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.

LITERATURE CITED

1. L. K. Vasanova, N. I. Syromyatnikov, and A. I. Evplanov, Inzh.-Fiz. Zh., 27, No.6 (1974).
2. S. S. Zabrodskii, Hydrodynamics and Heat Transfer in Fluidized Beds [in Russian], GÉI, Moscow (1963).
3. A. P. Baskakov and N. F. Filippovskii, Kuznechno-Shtampovochnoe Proizvodstvo, No.1 (1971).
4. L. K. Vasanova and A. I. Evplanov, in: Heat and Mass Transfer and Nonequilibrium Thermodynamics of Disperse Systems [in Russian], Izd. UPI, Sverdlovsk (1974), p.135.
5. A. V. Lykov, Theory of Drying [in Russian], Énergiya, Moscow (1968).
6. S. S. Zabrodskii and L. V. Gorbachev, in: Investigation of Heat and Mass Transfer in Engineering Processes and Equipment [in Russian], Nauka i Tekhnika, Minsk (1966), p.105.
7. P. D. Lebedev, IR Drying [in Russian], Gosénergoizdat, Moscow—Leningrad (1955).
8. L. K. Vasanova, A. I. Evplanov, and N. I. Syromyatnikov, Izv. Vyssh. Uchebn. Zaved., Énerget., No.4 (1973).
9. A. P. Baskakov and V. M. Suprun, Khim. Neft'. Mashinostr., No.3 (1971).

DRYING HEAT-INSULATED MATERIALS IN A FLUIDIZED BED*

N. I. Syromyatnikov

UDC 621.785:66.096.5

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

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

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

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

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

---

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

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 31, No. 1, pp. 134-138, July, 1976. Original article submitted June 4, 1975.

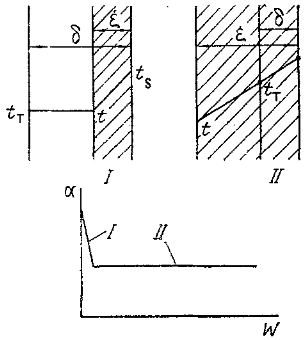

Fig. 1

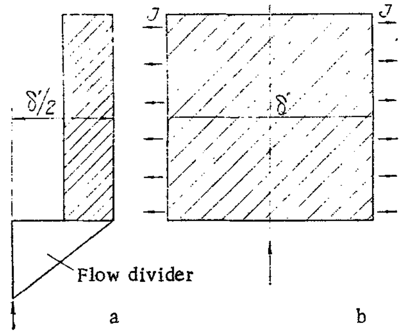

Fig. 2

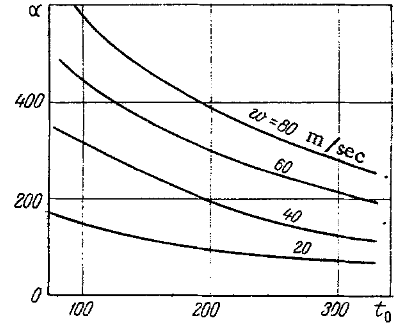

Fig. 3

Fig. 1. Calculation scheme according to Eq. (4): ξ is the thickness of the dry layer; δ is the depth of the thermocouple beneath the surface.

Fig. 2. Flow around a plate: a) according to [10]; b) real drying process.

Fig. 3. Dependence of heat-transfer coefficient on the temperature and velocity of the drying agent [13]. α, W/m^2·°C; t_0,°C.

thickness of the plate, this substitution gives a maximum error of 0.25% in determining the heat-transfer coefficient, since the amount of heat expended in heating the wet material is 5–8% of the total even at the initial moment of drying.

In these equations, no account is taken of the heat of wetting: it is negligibly small in comparison with the heat of vaporization and only becomes significant for samples of low moisture content ([4], p. 244). The equations also omit the heat expended in warming the vapor to the bed temperature, a process which occurs mainly outside the sample. This heat is included only in the thermal balance of the drying apparatus.

The surface considered in our calculations was the evaporation surface. The end surfaces of the plate, as in B. I. Pyatachkov's experiments, for example, were moisture-insulated. The temperature of the ends (measured by special experiments) was close to the bed temperature, and hence the heat transfer through the moisture-insulated ends can be neglected.

In our calculations, the heat-transfer coefficient was based upon the difference between the temperature of the bed and the temperature at the thermocouple site (0.5 mm from the surface), since direct determination of the surface temperature in the course of drying is practically impossible in view of the change over time of the roughness and physical properties of the material.

At the initial instant when the sample temperature differs sharply from the bed temperature (t_b) and changes weakly over the sample thickness, the temperature at the thermocouple site (t_T) is close to the surface temperature (t_s) ($t_T \approx t_s$), and the difference between the values α and α_{calc} obtained using $t_b - t_s$ and $t_b - t_T$ is negligible ($\leq$ 3.0%).

As is known, the temperature drop in the surface layer depends on the heat flow and the thermal conductivity of the material:

$$\Delta t = \frac{q}{\frac{\delta}{\lambda}}, \qquad (3)$$

where the specific heat flux q and the effective heat conduction of the material λ_{eff} vary over time.

At the initial moment, as shown in a number of investigations, a part of the moisture (in the form of droplets) is displaced to the boundary gas layer, where a corresponding proportion of heat is expended in their evaporation. Then the temperature drop in the surface layer will be even smaller, as the heat flow in the plate decreases.

In the latter period of drying, because of the decrease in moisture content, the temperature at the thermocouple site will in fact differ from the surface temperature and hence the corresponding heat-transfer coefficients will also differ. However, the discrepancy is not as much as an order of magnitude, the figure suggested by Baskakov. In deriving this estimate, Baskakov took an arbitrary value of 1.5 mm instead of 0.5 mm for the depth of the embedded thermocouple δ, and he also used the heat conduction of the dry material instead of the effective heat conduction λ_{eff}, which depends (see [8], p. 315) on the process of phase transition, the diffusional flow of vapor, and the temperature. Furthermore, he assumed a constant value of α from the bed to the surface and adopted a two-layer scheme (Fig. 1, I, II) comprising a layer of wet material and a layer of dry material of thickness ξ, in which the temperature varies linearly, while the value of λ is as for the dry material. In this scheme, there is not a zone of evaporation but a surface of evaporation; then

$$\frac{\alpha}{\alpha_{calc}} = 1 + \frac{\alpha\delta}{\lambda}. \tag{4}$$

Proceeding from the given scheme, the calculated value of α is constant for $\xi \geq \delta$ (Fig. 1); this does not correspond to the physical drying process, in which the intensity of heat transfer changes because of change in the transverse mass flow. The scheme of the real process, as A. V. Lykov notes, is more complex: "... there is no sharp boundary between the evaporation surface and the subsequent layers .... It is possible to speak only of an evaporation zone and not of an evaporation surface. Evaporation occurs ... over the whole thickness of the surface layer" ([4], p. 149).

The use of the given scheme leads to an incorrect interpretation of the obtained dependence for α_{max}, the maximum (corresponding to the initial moment of drying) value of the heat-transfer coefficient. Thus, it is asserted that increase in the plate thickness leads to increase in the heat-transfer coefficient.

For pure heat transfer, the effect of the probe thickness on the heat-transfer coefficient has been established, for example, in [9] (p. 121): $\alpha \sim D^{-0.34}$. Heat transfer in thick bodies has yet to be investigated. In the limit, increase in plate thickness for a given length may result in a transition from the case of flow around a vertical plate to that of flow around a horizontal plate. As is known [10], the heat-transfer coefficient is considerably less for a horizontal disposition of the plate. Also in [10], different effects of "thickness" on the intensity of heat transfer were obtained: for small flow rates, α increases with rise in δ'; for larger flow rates, it is independent of δ'; and in some cases it falls (see Fig. 6 in [10]).

The explanation is that in the experiments of [10] the supply of the flow to the plate was controlled by means of a flow divider, which produces not an increase in plate thickness, but a change in the flow pattern around the plate (Fig. 2); as the authors remark: "It is perfectly evident that the distribution of the fluidizing agent over the sides of the thick vertical plate heated in a fluidized bed depends on the shape of the lower end." The converse is also true: "Change in plate thickness may be simulated by setting at its lower end different flow dividers feeding air to the heat-emitting surface of the calorimeter."

Comparative experiments on heat transfer for a rough plate with sharp edges in the presence of transverse gas flow (Fig. 2b) and with a plate the thickness of which is simulated by change in width of a flow divider (Fig. 2a) have not been carried out.

The results of our investigations have shown that, for a high intensity of drying of a plate in a fluidized bed, increase in bed temperature will be accompanied by decrease in α_{max}.

A similar dependence of α on the drying-agent temperature in the period of constant drying rate was obtained for drying by hot vapor in [11], for drying in a fluidized bed in [12], and for nozzle drying in [13] (Fig. 3). Comparison with the effect of the bed temperature in the heat transfer to a smooth metallic surface is impossible, since this would once again mean discounting the effect of the mass flow on heat transfer during drying.

There is no formula for the heat transfer in the course of drying which extends into the region of convective heat transfer; our formula

$$\mathrm{Nu} = \mathrm{Nu}_{max} \exp(-\beta \mathrm{Fo}) \tag{5}$$

is generalized only for the change of moisture content in a "sovelite" sample from 200 to 50% and, of course, does not hold as $\mathrm{Fo} \to \infty$, as is clear from the curve in [1]. The upper limit is $\mathrm{Fo} \leq 2$. We introduced the gas parameters in this equation for the sake of formal completeness.

Hence, in our opinion, the two-layer scheme from which A. P. Baskakov proceeds, comprising a layer of wet material and a layer of dry material of heat-transfer coefficient equal to that of "sovelite" after calcining at $t = 600°\mathrm{C}$ ($\lambda = 0.07\ \mathrm{W/m^2 \cdot °C}$), is incorrect. In fact, taking the thermal resistance of the surface layer into account (as far as the thermocouple site) necessitates the use of an effective heat-transfer coefficient which depends on the phase transition, the diffusional vapor flow, and the temperature, and varies over time.

Furthermore, it cannot be assumed that the heat-transfer coefficient between the surface and the medium in the course of drying is a constant equal to the heat-transfer coefficient between a vertical plate with a flow divider and the fluidized bed in the absence of a transverse gas flow.

Since, at the initial moment, the temperature at the thermocouple is close to the surface temperature and the values α and α_{calc} calculated from $t_b - t_s$ and $t_b - t_T$ are negligibly different ($\leq 3\%$), to speak of an "anomalous" dependence for α_{max} is without foundation.

LITERATURE CITED

1. L. K. Vasanova, N. I. Syromyatnikov, and A. I. Evplanov, Inzh.-Fiz. Zh., 27, No.6 (1974).
2. L. K. Vasanova and A. I. Evplanov, in: Heat and Mass Transfer and Nonequilibrium Thermodynamics of Disperse Systems [in Russian], Izd. UPI, Sverdlovsk (1974), p.135.
3. L. K. Vasanova, A. I. Evplanov, and N. I. Syromyatnikov, Izv. Vyssh. Uchebn. Zaved., Énerget., No.4 (1973).
4. A. V. Lykov, Theory of Drying [in Russian], Énergiya, Moscow (1968).
5. P. D. Lebedev, IR Drying [in Russian], GÉI, Moscow—Leningrad (1955).
6. B. M. Smol'skii, External Heat and Mass Transfer in Convective Drying [in Russian], Izd. BGU, Minsk (1957).
7. P. S. Kuts, Heat and Mass Transfer [in Russian], Vol.5, Énergiya, Moscow—Leningrad (1966), p.546.
8. O. Krisher, Scientific Principles of Drying Engineering [Russian translation], IL, Moscow (1961).
9. A. P. Baskakov, Rapid Oxygen-Free Heating and Heat Treatment in Fluidized Beds [in Russian], Metallurgizdat, Moscow (1968).
10. A. P. Baskakov and N. F. Filippovskii, Kuznechnoe-Shtampovochnoe Proizvodstvo, No.1 (1971).
11. O. L. Danilov, Author's Abstract of Candidate's Dissertation, Moscow Power Institute, Moscow (1961).
12. A. A. Sal'nikov, Author's Abstract of Candidate's Dissertation, Kalinin Polytechnic Institute, Kalinin (1967).
13. V. V. Krasnikov and V. A. Danilov, in: Heat and Mass Transfer [in Russian], Vol.5, Nauka i Tekhnika, Minsk (1968), p.519.