A STUDY OF THE HEAT TRANSFER IN A MODERATED FLUIDIZATION BED

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Measurements were made to determine the coefficient of heat transfer between a vertical cylindrical surface and a fluidization bed with eight different kinds of fixed packing. The data for the maximum heat transfer coefficient have been generalized into design formulas.

Many applications are found in the chemical industry for fluidization systems where a rather homogeneous structure can be achieved by the use of small-size fixed packings [1-5]. Published information about the heat transfer between a surface and a fluidization bed with many stationary packing elements is very sporadic [6-9]. Essentially, it pertains to a bed of balls, of perforated cylinders [8], and horizontal or vertical tube bundles [6, 7]. A limited amount of data is also available on the rate of heat transfer in a fluidization bed with packing in the form of finned tubes or wire spirals [9].

The object of this study was a systematic analysis of the heat transfer rate at a surface immersed in a moderated fluidization bed with various kinds of fixed packing and, at the same time, to detect the basic trends of the heat transfer process.

We present now the results of our experimental study.

The test apparatus, including a column 300 and 150 mm in diameter, was similar to the one described earlier in [9]. Several kinds of packing were used here, their characteristics as listed in Table 1. The dispersed material was sand d = 0.23 and 0.63 mm, silica gel d = 0.19 mm, corundum d = 0.09 mm, and "spherical" silica gel d = 0.34 and 0.76 mm. The heat transfer between a vertical cylindrical surface and the moderated fluidization bed was measured by the steady-state method with a heater-probe 20 mm in diameter a thorough description of which had been given earlier in [9]. We first measured the power dissipated by the probe as well as the temperature difference between its surface and the bed. From these data we then calculated the heat transfer coefficient with a maximum error not exceeding 3%. In every test the probe was placed at the center of the column. Its lower edge was then 100 mm away from the gas distributor grid. In addition to a smooth cylindrical probe, we had also prepared probes with fins (items 5, 6, 7 in Table 1). The fin cross section was 2 × 20 mm. In these probes the fins were not in contact with the cylindrical part.

Some empirical relation are shown in Fig. 1 for a free and a moderated fluidization bed. They reflect the change in the rate of heat transfer between a fluidization system and a vertical cylindrical surface. The curves for a moderated bed lie below those for a free fluidization bed. An analogous pattern was observed in the tests with other materials and fixed packings. This is probably due to the lower replacement rate of particle "packets" at the heat transfer surface in fluidization beds with small-size packing. As is well known [2], the flow of the solid phase in a fluidization bed depends on the size of the collapsing gas bubbles. The larger the gas bubbles are, the higher is their lift velocity. The gas bubbles are broken up by stationary packing elements immersed in the fluidization bed and the velocity of the circulating solid phase becomes lower at the surface [14], as a result of which the rate of heat transfer in the system also drops somewhat.

The curves in Fig. 1a, b have rather sharp peaks. A further evaluation of test data was to have revealed the trends of the maximum heat transfer rate in the given system. A generalization of the test data

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TABLE 1. Characteristics of the Packings

Kind of packing	Item No.	Diameter, cm	Bundle spacing, mm	Effective dimension, cm	Fraction of volume filled with packing, %
Heap of wire spirals [13]	2 3 4	5,5 2 1		3,0 0,52 0,34	3,2 4,8 7,4
Bundle of vertical tubes with three straight axial fins	5	2	63×63	2,7	8,6
Bundle of vertical tubes with single-cut helical fins, S= 132 mm	6	2	63×63	5,52	7,23
Bundle with double-cut helical fins, S= 132 mm	7	2	63×63	4,5	8,22
Bundle with double-cut helical fins, S= 132 mm	8	2	36×63	2,72	13,5
Packing No. 7. Probe with triple-cut helical fin	9	2	63×63	4,3	8,3

has established that the maximum heat transfer coefficient in a moderated fluidization bed follows the relation

$$\mathrm{Nu}_{\max} = f\,(\mathrm{Ar})^{0.25}, \tag{1}$$

which differs from the well known relation for a free fluidization bed [10, 11] by the exponent of the Archimedes number (0.20 to 0.22).

The graph indicates clearly that the heat transfer coefficient in a moderated bed depends on the kind of packing. The denser the packing is, the lower is the value of $\alpha_{\max}$. A similar trend of this relation was noted in all other tests.

In order to determine the effect of packings, we introduce the parameter (d/l_p). Here l_p characterizes the hydraulic diameter of a fixed packing and is equal to the bed volume per unit of packing surface area.

In Fig. 2 the test data have been evaluated in coordinates

$$\frac{\mathrm{Nu}_{\max}}{\mathrm{Ar}^{0.25}} = f\left(\frac{d}{l_p}\right). \tag{2}$$

On this graph we have plotted the test points for all the kinds of packing and bed material in this study. On the same graph we also show other researchers' test results pertaining to a horizontal close-packed staggered tube bundle 50 mm in diameter [6] and a vertical staggered tube bundle 20 mm in diameter [7], also data from [8] pertaining to the heat transfer from the wall of a 74 mm in diameter column to a bed with spherical packing of elements 6, 14.7, and 19 mm in diameter.

Furthermore, we have also plotted here our test data for a spherical packing.* The tests were performed with a rectangular column $F = 0.032\ \mathrm{m}^2$ in cross section area, where zeolite was fluidized with air in a packing of ceramic balls 15 mm in diameter.

According to Fig. 2, the test points for all the kinds of packing in this study, except the spherical, fit closely about a single straight line. This indicates that the selected effective dimension does reliably characterize small-size packings of diverse designs.

On the basis of the preceding discussion, we recommend the following formula based on a generalization of test data

$$\mathrm{Nu}_{\max} = 0.32\,\mathrm{Ar}^{0.25}\left(\frac{d}{l_p}\right)^{-0.07} \tag{3}$$

* The tests were performed jointly with G. I. Kovenskii.

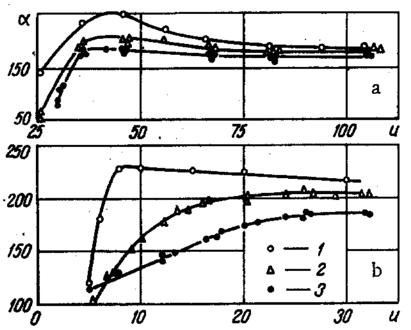

Fig. 1. Heat transfer coefficient α (W/m^2·deg) as a function of the filtration velocity u (cm/sec): (a) sand d = 0.63 mm, (b) spherical silica gel d = 0.34 mm; 1) free bed, 2, 3) with No. 3 and No. 4 packing respectively (see Table 1).

for calculating the maximum coefficient of heat transfer between a moderated fluidization bed and a vertical tubular surface. This relation is valid within the range $90 < Ar < 21{,}850$ and $0.0015 < d/l_p < 0.225$. The maximum dispersion of test values does not exceed 10%.

The test points for spherical packings follow a somewhat different trend and fit another straight line, somewhat below and steeper than the other one. For calculating α_{max} between a vertical tube and a moderated fluidization bed packed with a heap of balls we suggest the formula

$$\mathrm{Nu}_{max} = 0.19\,\mathrm{Ar}^{0.25}\left(\frac{d}{l_p}\right)^{-0.15}. \tag{4}$$

This relation is applicable within the range $100 < Ar < 300$ and $0.020 < d/l_p < 0.07$. Some departure of point 30 from the universal straight line is due to a poor lay of large balls (19 mm in diameter) in a small column (74 mm in diameter).

It is evident, according to Fig. 1, that the heat transfer coefficient approaches its maximum within a wide range of filtration velocities. The trend of the curves here depends on the size fraction of the dispersed material. In the case of relatively large particles (Fig. 1a), the heat transfer coefficient reaches its maximum value fast and then decreases slightly with increasing filtration velocity, until erosion of the bed material begins. In a fluidization bed of smaller particles (Fig. 1b) the heat transfer coefficient increases gradually up to its maximum value. It then remains almost constant over a rather wide range of filtration velocities.

Thus, for a moderated fluidization bed there is a sufficiently wide range of gas filtration velocities where the heat transfer coefficient is almost maximum and constant within 5%.

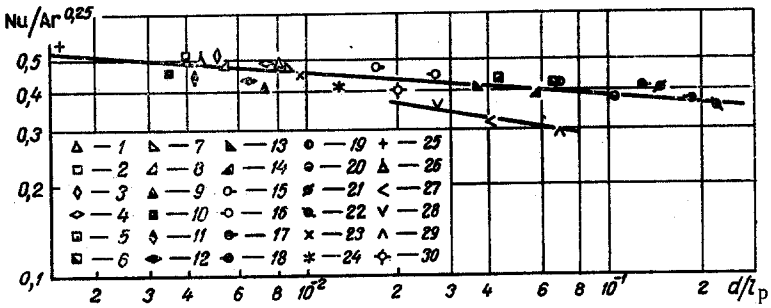

Fig. 2. Universal graph. Dispersed material: sand d = 0.23 mm, curves 1, 2, 3, 4, 5, 6, 7, 8) for packing No. 5, 6, 7, 2, 3, 4, 8, 9 respectively (see Table 1); silica gel d = 0.19 mm, curves 9, 10, 11, 12, 13, 14) for packing No. 5, 6, 7, 2, 3, 4 respectively (see Table 1); corundum d = 0.09 mm, curves 15, 16) for packing No. 3, 4 respectively (see Table 1); sand d = 0.63 mm, curves 17, 18) for packing No. 3, 4 respectively (see Table 1); spherical silica gel d = 0.76 mm, curves 21, 22) for packing No. 3, 4 respectively (see Table 1); curves 23, 24) based on test data in [9]; curves 25, 26) based on test data from [10]; curve 27) for zeolite d = 0.2 mm with packing of balls 15 mm in diameter; curves 28, 29, 30) based on test data in [11].

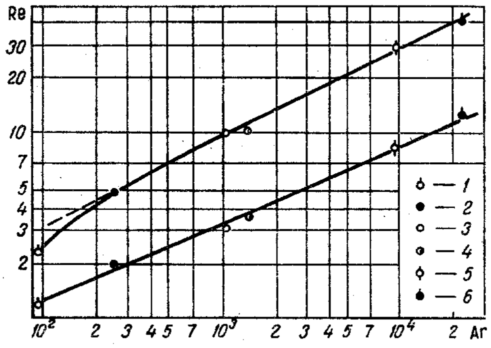

Fig. 3. Range of gas velocities and particle sizes where Nu_{max} is attained: 1, 2, 4, 5, 3, 6) corundum d = 0.09 mm; silica gel d = 0.19 mm; spherical silica gel d = 0.34 and 0.76 mm; sand d = 0.23 and 0.63 mm, respectively.

In the general case, the heat transfer coefficient is a function of three dimensionless groups:

$$Nu = f\left[Ar;\ \frac{d}{l_p};\ Re\right]. \tag{5}$$

From here we find the following conditions for a maximum heat transfer coefficient in a fluidization bed with a packing of any given design:

$$\frac{\partial f}{\partial Re} = 0, \qquad \frac{\partial f}{\partial Ar} = 0 \tag{6}$$

and, consequently, as a function of two variables

$$\varphi(Ar,\ Re) = 0. \tag{7}$$

The boundaries of the field of test points where the heat transfer coefficient is approximately (within 5% accuracy) maximum and constant have been drawn in Fig. 3 in Re, Ar coordinates. The lower boundary marks the beginning of the region where α differs from α_{max} by not more than 5%. The test points fit closely enough on the straight line described by the following empirical equation:

$$Re_p = 0.18\,Ar^{0.42}. \tag{8}$$

The other straight line on the graph represents the upper boundary of the region where the heat transfer coefficient is maximum. It approximately corresponds to the beginning of erosion of the dispersed material. The test curve can be described by the following relation:

$$Re_p = 0.43\,Ar^{0.48}. \tag{9}$$

According to Fig. 3, approximations (8) and (9) generalize our test data, with the dispersion of test values not exceeding 10%.

Thus, our tests have revealed some basic trends in the heat transfer between a vertical cylindrical surface and a moderated fluidization bed. On the basis of these data, we propose formulas (4), (3) for the maximum heat transfer coefficient and formulas (8), (9) for the optimum filtration velocity.

NOTATION

u	is the gas filtration velocity, based on the total bed cross section;
d	is the mean diameter of particles;
l_p	is the characteristic packing dimension;
α	is the heat transfer coefficient;
α_{max}	is the maximum heat transfer coefficient;
S	is the pitch of helical fins.

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