HEAT TRANSFER BETWEEN A SPHERICAL PROBE AND A COUNTERFLOW-VENTED GRAVITY BED

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Experimental results are presented pertaining to the heat transfer between a spherical probe and a dense bed of granular material vented by a rising stream of air.

A study of the heat transfer between walls and a counterflow-vented granular bed is not only of theoretical interest but also of purely practical importance, especially in the case of reactors operating with a moving dense catalyst bed. Nevertheless this problem has not been treated adequately in the literature.

Tests were performed with an apparatus shown schematically in Fig. 1. A counterflow-vented gravity bed was produced in the vertical tube 3100 mm in diameter and 3000 mm long, to the upper part of which granular material (aluminum silicate catalyst pellets $\delta = 3.5$-5.0 mm in size) was continuously fed from tank 1 while air was supplied to its lower part. The bed velocity was regulated by means of interchangeable diaphragms 11 with different hole sizes and placed at the tube exit. An electrically heated spherical probe 25 mm in diameter with a thermal flux sensor attached to its surface was held in place along the tube axis at an 800 mm distance from top section of the tube. The probe design has been described in [5]. From tube 3 the loose material was fed from tank 7 into tank 1 by continuous-flow pneumatic transport. For this purpose, the slider 8 was opened periodically and the material was passed into the intermediate tank 9. After that, the slider was again closed and air was supplied under a pressure of 1.5-2.0 bars.

The mean velocity of the bed was determined by two methods: a) by measuring the flow rate of material through tube 3 during a definite period of time; and b) by directly measuring the velocity of particles at the tube wall. For this purpose, a groove had been cut in the tube, parallel to its axis, into which a strip of Plexiglas was mounted flush with the inside tube surface. The mean velocity of the bed differed from the velocity of particles on the average by 8-12%. The flow rate of venting air was measured with a knife-edge diaphragm which had been precalibrated against a gas meter. In these tests the bed velocity was varied from $0.42 \cdot 10^{-2}$ to $4.32 \cdot 10^{-2}$ m/sec (15-155 m/h) and the air velocity was varied from 0.05 to 0.5 m/sec.

It follows from the differential equations of continuity, motion, energy, and heat transfer, with the boundary conditions and the uniqueness conditions taken into account, that the general critical equation of the steady-state heat transfer between a counterflow-vented gravity bed and a spherical surface is

$$\mathrm{Nu}_{\mathrm{cf}} = f(\mathrm{Pe}_{\mathrm{b}}, \mathrm{Pe}_{\mathrm{f}}\mathrm{Fr}_{\mathrm{b}}, \mathrm{Pr}, d/\delta, (D-d)/2\delta). \qquad (1)$$

For the specific test conditions (uninterrupted bed flow, constant values of d, D, and δ, and bed ventilation with air at a constant temperature) relation (1) becomes

$$\mathrm{Nu}_{\mathrm{cf}} = f_1(\mathrm{Pe}_{\mathrm{b}}, \mathrm{Pe}_{\mathrm{f}}). \qquad (2)$$

The coefficients of local heat transfer were determined directly at the probe surface. The mean coefficient of heat transfer between probe and bed α_{cf} was calculated from the test values of α_{loc} at various attitude angles (between the velocity vector w and the normal to the sphere surface at the point where the thermal flux sensor was attached).

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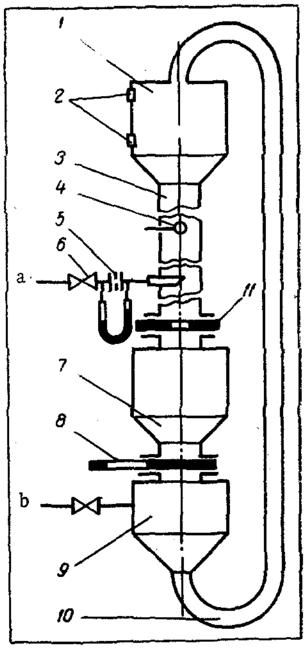

Fig. 1. Schematic diagram of the test stand: 1, 7, 9) tanks; 2) sighting glasses; 3) test segment; 4) probe; 5) diaphragm; 6) valve; 8) gate; 10) slider, stand pipe; 11) limit washer; a) air inlet; b) compressed air.

The test values for the heat transfer between the probe and the counterflow-vented gravity bed at various values of w and u could be generalized by the following relation (Fig. 2):

$$\frac{Nu_{cf}}{Nu_f} = 1 + 1.55\left(\frac{Pe_b}{Pe_f}\right)^{0,32} \qquad (3)$$

Here Nu_{cf}, Nu_f, and Pe_f were referred to the thermophysical properties of the boundary gas layer at the sphere surface at a mean temperature $t = 0.5(t_p + t_b)$, while Pe_b was referred to the thermophysical properties of the bed. The effective thermal conductivity was calculated by the formula suggested in [2]:

$$\lambda_{eff} = 29.7\lambda \lg \frac{0.31\varepsilon + 0.43}{\varepsilon - 0.26}.$$

When calculating the effective thermal conductivity λ_{eff} and thermal diffusivity $a_{eff} = \lambda_{eff}(1 - \varepsilon)\rho_T c_T$, it was assumed that $\varepsilon = 0.4$, $\rho_T = 1300$ kg/m^3, and $c_T = 0.837$ kJ/kg·deg [6]. The second term on the right-hand side of (3) characterizes the additional heat transfer in a counterflow-vented bed above that in a stationary vented bed of granular material which is due to the motion of the bed. Evidently, the increase in Nu_{cf} above N_f will be greater as the filtration velocity decreases relative to the bed velocity. On the basis of a test series at $u = 0$, we have obtained the following relation:

$$Nu_f = 6.6\,Pe_f^{0.47}. \qquad (4)$$

The values of α_f calculated according to (4) agree satisfactorily (within about ±10% discrepancy) with published data on the heat transfer in a stationary bed of granular particles with filtration [1].

Relation (3) is valid for $56 \le Pe_f \le 600$ and $160 \le Pe_b \le 1600$. The dispersion of test points did not exceed ±8%. With d, D, and δ having been held constant, relation (3) does in fact reflect only the effect of the bed velocity and of the filtration velocity and is, in this sense, of a limited scope.

The distribution of α_{loc} over the probe surface at various test conditions is shown in Fig. 3.

When $w = 0$ (probe in an unvented gravity bed), the minimum α_{loc} was observed at the front point of the probe ($\varphi = 0°$). At larger attitude angles α_{loc} increased. Unlike in [4], where the heat transfer between a horizontal tube and an unvented gravity bed was studied, no stagnant prism of particles had built up at the stern of the probe and the maximum α_{loc} was observed at the stern point ($\varphi = \pi$). Apparently, this can be explained by the fact that the particles in our test were larger than in [5]. As the bed velocity was increased, we observed a faster increase in α_{loc} at the stern part of the probe. At the front part α_{loc} varied slightly, which had to do with the separation of particles from the probe surface. When $u = 0$ (filtration through a stationary bed), the maximum α_{loc} was at the front of the probe. The α_{loc} distribution over the probe surface in this case resembled the α_{loc} distribution over the sphere surface and the circular cylinder surface in a laminar stream of pure air [3], with the difference that in a stream of pure air the

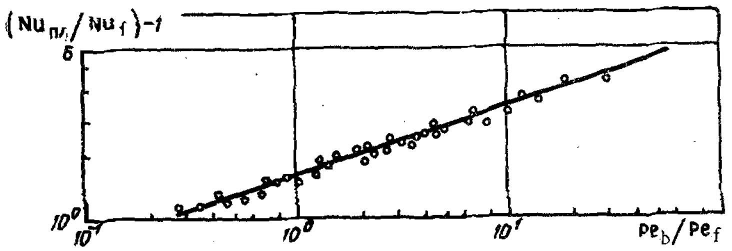

Fig. 2. Generalized relation characterizing the heat transfer between a spherical probe and a counterflow-vented dense gravity bed.

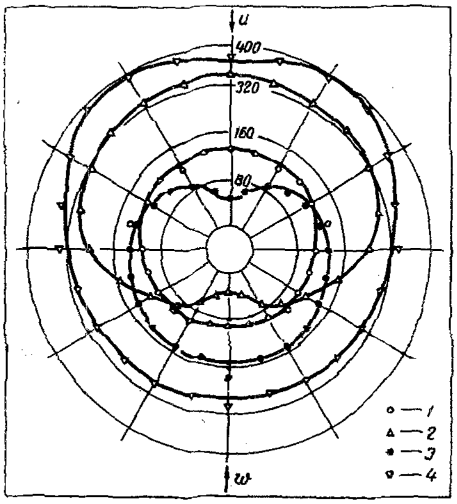

Fig. 3. Distribution of local heat-transfer coefficients α, W/m^2·deg, over the probe surface: 1) unvented gravity bed with $u = 1.2 \cdot 10^{-2}$ m/sec; 2) stationary vented bed with $w = 0.27$ m/sec; 3) counterflow-vented bed with $u = 0.42 \cdot 10^{-2}$ m/sec and $w = 0.05$ m/sec; 4) counterflow-vented bed with $u = 4.32 \cdot 10^{-2}$ m/sec and $w = 0.1$ m/sec.

value of α_{loc} increased stepwise at the stern of the probe. In a vented stationary bed α_{loc} decreased monotonically with increasing φ and the minimum α_{loc} was at the stern point of the probe.

In the counterflow-vented gravity bed the α_{loc} distribution over the probe surface was more uniform than in the unvented and in the stationary bed. It is interesting to note that the point of maximum α_{loc} in the counterflow-vented bed was somewhat displaced from the stern point of the probe. Except in the test series with $u = 0.42 \cdot 10^{-2}$ m/sec, where the α_{loc} distribution over the probe surface was almost uniform, α_{loc} at the stern part of the probe was higher than at the front part. This indicates that in these tests the downward flow of the bed had the predominant effect on the total heat transfer between the probe surface and the counterflow-vented bed of granular material.

NOTATION

a	is the thermal diffusivity;
c	is the specific heat;
d	is the probe diameter;
D	is the tube diameter;
t	is the temperature;
u	is the bed velocity;
w	is the filtration velocity;
α	is the heat-transfer coefficient;
δ	is the grain diameter;
λ	is the thermal conductivity;
ρ	is the density;
ε	is the bed porosity.

Subscripts

p	refers to the probe;
loc	refers to local;
o	refers to initial;

cf	refers to counterflow;
b	refers to bed;
T	refers to material;
f	refers to filtration;
eff	refers to effective.

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