. Diagram of the apparatus: 1, 6) flow-meter diaphragms; 2, 4) screens; 3) ball bed; 5) heater; 7) autotransformer; 8) tank containing UF_6; 9) water bath; 10) thermostat.

Fig. 2. Distribution of the mass-exchange coefficients over the radius of the bed (Re_e = 195; x/L = 0.5).

balls were recorded, and the absorbed mass Δm was measured. For this, the ball under investigation was treated with 0.1 N nitric acid, the uranium went into solution from the surface, and then its mass was determined by the internal-scintillator method.

Some parameters of the apparatus and test modes: ball diameter d = $(2.5; 4.5)\cdot 10^{-3}$; bed height L = $(2.5; 4.5)\cdot 10^{-2}$ m; range of Reynolds numbers Re_e = 30-800; pumping time τ = 30-60 sec; UF_6 concentration in argon $c_0 = (1\text{-}5)\cdot 10^{-4}$ kg/m³; charge porosity ε = 0.38-0.40.

After each blow-through in the experiments, 60-100 measurements were made over the volume of the bed. With allowance for the constancy of the absorption rate (for this the concentration of uranium hexafloride in the stream far exceeded the concentration at the solid surface, i.e., the condition $c_0 \gg c_s$ was assured), the mass-transfer coefficient was found from the formula $\beta = \Delta m/S\tau c_0$. Then we calculated the diffusional Nusselt number,

$$Nu_e' = \frac{2\varepsilon}{3(1-\varepsilon)} \frac{\beta d}{D},$$

where D is the coefficient of diffusion of UF_6 in argon. The error in determining Nu_e' did not exceed 15% for $Re_e \geq 300$.

The Nusselt number averaged over the bed volume has the following dependence on the Reynolds number:

Re_e	30	45	50	195	508	783
$\overline{Nu_e'}/Sc^{1/3}$	3,56	4,10	4,91	10,1	19,8	25,5

The departure of our data from the generalizing results of many investigators of the function recommended in [4], $Nu_e/Pr^{1/3} = 0.395Re_e^{0.64}$, did not exceed 12%.

The distribution of the complex $Nu_e'/Sc^{1/3}$ over the radius of the bed has a random, sawtooth character (see Fig. 2). In computing Nu_e' we used the data of [5], averaged within the respective annular zones of width d, which enabled us to reduce the averaging of the coefficient of convective exchange and the porosity to a single scale. It is seen that the function $Nu_e'/Sc^{1/3}(R)$ has a random and nonmonotonic character.

In Fig. 3 we give the statistical distribution of the Nusselt number for the same value Re_e = 195; the total number of points is l = 72. The relative mean-square deviation for this distribution,

$$\delta_{Nu_e'} = \frac{\sigma_{Nu_e'}}{\overline{Nu_e'}} \frac{1}{\overline{Nu_e'}} \sqrt{\left[\sum_{i=1}^{l} (Nu_{ei}' - \overline{Nu_e'})^2\right] / l}$$

was 23%. In the calculations we excluded a boundary region of width 2d, two layers of balls at the entrance to the bed, and one at the exit. The normal probability distribution is given in the same figure. It is seen that at individual points the mass-transfer coefficients differ from the mean by more than a factor of two. The histogram is not symmetrical, which is probably a consequence of the asymmetry in the departure of the maximum (ε = 0.476) and minimum (ε = 0.26) possible porosities in a bed of single balls from the mean (ε = 0.39) [7].

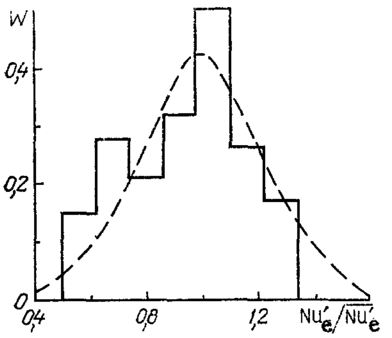

Fig. 3

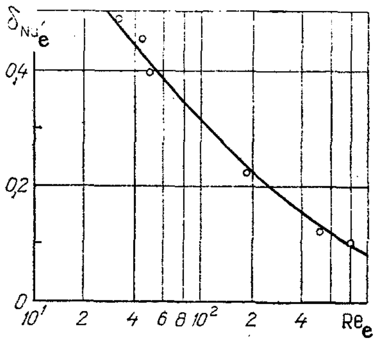

Fig. 4

Fig. 3. Histogram of probability density for the exchange coefficients over the radius of the bed (Re_e = 195; x/L = 0.5).

Fig. 4. Mean-square deviation of the exchange coefficients as a function of the Reynolds number.

On the basis of the data obtained, we can presume that the actual Nusselt number is the sum of the mean and "pulsation" numbers. Then the mean-square deviation, normalized to Nu_e', represents a certain analog of turbulent exchange. We note that, in the present case, we are dealing with random deviations in the exchange coefficients, determined by the deviations of porosity and structure of the SGB. In essence, the additional convective transfer due to the complex mechanism of motion of the fluid in the pore space, predicted by the theory of [6], was recorded experimentally.

From Fig. 4 it follows that the values of the local inhomogeneities of the exchange coefficients fall off rapidly with an increase in Re_e. This is consistent with the decrease in the relative pulsation component of the velocity with an increase in the mean flow-rate velocity, noted earlier [3], and also with the transition to flow of a vortical character in the nonflow-through zones of the free volume of the SGB [2].

In conclusion, we note that similar processes and departures in the exchange coefficients obviously will also be inherent to porous media that are widely popular. Significant departures of the exchange coefficients from the mean, especially in the region of low Reynolds numbers, can serve as the reason for loss of stability in the operation of various engineering devices. The results obtained can pertain, in equal measure, to convective heat exchange, by virtue of the analogy between processes of heat and mass exchange [4].

NOTATION

d, ball diameter; D, molecular diffusion coefficient; c, concentration; L, length of the charge; Δm, absorbed mass; u, filtration rate; β, mass-transfer coefficient; ν, coefficient of kinematic viscosity; ε, porosity; τ, time; S, absorption surface area; R, radius of the charge; δ, relative mean-square deviation; $Re = ud/\nu$, Reynolds number; $Re_e = 2Re/3(1 - \varepsilon)$, equivalent Reynolds number; Nu_e', Nu_e, equivalent diffusional and thermal Nusselt numbers; Pr, Sc, Prandtl and Schmidt numbers.

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