CHANGE IN HEAT-TRANSFER COEFFICIENT IN THE DRYING OF HEAT-INSULATED MATERIALS IN A FLUIDIZED BED

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An analysis is presented of the causes of the apparent reduction in the heat-transfer coefficient from a fluidized bed to the surface of an article immersed in it in the course of drying.

In [1], in connection with the development of an effective method of drying thin-layer materials, a study was made of the heat transfer from a fluidized bed to a wet "sovelite" plate, and it was found that the heat-transfer coefficient α decreases with increase in the fluidized-bed temperature and with increase in plate thickness. At the same time, it is well known that, in the absence of evaporation, increase in temperature leads to increase in the value of α [2], while with increase in plate thickness α rises or remains unchanged, depending on the rate of fluidization [3]. In [1], the effect of the plate thickness is explained by the increase in internal diffusional resistance and also in that "... around the surface a wedge of greater porosity is formed," displacing the zone of intensive mixing of the material from the surface; the decrease in α with rise in fluidized-bed temperature is attributed to the effect of a vapor flow leaving the surface of the body and of the increasing thickness of the boundary layer. However, a more unexpected result is the significant decrease in the heat-transfer coefficient with time shown in Fig. 1 (which is constructed using the data given in Figs. 1 and 2 of [4]). It is evident that for mean moisture content of the plate of W = 50% the heat-transfer coefficient in a 120-μm corundum fluidized bed, for a fluidizing agent of velocity 0.4 m/sec and temperature 200°C, totals around 20 W/m^2·deg. According to the formula proposed in [1], we have

$$\mathrm{Nu} = \mathrm{Nu}_{\max} \exp(-\beta\,\mathrm{Fo}), \tag{1}$$

$$\alpha \to 0 \quad \text{as} \quad \tau \to \infty.$$

However, experiments with a metallic calorimeter [3] have shown that, for practically identical conditions but a fluidized-bed temperature of 30°C, the heat-transfer coefficient is approximately 400 W/m^2·deg, regardless of the plate thickness (in the range 3-100 mm), the rate of fluidization (in the range 0.35-0.5 m/sec), and the duration of the experiment. In accordance with the formula of [2], increase in temperature to 200°C should lead to an increase of approximately 25% in α; i.e., α should reach 500 W/m^2·deg. The causes of the considerable decrease in α as the material is dried were not discussed in [1,4].

In view, apparently, of the colossal difficulty associated with measuring the surface temperature of the submerged body, Sherwood (cited in [5], p. 147) determined the heat-transfer coefficient as the ratio of the heat flow to the difference between the temperatures of the fluidized medium and the middle of the drying plate. In this case, the decrease in heat-transfer coefficient in the period of falling drying rate can be explained, since drying is associated with a deepening of the zone of evaporation and thickening of the dried layer and hence the thermal resistance of the object also increase as drying proceeds ([5], p. 148). The same applies to the drying of tissues in [6], in which the heat-transfer coefficient was calculated using the difference between the fluidized-bed temperature and the mean temperature taken over the thickness of the layer.

In [1], however, the heat-transfer coefficient was calculated from the expression

$$\alpha = \frac{\left(c_0 + c_\mathrm{B}\dfrac{W}{100}\right)\dfrac{G_\mathrm{b}}{F}\dfrac{d\bar{t}}{d\tau} + r\dfrac{dW}{d\tau}\cdot\dfrac{1}{100}}{t_\mathrm{b} - t_\mathrm{s}}, \tag{2}$$

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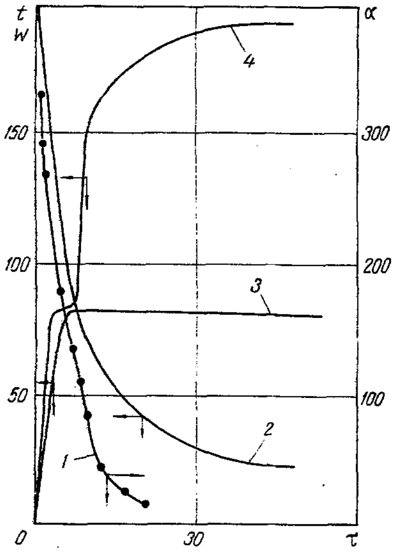

Fig. 1

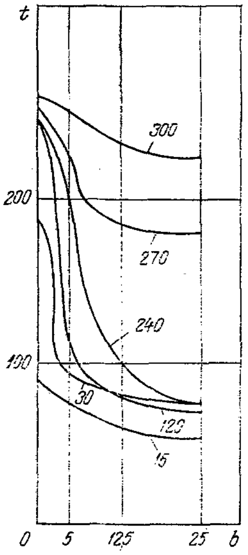

Fig. 2

Fig. 1. Change in heat-transfer coefficient (1), moisture content of "sovelite" plate (2), and temperature at the center (3) and surface (4) of the plate in the course of drying in a 120-μm corundum fluidized bed, according to the results of [4]. Air velocity 0.4 m/sec, $t_b = 200°C$. α, W/m^2·deg; τ, min; W, %.

Fig. 2. Distribution of temperature over the thickness of a "sovelite" plate in the course of drying according to the data of [8]. The figures on the curves give the drying time, min; 120-μm corundum, fluidization rate 0.2 m/sec, $t_b = 270°C$.

i.e., the heat flow was referred to the difference between the fluidized-bed temperature t_b and the plate-surface temperature t_s and, in that case, the thermal and diffusional resistances of the drying body do not appear in the expression for α. The significant difference between experiments with metallic and with "sovelite" plates is that in the latter case a vapor flow is present, which may affect the heat transfer. Of course, the effect of this flow must weaken as the flow decreases, i.e., as the body dries. However, as drying proceeds, the difference between the values of α for metallic and "sovelite" plates increases, since, as is evident from Fig. 1, α decreases by a factor of 10-15 and is a factor of 20-25 less than the value obtained in experiments without drying. In consequence, it is expedient to estimate the accuracy of the value of α obtained, especially as no mention of errors of measurement was made in [1].

A certain error arises from the use in Eq. (2) of the latent heat of vaporization r instead of the difference between the enthalpy of the vapor heated to the temperature of the surface (or the fluidized bed, depending on the sense taken in the value of α) and the enthalpy of the water in the material ([5], p. 251) and also from neglecting the heat of desorption (moistening) ([5], p. 112). Another error may arise in that, according to Eq. (2), the amount of heat expended in heating the moisture in the body is determined from the mean temperature $\bar{t}$ of the body, without taking into account the distribution of the moisture over the thickness of the plate. Finally, there may be an error associated with the loss of heat through the end of the plate: in accordance with [7] (p. 97), the side surfaces in [1, 4] were coated with moisture insulation (bakelite lacquer) but not heat insulation. In studying radiational drying, heat insulation of the ends is unnecessary, but in a fluidized bed considerable amounts of heat may pass through the ends, especially for the thicker plate of 60 × 120 × 170 mm [4, 8], where the total area of the end surfaces is found to exceed the area of the sides. However, all these factors give an error of no more than 20-30%. A more significant error may be that associated with the inaccurate measurement of the surface temperature of the body.

In [1], a slot of depth about 1 mm was made in the wet plate and a thermocouple composed of 0.1-mm-diameter electrodes was inserted, the slot being covered over with "sovelite." In view of the junction diameter (0.5 mm) and the extreme pliability of the wet "sovelite," the thermocouple may be assumed to be set within the body at a distance from the surface determined with an accuracy of up to 1.5 mm.

As an approximation, it will be assumed that the temperature of the dried material varies linearly from the surface to the evaporation front, but does not change beyond the evaporation front over the remaining thickness of the plate. Let the layer of dried material be of thickness ξ, and the thermocouple be a distance δ from the surface. By t_b, t_s, t_T, and t_M, we denote, respectively, the temperature of the fluidized bed, the surface of the body, the thermocouple, and the wet material outside the evaporation zone. In fact, the heat-transfer coefficient will be represented by the expression

$$\alpha_{\mathrm{calc}} = \frac{q_s}{t_b - t_T} \tag{3}$$

instead of the formula

$$\alpha = \frac{q_s}{t_b - t_s}. \tag{4}$$

We estimate the resulting error. In a quasisteady approximation $(t_s - t_T)/(t_s - t_M) = \delta/\xi$. Rewriting this relation as an expression for t_T, and substituting in Eq. (3), it is simple to obtain

$$\frac{\alpha}{\alpha_{\mathrm{calc}}} = 1 + \frac{\alpha\delta}{\lambda}. \tag{5}$$

For $\alpha = 500$ W/m^2·deg, $\delta = 1.0 \cdot 10^{-3}$ m, and $\lambda = 0.07$ W/m·deg, Eq. (5) gives $\alpha/\alpha_{\mathrm{calc}} \simeq 8$, i.e., the heat-transfer coefficient calculated in [1] is an order of magnitude too low. From Fig. 1 it is evident that α_{calc} in fact decreases by approximately an order of magnitude in the course of drying. It is obvious that Eq. (5) is suitable only in conditions where the depth of drying ξ exceeds the depth of the thermocouple seal δ. At the beginning of drying, when $\xi < \delta$, the surface temperature of the body t_s gradually increases, the heat flux $q = \alpha\,(t_b - t_s)$ decreases, and the temperature t_T at the thermocouple site does not change; hence α_{calc} gradually decreases, reaching the value given in Eq. (5) at the moment when the evaporation front reaches the thermocouple. This explains the time dependence of α_{calc} following from Eq. (1) and also shows that in [1] the thermal conductivity of the gas was arbitrarily introduced in the parameter Fo. The reduction in α_{calc} in comparison with α is a consequence of the change in the effective heat conduction of the "sovelite" layer of thickness δ in the course of drying, i.e., is independent of the properties of the fluidizing agent.

In fact, it is better to speak of an evaporation zone rather than an evaporation surface ([5], p. 148), i.e., of a nonlinear temperature distribution in the dry layer of material, the temperature gradient decreasing in absolute value with increasing distance from the surface. This leads to a larger error than that given in Eq. (5).

If the heat-transfer coefficient is to be determined with an error not exceeding 10%, the additional heat resistance of the layer of dry material must not exceed 10% of the heat-transfer resistance; for $\alpha = 500$ W/m^2·deg, this corresponds to a depth of the thermocouple beneath the surface of $\delta = 0.1 \cdot 0.07/500 = 14 \cdot 10^{-6}$ m, i.e., of the order of 0.01 mm. Such an accuracy of the thermocouple position is unlikely to be attained for electrodes of diameter 0.1 mm in a material like "sovelite." Thus the "reduction" in the heat-transfer coefficient in [1] results from the use in Eq. (2) of a temperature measured some distance away from the surface rather than the surface temperature t_s itself. This accounts for the anomalous dependences of α and $\alpha_{\max}$ on the time, fluidized-bed temperature, and plate thickness obtained in [1], since all these factors lead to an increase in the difference between the temperature at the surface and that at the site of the embedded thermocouple.

The curves in Fig. 2 (constructed from the data of [8]) provide additional confirmation. The thermocouples considered in Fig. 2 were positioned not at the surface but at distances of 5, 12.5, and 25 mm away. A notable feature is the reduction in the temperature gradient at the surface in comparison with the gradient 3-4 mm away, for a surface temperature above 100°C, i.e., when the surface layer is dry. The heat-flux density q at the surface is higher than in the depth of the bed, while the moisture content, i.e., the heat conduction of the "sovelite," is lower, and hence $\nabla t = q/\lambda$ should increase as the surface is approached, as is found to be the case in the curves of Fig. 2, provided the "surface" point is shifted a certain distance into the depth of the body. In principle, knowing the accurate distance of the thermocouple from the surface, the surface temperature may be found by extrapolation [5, 7], but this would require considerably more points in the region of sharp changes of temperature (5-10 mm) and an accurate knowledge of their distance from the surface.

A more reliable value of the heat-transfer coefficient could be obtained in conditions of constant drying rate, when the temperature is approximately constant over the whole thickness of the plate. Measurements in this region would cast additional light on the unresolved discussions of the amounts of heat transferred by conduction to the surface of the particles and by gas convection and, in particular, would confirm or disconfirm the data in [9], since the difference between the temperatures of the surface and the moist thermometer directly characterizes the proportion of particles in the total heat transfer. It was pointed out in [4, 8] that a period of constant velocity exists in a number of conditions but for some reason these data were excluded from the subsequent analysis.

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DRYING HEAT-INSULATED MATERIALS IN A FLUIDIZED BED*

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In his article, A. P. Baskakov considered our papers [1-3] devoted to the heat transfer and kinetics of the drying of a very wet plate of considerable thickness in a fluidized bed. There had been practically no earlier works on this problem, and therefore it would have been impossible, because of the absence of similar cases, to carry out an analysis of the results of experiments on drying by comparing them with data for a completely different case: the heat transfer between a smooth metallic surface and a fluidized bed in the absence of transverse flow of material. A transverse flow of material is always present in the case of a drying body, and to attempt an analysis of this kind would imply a failure to acknowledge the effect of mass transfer on the heat transfer in drying processes.

As is known, the accurate equation for the heat-transfer coefficient takes the form

$$\alpha_{\mathrm{wet}} = \frac{\frac{1}{F}\int\limits_{V}\left[c_0\rho_{\mathrm{dry}}\frac{\partial t}{\partial\tau} + c_{\mathrm{B}}\rho_{\mathrm{dry}}W\frac{\partial t}{\partial\tau}\right)dV + rm}{\Delta t}. \qquad (1)$$

As is recommended in [4-7], we used instead the approximate equation

$$\alpha_{\mathrm{wet}} = \frac{\left(c_0 + c_{\mathrm{B}}\frac{\overline{W}}{100}\right)\frac{G_{\mathrm{dry}}}{F}\frac{\overline{dt}}{d\tau} + rm}{\Delta t}. \qquad (2)$$

These equations differ in that the integration in Eq. (1) gives the mean derivative $\overline{W\partial t/\partial\tau}$, while in Eq. (2) the mean value $\overline{Wdt/d\tau}$ is used. Even for a parabolic distribution of temperature and moisture content over the

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* A comment on "Change in heat-transfer coefficient in the drying of heat-insulated materials in a fluidized bed" by A. P. Baskakov.

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