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EXPERIMENTAL STUDY OF CONVECTIVE HEAT TRANSFER IN BEDS OF SPHERES OF DIFFERENT THICKNESS

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Results are presented from an experimental study of convective heat and mass transfer in spherical beds with the number of layers N = 1, 2, 3, 5, and 13 in the Reynolds number range Re_e = 60-1900.

An analysis of the literature data on convective heat and mass transfer in spherical beds showed the following.

1. Nearly all experiments have studied spherical beds with a fairly large number of layers, when the mean heat- and mass-transfer coefficients are independent of bed thickness. At the same time, high-temperature heat exchangers [1] and selective catalytic reactors [2] developed in recent years require that experiments be performed in beds with the number of layers N = 2-5.

2. The distribution of the heat- and mass-transfer coefficients along beds with N > 10 has an inlet section 2-3 sphere layers long, a section of stabilized transfer, and an outlet section 1-2 layers long. Meanwhile, the heat- and mass-transfer coefficients on the stable section are higher than on the inlet and outlet sections [3-5].

The goal of this study is to empirically examine convective transfer in beds in which the inlet and outlet phenomena affect the mean heat- and mass-transfer coefficients.

We used an ion-exchange method in our experiments. A mass-transfer method was chosen as the method of study due to the relative simplicity of its realization and the absence of heat transfer by conduction through the bed. The analogy established between heat- and mass-transfer processes in spherical beds under certain conditions [6-8] makes it possible to use the mass-transfer data to study heat transfer as well. The analogy applies only to the convective components of heat and mass transfer.

Figure 1 shows a diagram of the experimental unit. Solutions of the salts Na_2CO_3 or $UO_2(NO_3)_2$ in distilled water were pumped through a monodisperse bed of grains of ion-exchange

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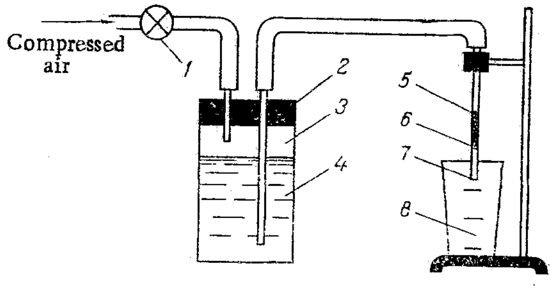

Fig. 1

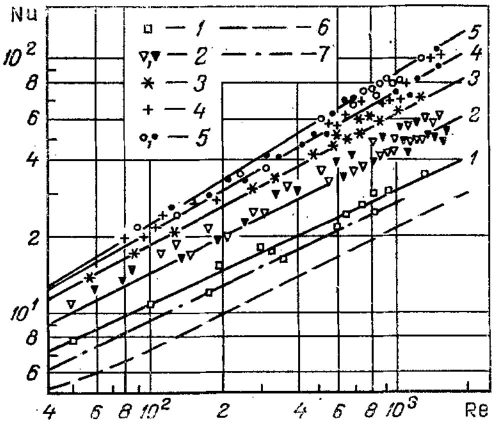

Fig. 2

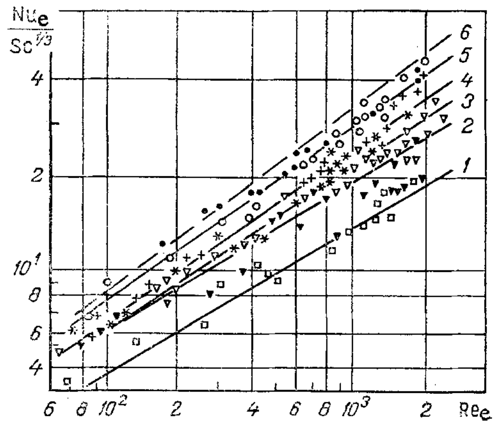

Fig. 3

Fig. 1. Diagram of unit: 1) valve; 2) stopper; 3) cylinder; 4) sorbate solution; 5) ion-exchange region; 6) reference grid; 7) tube; 8) measuring cylinder.

Fig. 2. Dependence of heat and mass transfer on Re: solid lines 1-5) sorption of UO_2^{2+} ions; points: 1) N = 1; 2) 2; 3) 3; 4) 5; 5) 13; dark points 2, 5) sorption of Na^+ with N = 2 and 13, respectively; 6) results from Eq. (2); 7) results from (3). The value of Nu' is plotted off the y axis.

Fig. 3. Dependence of heat and mass transfer on Re_e: 1-5) same as in Fig. 2; 6) from Eq. (4).

resin KU-2. A stereometric exchange of H^+ ions for Na^+ or UO_2^{2+} ions from the solution occurred on the surface of the grains. Uniform and adequately heavy flow of the solution through the bed was achieved by supplying compressed air to the cylinder 3. The monodispersity of the bed was assured by first passing it through a set of screens. The bed 5 was bounded above and below by a brass grid 6 with a mesh $0.5 \cdot 10^{-3}$ m and a wire with a diameter of $1 \cdot 10^{-4}$ m. The porosity of the bed was determined by a volumetric-gravimetric method using VLA-200M analytic balances and is shown in Table 1. The fullness of the first and last layers of spheres (i.e., the absence of large cavities) was checked by inspection. Water flow rate was measured by a volumetric method to within about 1%, while water temperature was measured with a thermometer to within ±0.05°K. Most of the test data was obtained for developed turbulent flow on the hydrodynamic flow stabilization section, which was 50 tube diameters in length. The fact that the data pertained to this section ensured a nearly uniform velocity profile at the inlet to the bed. The valve effect, i.e., an anomalous increase in the pressure drop in the bed with an increase in the Reynolds number Re_e, was not seen in the tests. This can evidently be attributed to the relatively low values of Re_e in the tests.

After the pumping, the resin grains were placed in a 2% solution of sulfuric acid for about 90 min. Here, the resin was converted to its initial ionic form, due to the reversibility of the ion-exchange reaction.

The mass of sodium in samples that were taken was determined by the method of flame photometry [9]. The uranium content was determined by measuring the α activity of the solution and comparing it with the α activity of a standard. The use of two different solutions

TABLE 1. Results of Analysis of Experiments

Parameter	N: 1	2	3	5	13	Remarks
ε	0,52	0,46	0,42	0,39	0,38	Pertains to all lines
a	0,768	0,755	0,674	0,581	0,569	Sorption of UO_2^{2+}
b	0,46	0,50	0,54	0,57	0,58	Sorption of UO_2^{2+}
a	—	1,02	—	—	0,551	Sorption of Na^+
b	—	0,45	—	—	0,57	Sorption of Na^+
a	0,768	0,755	0,674	0,581	0,569	Recommended value
b	0,46	0,50	0,54	0,57	0,58	Recommended value

with different Schmidt numbers and two methods of measuring the mass increased the reliability of the results.

The time of deposition and concentration of the substance being sorbed were chosen with allowance for the sensitivity of the mass measurement method, the capacity of the resin with regard to Na^+ or UO_2^{2+} ions, and the desire to ensure a constant rate of sorption during the experiment. The last condition was reflected by the fact that $c_p \ll c_0$.

Some parameters of the unit and the test regimes follow. Grain diameter $d = 0.775 \cdot 10^{-3}$ m, tube diameter $D_t = 1 \cdot 10^{-2}$ m, pumping time $\tau = 20$-45 sec; concentration of sorbate in solution for Na, $c_0 = 4 \cdot 10^{-2}$ kg/m³, for U, $c_0 = 2 \cdot 10^{-3}$ kg/m³; range of Reynolds numbers $Re_e = 60$-1874; range of Schmidt numbers of the solutions $Sc_{Na_2CO_3} = 804$-978, $Sc_{UO_2(NO_3)_2} = 2300$-2790; number of layers in the bed N = 1, 2, 3, 5, 13; temperature t = 20-24°C.

Considering that the ratio D_t/d was roughly 13, we could ignore the effect of wall phenomena on convective transfer [5, 6]. The sorption kinetics were extradiffusional, and the mass-transfer coefficient was calculated from the formula

$$\beta = \frac{\Delta m}{S C_0 \tau}. \tag{1}$$

Figure 2 shows test results in the form of the function Nu' = f(Re). The solid lines correspond to relations obtained by analyzing the corresponding test data by the least-squares method in the form $Nu' = a_0 Re^{b_0}$. It is apparent that Nu' is heavily dependent on the number of layers. The slope of the straight lines, meanwhile, increases with an increase in bed thickness.

The data on the sorption of Na^+ and UO_2^{2+} agrees well with each other. The figure shows the relation for a single sphere in a free flow recommended by Kutateladze [6, p. 141]:

$$Nu = 2 + 0.03\, Re^{0.54}\, Pr^{1/3} + 0{,}35\, Re^{0.58}\, Pr^{1/3} \tag{2}$$

and the theoretical solution of Pohlhausen for heat transfer with a laminar boundary layer on a flat plate [7], where as the determining velocity the investigators took the velocity in pores $u' = u/\varepsilon$ with a porosity corresponding to the value for a single-layer bed $\varepsilon = 0.52$:

$$Nu = 0.664\, (Re/\varepsilon)^{0.5}\, Pr^{1/3}. \tag{3}$$

It is apparent from Fig. 2 that the experimental data for N = 1 is roughly 1.4 times higher than the relation for a single sphere (2) (dashed line). Comparison with Eq. (3) (dot–dash line) shows that in this case laminar flow about the spheres is disturbed even when N = 1.

The data shown in Fig. 2 pertain to different values of bed porosity. To more correctly compare the data obtained, they were analyzed in the parameters of the internal flow model in [6] (Fig. 3). The solid lines in Fig. 3 also correspond to the relations obtained from a least-squares analysis of the test data in the form $Nu'_e = a Re^{b}_e$. The results of this analysis are shown in Table 1. The deviation of the experimental points from the approximate relations is no greater than 14% in the tests involving UO_2^{2+} sorption and 18% in the Na^+ sorption tests. Comparison of the test data with the relation recommended by Aérov and coauthors [6] for fairly thick beds,

$$Nu'_e/Sc^{1/3} = 0.395\, Re_e^{0.64}, \tag{4}$$

shows satisfactory agreement. The tests with the $UO_2(NO_3)_2$ solution had a smaller measurement error and spread of points, so these results can be recommended for practical use before the other findings.

It is apparent from Fig. 3 and Table 1 that an increase in bed thickness is accompanied by an increase in the slope tangent of the straight lines in the coordinates $\log (Nu'_e/Sc^{1/3}) - \log Re_e$ from 0.46 for a single-layer bed to 0.58 for N = 13. This increase in the slope of the lines is evidently connected with additional agitation of the flow with an increase in bed thickness. Theoretical estimates obtained from the above data show that the heat- and mass-transfer coefficients differ from the values corresponding to an infinite number of layers in the bed by less than the error of the experiments (10-15%) when N > 7-9. This means that inlet and outlet phenomena may affect the mean heat- and mass-transfer coefficients at N < 7-9.

In the above tests the conditions of the heat- and mass-transfer analogy were not violated, and the data obtained apply equally to convective heat transfer in spherical beds

$$Nu'_e/Sc^{1/3} = Nu_e/Pr^{1/3}.$$

NOTATION

C_0, concentration of sorbate in solution; C_p, concentration of sorbate near the surface of a grain; Δm, mass of sorbed substance; S, area of sorption surface; N, number of layers; $Nu = \alpha d/\lambda$, $Nu' = \beta d/D$, thermal and diffusive Nusselt numbers; α, β, heat- and mass-transfer coefficients; λ, thermal conductivity; D, coefficient of interdiffusion of ions H^+ and Na^+ or UO_2^{2+} in water; $Re = Ud/\nu$, Reynolds number; U, filtration velocity; $Sc = \nu/D$, $Pr = \nu/a$, Schmidt and Prandtl numbers; ν, a, kinematic viscosity and diffusivity; $Nu_e = 2\varepsilon Nu/3(1 - \varepsilon)$, equivalent Nusselt number; $Re_e = 2Re/3(1 - \varepsilon)$, equivalent Reynolds number.

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