HEAT TRANSFER BETWEEN TUBES OF DIFFERENT SECTIONS AND A STREAM OF GRANULAR MATERIAL

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Results are given of investigations of heat transfer when isolated tubes of different cross sections are washed by a stream of granular material. Equations obtained on the basis of the test data are also presented.

Previous investigations [1, 2] have shown the high efficiency of heat transfer between a tube and a moving granular material and have resulted in various types of heat exchanger being devised and applied in industry for heating and cooling such materials. The same references also note the possibility of using a similar kind of heat exchanger in a number of new thermal installations. It should be remarked that this study was performed mainly with tubes of circular cross section, and the question of the influence of the profile of the tube was left completely untouched. However, analysis of the test data shows that the heat transfer may be considerably enhanced by varying the cross section of the tube because of the improved flow of material over the heat exchange surface, to achieve which the tube section should have an elongated shape in the direction of motion of the material. It was decided, in particular, to check the heat transfer in tubes of elliptical and lenticular section.

The medium chosen for the tests was dry quartz sand with limiting particle sizes of 0–0.4, 0.4–1.0 and 1.0–3.0 mm. The tests were conducted in special equipment, whose construction is described in [1], together with the experimental technique. During the tests the nature of the motion of the granular material around the tube was observed, and measurement was made of the tube surface temperature, the quantity of heat supplied to the calorimeter, and the temperature and velocity of the incident stream.

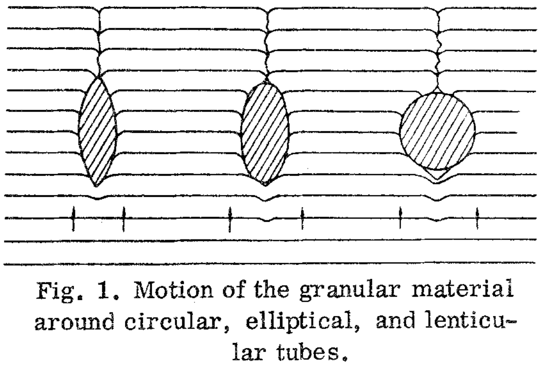

Fig. 1. Motion of the granular material around circular, elliptical, and lenticular tubes.

The data obtained were compared with the results of investigations of the flow of granular material over a tube of circular cross section.

Figure 1 shows schematically the motion of the granular material with grain size up to 0.4 mm. These observations were conducted in equipment with glass walls, through which the motion of the individual colored layers of material could be observed.

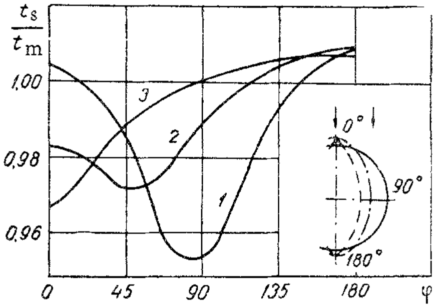

Fig. 2. Wall temperature variation for tubes of different cross section (φ is the angle of rotation, °): 1) circular; 2) elliptical; 3) lenticular.

It may be seen that the manner in which the stream of material flows over circular and elliptical tubes is roughly the same, there being a region of motionless material ahead of the tube, and an air pocket behind it.

The only difference is in the size of these regions, which are considerably less for the elliptical tube than for the circular one.

For the lenticular tube these regions did not appear, and the particles of material were in motion over its whole surface.

The manner in which the stream of granular material washed the tubes may be assessed from the temperature variation over their outer surfaces.

Figure 2 shows the variation of wall temperature of three tubes of different cross section washed by granular material. It may be seen that the form of the wall temperature variation of the elliptical and circular tubes is the same. In particular, the temperature is greater in the front and back parts of the tube, i.e., where the region of motionless material and the air pocket are located, and less in the equatorial part, i.e., where the tube is vigorously washed by the stream.

It will be noted, however, that the surface temperature minimum for the elliptical tube is located closer to the front than for the circular tube, being at an angle of about 45°. In addition, whereas for the circular tube the temperature of the front part is close to that of the back part, for the elliptical tube the front temperature is considerably less than that of the back part. This indicates that the region of motionless material is considerably less for the elliptical than for the circular tube. The air pocket is evidently also less.

Therefore, the part of the surface washed by the stream is greater for the elliptical tube than for the circular one, and so heat transfer is more effective with the former.

It was also established by the tests that whereas for the circular tube the minimum wall temperature moves toward the front of the tube as the velocity of the granular material is increased, for the elliptical tube it remains practically in the same place, at about an angle of 45°. This may be explained by the fact that for the circular tube, the region of motionless material shrinks considerably with increase of flow velocity. For the elliptical tube this region is small and varies little as the flow velocity is increased.

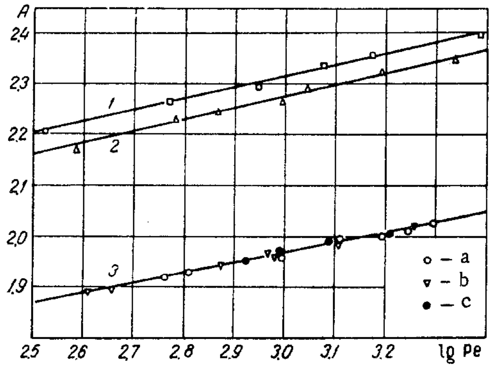

Fig. 3. Parametric relation $A \equiv \lg [10^3 \mathrm{Nu}/(d_t/\delta_m)] = f(\lg \mathrm{Pe})$ for the tubes: 1) lenticular; 2) elliptical; 3) circular; particle sizes up to a) 0.4 mm; b) 0.4–1.0; and c) 1.0–3.0.

Moreover, wall temperature measurements were made for the elliptical tube when washed by granular material of different grain-size composition, the stream velocity being held constant. The measurements showed that the region of motionless material decreased with increase of material particle size, and practically vanished for particles in the range 1 to 3 mm. The air pocket remained unchanged in all cases.

The nature of surface temperature variation for the lenticular tube was somewhat different from both the elliptical and circular tubes. As Fig. 2 shows, the wall temperature for this tube increased continuously around the tube, and we may therefore conclude that neither a region of motionless material nor an air pocket exists for the lenticular tube.

It was also established that as the velocity of the material was increased, the tube wall temperature decreased on the front part, while increasing on the back part. This is apparently due to the fact that, as the stream velocity increases, the material is pressed more densely to the tube wall (the number of particle contacts with the tube surface increases) on the front part, and less densely on the back part. Since the whole of the surface of the lenticular tube is washed by the stream of granular material, it may be supposed that the heat transfer will be more intense for it than for the circular and elliptical tubes.

This hypothesis was confirmed by tests to determine the heat transfer coefficients of tubes of different cross sections with a stream of granular material. It was established, in particular, that as the tube section varies from circular to lenticular, the heat-transfer coefficient increases. Thus, for the same equivalent diameter of the tube, the heat-transfer coefficient for the lenticular tube proved to be roughly twice that of the circular tube.

These tests also allowed us to establish that for a tube of any section profile, the heat transfer coefficient increases with increase in the velocity of the granular material, and that the heat-transfer coefficient depends on the 0.21 power of the stream velocity.

The grain size composition of the material proved to have a great influence on the heat-transfer process. It was shown by tests that, as the particle size of the medium was increased, the heat-transfer coefficient diminished, for tubes of any cross-sectional shape. This is explained by reduction in the number of contacts between the medium and the tube surface.

It was decided to reduce the test results for heat transfer with a solitary tube washed by a stream of dry, granular material in terms of the same parameters as in previous papers [1, 2], which are connected by a power relation of the type

$$\mathrm{Nu} = c\,\mathrm{Pe}^n (\delta_m/d_t), \tag{1}$$

where

$$\delta_m = \frac{1}{2}\sqrt[3]{100 \Big/ \sum \frac{a_n}{(d_n + d_{n+1})^3}}\,.$$

To simplify the use of empirical equations of type (1), it was decided, in processing the test data, to take quantities describing the physical properties of the granular material relating to its static condition. In addition, in calculating the parameters Nu and Pe in the tests with elliptical and lenticular tubes, we took the characteristic dimension d_t as the equivalent diameter, calculated as the ratio of four times the cross-sectional area of the tube to its perimeter.

The results of final processing of the test data for circular, elliptical, and lenticular tubes are presented in a logarithmic coordinate system in Fig. 3. It may be seen from the figure that the test points correspond very well to the straight lines described by the following equations, for the various tube profiles:

circular

$$\mathrm{Nu} = 0.0214\ \mathrm{Pe}^{0.21} (d_t\ \delta_m), \tag{2}$$

elliptical

$$\mathrm{Nu} = 0.0412\,\mathrm{Pe}^{0.21} (d_t\ \delta_m), \tag{3}$$

lenticular

$$\mathrm{Nu} = 0.0437\,\mathrm{Pe}^{0.21} (d_t\ \delta_m). \tag{4}$$

Equations (2)–(4) are valid in the range of Pe from 250 to 2000 for dry granular materials of mean grain size from 0.16 to 0.3 mm.

Equations (3) and (4) were checked for tubes with major to minor axis ratio (b/a) equal to 1.6 (lenticular) and 1.45 (elliptical).

Thus, our investigations of heat transfer between a tube and a stream of granular material allow the following conclusions to be drawn:

1. The heat-transfer coefficient depends appreciably on the tube cross section. It is greater for tubes of lenticular profile.
2. With an increase in the velocity of the granular material, the heat-transfer coefficient increases as the velocity to the power 0.21, which remains constant for circular, elliptical, and lenticular tubes.
3. The heat-transfer coefficient decreases with increase of particle size, the influence of this factor being the same for tubes of different cross section.

NOTATION

$Nu = \alpha_c d_t/\lambda$—Nusselt number; $Pe = v_0 c_p \gamma_b d_t/\lambda$—Peclet number; δ_m/d_t—a geometric parameter; v_0—approach velocity of stream of granular material, m/sec; α_c—mean heat-transfer coefficient around perimeter of tube, W/m^2 • degree; γ_b—bulk weight of granular material, kg/m^3; c_p—specific heat of granular material, j/kg • degree; λ—thermal conductivity of granular material, W/m • degree; d_t—tube diameter, m; δ_m—mean size of particles, m; d_n—mass composition of particles of individual fractions, %; d_n, d_{n+1}—mesh sizes of successive screens, mm.

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