HEAT AND MASS TRANSFER IN CAPILLARY-POROUS MATERIALS DRYING IN AN ELECTROMAGNETIC FIELD

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A description is given of the drying of capillary-porous materials with heat supplied by convection and contact from ferromagnetic elements heated in an alternating electromagnetic field. The laws and phenomena of internal heat and mass transfer and the interaction of the material with the ferromagnetic elements and the surrounding medium are examined.

In heat treatment and drying technology new methods of supplying heat, and combinations of these methods, are now being applied in such a way that the shortcomings of one method are made good by the advantages of another. For example, a combination of high-frequency current and convective heating gives favorable results in drying materials that are hard to dry.

One recently developed industrial method of heat treatment and drying involves the electromagnetic supply of heat using mains current. This technique was worked out at the Institute of Heat and Mass Transfer AS BSSR. The drying of capillary-porous materials (for example, wood pulp) with electromagnetic heat from ferromagnetic elements combines the merits of several methods of supplying heat.

The essence of the method is that the material or product requiring heat treatment or drying is placed, along with ferromagnetic heat-releasing elements, in the electromagnetic field of a winding supplied with 50-cycle alternating current.

The ferromagnetic elements (or with backing material) exposed to the alternating electromagnetic field are heated, and give up their heat to the material or product by conduction, convection and radiation. Depending on the physical arrangement of the ferromagnetic elements (volume, layer, stack, block), the transfer of heat to the material may be accomplished by one or a combination of several means of heat supply. Then the choice of means of heat supply will be determined to a known extent by the properties of the material.

In contact heating of moist material the mechanism of moisture transfer differs from that in convective drying, due to the characteristics of the temperature field in the surface layers of the material.

Whereas the temperature at the surface of the material during the first stage of convective drying is close to the wet bulb temperature, with direct heating of the moist material by a hot metal surface the surface temperature is considerably higher than the wet bulb temperature.

In the first stage of convective drying the temperature field of the material is almost uniform, i.e., the temperature drop inside the material is small. Evaporation of liquid proceeds at the surface of the material, and the supply of moisture to the surface is accomplished by capillary and diffusion-osmotic forces, i.e., by the action of a moisture content gradient.

However, under severe drying conditions isothermically is already disturbed. In the first stage of drying, although the drying rate may stay constant, the surface of evaporation gradually recedes into the body at a constant rate ($d\xi/d\tau$ = const), i.e., the distance of the evaporation surface from the surface of the material is a linear function of time (Fig. 1). In the second stage (period of falling drying rate), the rate of recession of the evaporation surface gradually diminishes ($d\xi/d\tau$ = var), and the relation between ξ and τ

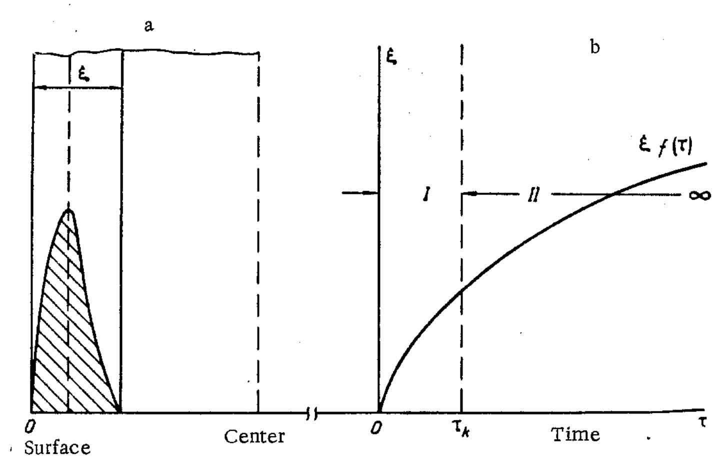

Fig. 1. Diagram showing recession of the evaporation zone during drying (ξ is the evaporation zone).

becomes nonlinear (Fig. 1b). Therefore, even in the first stage, evaporation must diffuse not only through the air and vapor boundary layer, but also through a certain layer of comparatively dry material (through a layer of thickness ξ). In this case the rate of transfer is determined to a considerable degree by the temperature gradient in the layer ξ.

The experiments of Zhuravleva have shown that in the actual evaporation process there is no sharp boundary between the surface of evaporation and the layer of dry material. There is an evaporation zone in which a maximum amount of moisture is evaporated at a certain distance ξ_m (Fig. 1a). The evaporation zone is drawn out to a considerably greater depth ($\xi > \xi_m$). At the surface of the material itself there is almost no evaporation; then the rate of evaporation increases, reaching a maximum at depth ξ_m and gradually decreasing to zero at depth ξ. This type of distribution of evaporation rate was found by calculating the transfer of liquid and salt dissolved in it during drying of moist material, with a correction for diffusion of the salt in the solution itself. An analogous mechanism is also found in convective + radiative drying.

In drying with hot air using contact heating of the material by ferromagnetic elements—grids or rods—heated in their turn in a mains-frequency electromagnetic field, heat is transferred directly by conduction from the metal surface to the surface of the material. In contrast with the pure contact method of drying (drying on heated drums or plates), the metal contact surface is not a solid surface, but takes the form of a grid (network of plates). Therefore the transfer of heat by conduction from the metal to the material is discrete in nature, and we shall call this technique local contact heating. As distinct from pure contact heating, local contact heating involves convective heat transfer from the air to the material through the openings in the metal surface. This local convective heat transfer is accompanied by external moisture transfer (Fig. 2), i. e., transfer of vapor from the surface of the material to the surrounding moist air.

Thus, the presence of openings in the heated metal surface allows one to combine the contact method with the convective method of drying, i. e., to describe the method as contact-convective. This contact-convective method of drying has advantages over the pure convective and the pure contact methods.

Local contact heating of the surface of the material increases the surface temperature and creates a temperature gradient within the evaporation zone. The presence of discrete contact surfaces makes possible strong external moisture transfer through the exposed surfaces of the material. This is not the main advantage of the method, however. The point is that the surface of the material in contact with the (metal) heating surface is characterized by an increased temperature and considerable local saturation of the air. Near a segment of the metal surface the humidity of the air is close to 100% ($\varphi \approx 1$). Because of this, and also because of the temperature gradient, the water vapor in this part of the evaporation zone diffuses inside the material, since the partial pressure of vapor at the surface is greater than inside the material in the evaporation zone. Since the pressure of saturated vapor P_s is a single-valued function of temperature T [$P_s = f(T)$], the flow of water vapor into the material is determined by the temperature gradient in the evaporation zone:

$$j_v = -\varepsilon D \frac{\partial P_i}{\partial x} = -\varepsilon D \left(\frac{\partial P_s}{\partial T} \right)_u \frac{\partial T}{\partial x}, \qquad (1)$$

where j_v is the flow of water vapor into the material (Fig. 2).

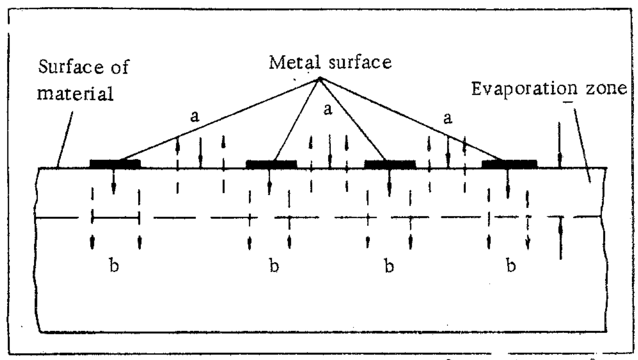

Fig. 2. Diagram of heat and moisture transfer within the material: a) supply of heat by convection (local convective heat transfer) -- continuous line and transfer of water vapor to the surrounding medium -- broken line; b) supply of heat by conduction (local contact heating) -- continuous line, and transfer of water vapor within the material -- broken line.

As the moisture progresses into the material it condenses, since the pressure of the moving vapor is greater than that of the saturated vapor in the material at a given temperature.* This condensation will be supplemented by capillary condensation.

Relation (1) was written for the region of the moist state, for the hygroscopic region it is written in the same form as the usual law of thermal diffusion of moisture:

$$j_v = -\varepsilon D \frac{\partial P_{mat}}{\partial x} = -a_m \delta \frac{\partial t}{\partial x} - a_m \frac{\partial u}{\partial x}, \qquad (2)$$

where δ is the thermal gradient coefficient.

The movement of water vapor will also be directed into the body, since simple calculations show that in absolute magnitude $\left| a_m \delta \frac{\partial t}{\partial x} \right| \gg \left| a_m \frac{\partial u}{\partial x} \right|$. Moreover, as the water vapor moves into the body it will condense.

When the moisture condenses there is considerable liberation of heat of vaporation (r ~ 600 kcal/kg),

*If, for example, the surface temperature of the material is 40° C, then, at $\varphi = 1$, $P_{surf} = 15.3$ mm Hg, but at some depth where $t_{mat} = 35°$ C ($\varphi \le 1$), $P_{mat} = 42.2$ mm Hg.

which contributes very strongly to the heating of the material as a whole. The overall coefficient of heat transfer k to the moist material, expressed as

$$\frac{1}{k} = \frac{1}{\alpha} + \frac{\xi}{\lambda_{eff}}, \quad (3)$$

increases considerably, since in the case λ_{eff} is the effective thermal conductivity, including heat transfer by condensation of water vapor.

The presence of water vapor condensation not only increases the heat transfer coefficient, but also creates a uniform temperature field in the moist material zone, i. e., in the greater part of the moist material.

However, the most important advantage of this mechanism of moisture transfer lies not only in the powerful heatin of the material, but also in the change in the form of the bond between moisture and material. The water vapor condensing in the material has a physico-mechanical bond (capillary moisture and wetting moisture) and is easily removed upon further drying. Adsorption and diffusion-osmotic moisture, the most difficult to remove, is evaporated in the evaporation zone to form vapor, part of which is removed into the surrounding air, while part migrates within the material upon condensing and is transformed into capillary moisture. Consequently, our method of drying involves partial removal of moisture and partial conversion of physico-chemically bound moisture (adsorption and diffusion-osmotic moisture) into physico-mechanically bound moisture. This is a very important factor which also affects the technical properties of the dried material (no warping or cracking).

Something similar is observed in the drying of wood by means of an electric current and during the baking of bread. In the latter case moisture is removed from the surface laters of the material (from the bread crust), while the main moisture content of the dough changes its type of bond (physico-chemically bound moisture is replaced by physico-mechanically bound moisture), whereupon the nature of the material also changes appreciably (the dough is transformed into bread).

It is known that the splitting of wood is connected with stresses arising from nonuniformities in the distribution of physico-chemically bound moisture. Therefore the gradual replacement during drying of physico-chemically by physico-mechanically bound moisture permits the drying of wood with a low specific surface area (thick boards) in a short time without checking and warping.

NOTATION

P_s) saturated vapor pressure; j_v) flow of water vapor into the material;) resistance coefficient for diffusion of vapor within the material; D) vapor diffusion coefficient in moist air; δ) thermal gradient coefficient; a_m) moisture diffusion coefficient within the material; k) coefficient of overall heat transfer to moist material; λ_{eff}) effective thermal conductivity.

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