INVESTIGATION OF MOTION OF TRANSVERSELY BLOWN LAYER ON AN INCLINED SURFACE

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UDC 536.244

On the basis of an experimental investigation recommendations are given for the computation of nonuniformities of the motion of a layer along an inclined surface in the presence of transverse blowing.

The present work has been done in connection with the investigation of heat exchangers with inclined transversely blown layer. Such a layer has the following advantages over a vertical one: a) the height of a heat-exchanger with inclined layer is appreciably smaller; b) in a heat exchanger with inclined layer one of the constructional surfaces bounding the layer from above may be absent, which in the case of blowing of polydispersive material eliminates the possibility of soiling of the upper grid. Besides, for higher temperatures of the heat-carrying agent correspondingly lower heat-resistant materials can be used. This may be one of the ways of increasing the maximum temperature of heating.

A scheme of a heat exchanger with inclined transversely blown layer is used in keramzite gravel refrigerators [1] developed by the Keramzite Scientific Research Institute. The use of this scheme in ignition of fuel [2] and thermal preparationof freely flowing raw material for baking [3] is also known.

In watching the operation of nine industrial keramzite refrigerators of similar type it is established that the motion of the layer of the freely flowing material along the inclined surface is marked by a large nonuniformity of the velocity field of the layer particles; as a result local values of the time of stay of the particles in the heat-exchange chamber, the final temperature of the particles, the intensity of heat exchange, and other indices differ appreciably from their mean values. This makes it difficult to satisfy the technological requirements on the treatment of materials (for instance, restrictions on the rate of cooling after baking) and also lowers the mean temperature thrust and the efficiency of the heat exchangers. The coefficients of heat transfer, obtained by us in tests on semiindustrial equipment, are lower than those computed for a stationary layer by an order of magnitude or more.

Data on reasons for the mechanical nonuniformity in an inclined transversely blown layer are not available in literature. We have made an attempt to investigate this nonuniformity under conditions of plane flow. An experimental bench (Fig. 1) was prepared, in which the bin, the loading device, and the working segment of the inclined layer have identical width 0.26 m. The unloading and loading is done by a uniform motion of a loading carriage and the presence of vertical stabilizing entrance and exit segments. The effect of the side walls is eliminated as far as possible. The ratio of the width of the layer to the diameter of the particles is more than 20. One of the walls is made of glass.

The basis of the technique is the study of the curves and fields of the velocities of tinted particles introduced in the layer. The experiments were carried out in the following sequence: for the formation of the layer the blowing and the loading device were started for a while, after which streaks of colored particles were introduced into the layer. From photographs taken after a certain time the local velocities were computed and the angles of inclination of the free surface of the layer were determined. The following parameters were varied in the experiments: the angle of inclination of the bed surface (grid) β from 0 to 45°, the rate of blowing from 0 to 3 m/sec, the average velocity of the layer $\bar{w}_l$ from 2 to 40 mm/sec, height of the layer h from 50 to 200 mm. The direction of blowing and the form of the grid were also changed. The material used, i.e., keramzite, had particle sizes of 2.5-5 and 5-10 mm.

M. V. Lomonosov Technological Institute, Odessa. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 18, No. 3, pp. 403-408, March, 1970. Original article submitted May 7, 1969.

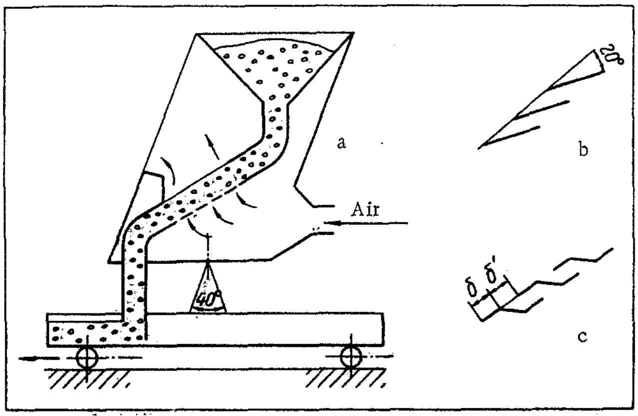

Fig. 1. Experimental bench: a) schematic diagram of the equipment; b, c) grids used in experiments.

TABLE 1. Physical Characteristics of Dispersed Materials used in the Experiments

Coefficient of friction	Keramzite, sample No. 1, ϕ2.5-5mm	Keramzite, sample No. 2, ϕ5-10mm
Internal	0,57	0,7
On steel	0,494	0,515
On fire-clay brick	0,53	0,657
On grid:		
type a	0,615	0,685
type b	0,429	0,575

For the materials used in the experiments the porosity, the bulk density, and the coefficient of viscosity were determined experimentally beforehand (Table 1). The viscosity was determined by a tribometer made by us. The coefficients of friction of freely flowing materials on constructional materials and the base grids used were also determined on the same tribometer. Each value of the coefficient of friction was obtained as the average of results of ten tests. Grids of the form b and c (Fig. 1) and a plane steel sheet were used. For the grid of form c the effect of the ratio of the width of the slit δ' to the grid step δ on the coefficient of friction was investigated. It was found that for closed steps and large values of δ'/δ the coefficient of friction f_e is close to the coefficient of friction of the same material on steel. With the increase in the grid step the coefficient of friction approached the coefficient of internal friction of the material. Thus, for $\delta'/\delta = 2.5$, $f_e = 0.665$.

Observations of the motion of the layer showed that two types of nonuniformities occur: nonuniformity of the particle velocities along the height of the layer (transverse nonuniformity) and nonuniformity of the height of the layer along its length (longitudinal nonuniformity).

In the presence of the nonuniformity of the first type the form of the velocity curve changes from convex (reminiscent of the velocity curve of a turbulent motion) at small values of the coefficient of nonuniformity of the particle velocities $w_{\max l}/\bar{w}_l$ to concave for large $w_{\max l}/\bar{w}_l$ with the predominant motion interspersed along the free surface of the layer. The reason for this type of nonuniformity is the presence of friction of the moving layer on the stationary bed surface.

The nonuniformity of the height of the layer along its length is a characteristic of the inclined layer, in which the upper surface is formed not by a sustaining plane, but by the frictional force, blowing and so forth. The free surface formed by these factors can have an angle of inclination smaller or larger than the angle of inclination of the bed surface; the height of the layer correspondingly increases or decreases with respect to the grid below.

The criterial relation

$$w_{\max l}/\bar{w}_l = f(\mathrm{K})^*$$

was used to generalize the experimental data on the nonuniformity of the velocities. The flowage number [4] for the moving blown layer occurring here represents the ratio of the inertial forces to frictional forces of the layer:

$$\mathrm{K}^* = \bar{w}_l D_e \rho_s / s\tau.$$

Here $\tau = L/\bar{w}_l$. D_e was chosen as the controlling dimension, since the flowage number characterizes the behavior of the entire dispersed system. The stress s is obtained as the result of the action of the frictional force F_{fr} on the bed surface F and the acting forces P_a (coinciding in direction with the direction of motion, Fig. 2):

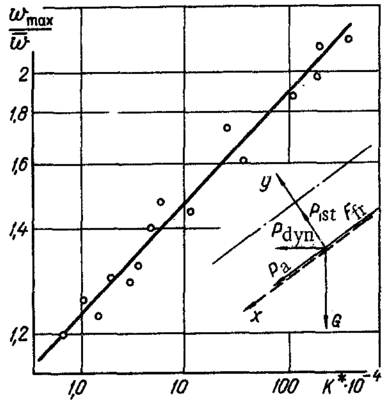

Fig. 2

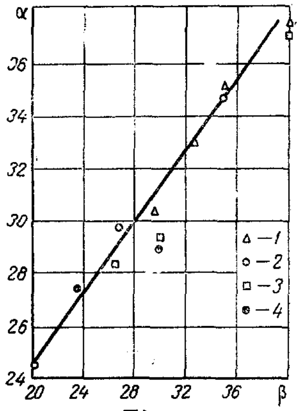

Fig. 3

Fig. 2. Dependence of the coefficient of nonuniformity of the velocities $w_{max\,l}/\bar{w}_l$ on the flowage number K^*.

Fig. 3. Dependence of the angle of inclination of the free surface of the layer α(deg) on the angle of inclination of the bed surface β(deg): 1) keramzite No. 1 on steel; 2) keramzite No. 2 on steel; 3) keramzite No. 2 on grid c; 4) keramzite No. 2 on grid b.

$$s = (P_a - F_{fr})/F.$$

The frictional force F_{fr} is obtained by multiplying the sum of the projections of the forces of weight and statistical and dynamical components of blowing on the y axis by the coefficient of external friction f_e:

$$F_{fr} = f_e(G_y + P_y^{st} + P_y^{dyn}).$$

The force acting in the direction of motion is equal to the sum of the projections of the above-mentioned forces on the x axis:

$$P_a = G_x + P_x^{dyn} \ .$$

In the experiments the flowage number was varied from $400\cdot10^{-4}$ to $0.5\cdot10^{-4}$ (Fig. 2). The coefficient of nonuniformity changed from 2.2 to 1.09, thus reaching satisfactory values for small K^*. The experimental data are well approximated by the relation

$$w_{max\,l}/\bar{w}_l = 2.42\,(K^*)^{0.109}.$$

The main possibilities of the action of the coefficient of flowage are included in s which can be controlled through such factors as the intensity and direction of blowing, and also the angle of inclination of the bed surface and the coefficient of friction of the material on the bed surface.

Froude number $Fr = gD_e/\bar{w}_l^2$ was varied from 10^3 to $5\cdot10^5$. In this range the coefficient of nonuniformity of the velocities is selfsimilar with respect to Froude number, since it is considerably larger than the critical number $Fr_{cr} \simeq 5$ [5], which indicates the compact structure of the moving layer. There were no breaks and pseudomotions of the layer observed in the experiments.

Since in all three dispersed materials and three bed surfaces were investigated, it was possible to trace only a qualitative dependence of the coefficient of nonuniformity of the velocities on the coefficients of internal and surface friction: with their increase the nonuniformity increases, other conditions being equal. The nonuniformity of the second type, i.e., the nonuniformity of the layer thickness along its length, was investigated mainly as a function of the slope of the bed surface and blowing of the layer. The effect of the angle of the bed surface β on the angle of the free surface α is illustrated in Fig. 3. In these experiments the angle of the bed surface was varied from 21 to 45°. Two types of probe and three types of bed surface were used. There was no blowing. The effect of the angle of inclination of the bed surface on the angle of inclination of the free surface α is more noticeable than the effect of coefficients of internal and surface friction of different materials. The points lie about the straight line

$$\alpha = 0.68\beta + 11° \ .$$

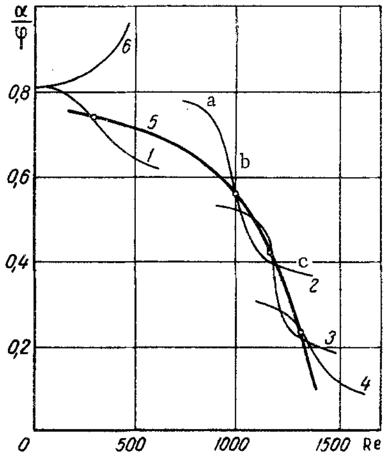

Fig. 4. Effect of blowing on the angle of inclination of the free surface: 1) for $\beta = 26°30'$; 2) $\beta = 20°$; 3) $\beta = 15°$; 4) $\beta = 10°$; 5) curve for layer of uniform thickness; 6) for blowing of the layer from above for $\beta = 26°30'$.

The effect of the second factor, i.e., blowing, is shown in Fig. 4. The intensity and direction of blowing has a significant effect on the angle of inclination of the free surface of the layer. The graph shows the dependence of the ratio of the angle of inclination of the free surface α to the angle of internal friction φ on Re for keramzite No. 2 (Table 1). Curve 1 joins the values of $\alpha/\varphi = f(Re)$ for the angle of inclination of the bed surface equal to 26°30'.

The curves are similar in form and have three characteristic segments. The segment a in the zone of smallest values of Re is characterized by a nonsteady motion in jamming and collapse of the layer. Segment b is the steepest and is characterized by a linear decrease of the angle of inclination of the free surface of the layer with the increase in Re. It is the operating segment for heat exchangers with compact unmixed blown layer. The third segment c is a transition to the pseudoliquefaction of the layer. The points, at which the angle of inclination of the bed surface is equal to the angle of inclination of the free surface of the layer, lie on the operating segments. The intensity of blowing, necessary for creating a layer of equal thickness for different angles of inclination of the bed surface, can be found from curve 5 joining these points.

NOTATION

$w_{max\,l}$ and $\bar{w}_l$	are the maximum and average velocities of the layer;
K^* and Fr	are the flowage number of the layer and Froude number;
f_e and f_{in}	are the coefficients of surface (external) and internal friction;
ρ_s and ρ	are the density of solid particles and gas;
D_e	is the equivalent diameter of the layer;
τ	is the time of motion of the layer;
α	is the angle of inclination of the free surface of the layer;
β	is the angle of inclination of the bed surface (grid);
φ	is the angle of internal friction.

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