MASS TRANSFER IN PROCESSES OF HEAT TECHNOLOGY

V. V. Krasnikov and S. G. Il'yasov UDC 536.2

It is found experimentally that fields of moisture content with local minima on the moisture distribution curves, explained by the proposed mechanism of mass and heat transfer in conductive and conductive-convective drying of the materials, are atypical. Characteristic fields are given for moisture content and excess pressure in the layer of the colloid capillary-porous materials under infrared irradiation at different stages of drying, sintering, thermal treatment, etc.

The outstanding Soviet scientist, Academician of the Academy of Sciences of the Belorussian SSR A. V. Lykov was deeply and fruitfully engaged in the problem of mass transfer in capillary-porous bodies.

A. V. Lykov and his school of thermophysicists performed extensive research on heat and mass transfer in phase transitions and chemical transformations. An integrated treatment of heat and mass transfer and their interaction allowed A. V. Lykov to formulate the mechanism of heat and mass transfer and propose a system of differential equations for heat and mass transfer in capillary-porous bodies [1].

The regularities in diffusion and effusion moisture transport and the effect of molar moisture transfer caused by thermal and diffusion slip were defined. The problem of heat and mass transfer is still of interest and many researchers continue to develop it in the field of drying and thermal moisture treatment in the search for associations between technological properties of the drying material and the mechanism of moisture transfer in it, discovering peculiarities of this transfer under different techniques of heat supply, methods of control of technological processes, their intensification, creating new proceeses, types

In conductive drying, sintering, baking, firing, and other technological processes, the mechanisms of mass transfer differ from one another depending on the temperature of the heated surface (t_h), thickness of the solid body or liquid, pasty, and dispersed media, types of bonds of the moisture with the media and the structure [2].

On the boundary of the contact of the moist body with the heating surface and in the region of the contact layer (0.08-0.12 mm in thickness), two simultaneous and interrelated processes take place. Firstly, conductive (and partially radiant) heat exchange between the heating surface and a solid body is complicated by the phase transition and moisture transfer. Secondly, under high temperatures t (above 85-100°C) and small thickness during heating and in the first period of drying in the contact layer a heat drain arises due to vaporization in the region of the contact layer — the vaporization zone [densities of flow of vapor may be as high as 35 kg/(m² × h) and higher, and 100 kg/(m² × h) and above for liquid and pasty products]. In this case heat exchange in the contact layer due to phase transition and moisture transfer prevails over conductive heat exchange and changes the mechanism of moisture transfer through the body. The vapor formed due to the presence of the free space and air in the contact layer under the action of the gradient of the total pressure tends to penetrate inside a capillary-porous colloid body along free capillaries and pores through the cell cavities and fiber walls. The higher the porosity and permeability of a moist body the more probable is vapor transfer inside the body.

During heating this vapor colliding with still nonheated layers of the body condenses and transmits to it its heat; as a result the body is heated more intensively and moisture evaporates in these layers. The next portions of vapor penetrate deeper into the body condensing in it and forming the "new" vapor. At the end of this heating period the body is heated and the next vapor surmounting the resistance to its transfer passes into the ambient medium together with vapor formed in the layers near the open surface of the body.

Moscow Technological Institute of the Foodstuffs Industry. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 59, No. 3, pp. 373-379, September, 1990. Original article submitted April 16, 1990.

 0022-0841/90/5903-1084$12.50

The distinguishing feature of moisture transfer in the period of heating of the body is the mechanism of sequential cycles of heating—vaporization throughout the thickness of the body and the formation of the second zone of vaporization near its open surface.

The stability of both vaporization zones in the first period of drying is explained by the fact that they "are fed" by the moisture in the zones and moisture transferred toward the zones from the inner layers of the body, partially compensating for the loss of moisture in peripheral layers. The distribution of moisture inside the body is created at the expense of its transfer in the form of a liquid from the vaporization zone at the open surface toward the vaporization zone near the heating surface. The transport of the capillary and osmotically bounded liquid toward the open surface is realized via mechanisms of capillary thermodiffusion and diffusion transfer, and toward the contact layer near the heating surface by means of the capillary absorption, overcoming the resistance of thermodiffusion (in the first period of drying at high t_h for small thicknesses). Vaporization does not take place in the rest of the volume of the body, empty pores and capillaries are filled with saturated vapor and air.

A transit transfer in porous bodies takes place according to the molar-molecular (filtration and diffusion) mechanism under the influence of the gradient of the partial pressure of the saturated vapor. The fraction of the filtration in the total vapor transfer increases with the increase in t_h, porosity, and decrease in the thickness of the body. In the beginning of the process at high moisture concentrations of the body, vapor transfer is realized chiefly via filtration since the resistance of vapor diffusion in the porous body is very high.

The notion of "thick," "medium," and "thin" capillary-porous colloidal bodies as applied to conductive drying agrees well with the value of the coefficients of the molar-molecular vapor transfer k_M and diffusion vapor transfer k_D. If $k_M/k_D > 1$, then the body is considered to the "thin"; if $k_M/k_D \approx 1$, then "medium"; and if $k_M = 0$, then "thick." In the latter case the transit transfer of vapor from the contact layer toward the open surface is impossible. The vapor formed in the "thick body" near the heating surface condenses in the contact layer and the layer nearest to it.

An important feature of mass transfer in conductive drying in the first period is differentiation of flows of vapor and liquid. In the contact layer of the body there exist two opposite moisture flows: in the form of a liquid (from the contact layer and the layer nearest to it toward the vaporization zone) and in the form of vapor (from the contact layer inside the body toward its open surface). In the outer layers of the body, directions of heat flows of the vapor and liquid coincide.

Transfer in the contact layer of a liquid, somewhat dehydrated due to vaporization, and its vaporization result in the consolidation of water-soluble matter in a greater quantity than in other layers of the body. The same occurs in the vaporization zone near the open surface, where concentration of the water-soluble matter also takes place. This is utilized for technological purposes (in manufacturing printed fabrics, dressing of leather, footwear parts, kintted garments) or to avert the burning of a dress in drying the fabric or the formation of a "fur coat" in the drying of paper, etc.

A feature of mass transfer is that at high temperatures t_h in the body at the end of the first period of drying on the boundary between the contact layer and the next layer a "watershed" surface is formed from which the liquid is transferred in opposite directions toward both zones of vaporization. This results in the emergence in the body of a spatial zone around the watershed surface in which the water screen is broken; i.e., at the beginning of the second period a relatively dehydrated zone appears which spreads out with the passage of time because of evaporation of slowly moving microcapillary and adsorptively bounded liquid remaining in the first new vaporization zone. Then, with the passage of time a second new watershed surface emerges in the more remote layers, leading to a break in the water screen and the emergence of another relatively dehydrated expanding vaporization zone. Depending on the thickness of the body a few such new vaporization zones can exist; they are, in particular, observed in the cut end of a veneer sheet 2-3 mm in thickness when the drying cellulose is separating.

In the second period of drying a liquid moves in the body between zones, replenishing them with moisture and evaporating in them in the direction of the open surface of the body. Moisture transfer near the heating surface from the contact layer stops in the beginning

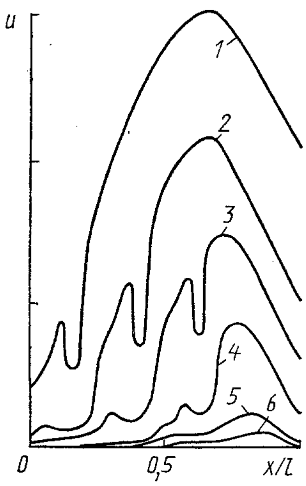

Fig. 1. Characteristic fields of moisture content in the material layer in conductive drying in the second period: beginning of the period, 2, 3, 4) intermediate stages, 5, 6) the end of the process.

of the second period of drying due to deepening of the contact vaporization zone because of the liquid deficit in the first new vaporization zone. For this reason and also because the mechanism of the diffusion vapor transfer starts acting, the rates of expansion of the vaporization zones in the first part of the second period are not high. In the second period (the contact layer practically "drys out") the rates of expanding of new vaporization zones increase sharply. This takes place since the resistance to the diffusion vapor transfer is reduced due to releasing pores and capillaries from the liquid.

The vaporization zone near the open surface of the body, in spite of current mass exchange, remains "moist" during the first period and part of the second period because it is constantly supplied by the liquid transported from within the zone to intensify the process by delivering additional heat to the open surface of the body. At the end of drying all vaporization zones are combined into one, which fills a part of the volume of the body near its open surface. In the middle layers of the body concentration of the salt is much greater than zero but less than the initial concentration, which indicates that a certain amount of the transferred salt solution evaporates during the second period.

In colloidal moist bodies, possibilities for internal vaporization and vapor transfer are extremely limited; therefore, moisture removal in them is related to the transfer of the osmotically bound liquid through thermodiffusion, by a way which is defining also for the contact layer.

Conductive drying of the liquid and paste media under high temperatures is preceded by a period of violent vaporization, the mechanism of mass transfer of which is related to the existence of the gradient of the total pressure.

The mechanism of combined conductive-convective drying, consisting of sequentially repeated heating and cooling of the body, complicated by a phase transition, in spite of certain features is close to the mechanism of convective drying. In the conductive region, liquid and vapor transfer takes place under the action of the same forces that act in conductive drying but it lasts for a shorter period of time.

In the convective region, the vapor formed in the conductive region in the contact layer is removed from the body, the moisture evaporates fro the two surfaces of the body and it is cooled. In this region the moisture tends to "redistribute" itself and it flows from central layers toward the periphery under the action of thermodiffusion and diffusion having the same directions in the "former" outer layers and opposite, in the "former" contact layer. As a result, the moisture levels off through the thickness, and the external surfaces are filled with moisture, which aids in the intensification of heat and moisture exchange for subsequent contact of the body with the heating surface.

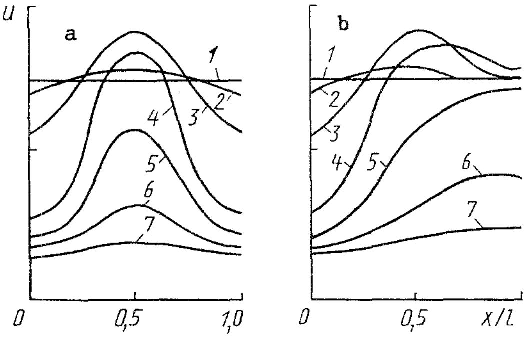

Fig. 2. Characteristic fields of moisture content in the layer of colloid capillary-porous materials under two-side (a) and one-side (b) infrared irradiation at different stages of the process: 1, 2) initial; 3, 4, 5, 6) intermediate; 7) final.

In the second period of drying new vaporization zones arise inside the body, similar to the zones in conductive drying, but in both halves of the body, i.e., their number is twice as large. Therefore, the processes of moisture transfer in conductive and combined drying are similar. The latter is also characteristic of the different versions of the combined drying (including drying with agitation of the product, when the heating surface vibrates, etc.), which is suitable for dehydrating matterials that are medium and large in thicknesses.

The curves of the fields of moisture content in conductive and combined drying are atypical: variation of the moisture content along the thickness of the body in the second period is not monotonic; it is represented by the curve with local minima (Fig. 1). Such character of the fields of moisture content has been found experimentally and is explained by the above proposed mechanism of moisture and heat transfer.

It is of theoretical and practical interest to find a mathematical model describing adequately the process of moisture transfer. It should be noted that the A. V. Lykov equations allow one to obtain an average, with respect to the body, thickness curve of moisture content in the second period of conductive drying without local minima.

Widely used oscillation regimes allow one to exclude overheating of the body at high densities of the heat flow and to intensify the process of heat and mass exchange owing to organized moisture transfer in the region of wetting (or cooling).

Oscillation regimes are periodic processes; therefore, it is important to evaluate the infleuence of the oscillation period on the process of moisture transfer. For a specific material and a defined mechanism of moisture transfer there is an optimal oscillation period T. As a result of solving the system of linear differential equations of heat and mass transfer, the optimal oscillation period can be defined from the equation $T = 2R^2/\pi a_m$ obtained by V. V. Krasnikov in collaboration with M. S. Kozlova.

The influence of infrared radiation in the oscillation regime on a moist material leads to the sharp increase in the intensity of mass transfer and increase in mass exchange kinetic characteristics. As a result of short-duration infrared irradiation (initial impulse) of the material (for example, fruit, grapes, vegetables, etc.) before the drying, due to the absorption of the energy of penetrating infrared radiation, there is local destruction of cytoplasmic membranes of fruit cells, which is the main obstacle to diffusion-osmotic processes. In infrared treatment the cell permeability increases significantly and the rate of drying increases 8 to 12 times.

Generalization of the experimental fields of moisture content in the colloid capillary porous materials shows that dry and moist zones are formed in the irradiated material separated from one another by the moving vaporization zone [3, 4]. Initially, in spite of intensive heating of the surface layer under infrared irradiation a noticeable loss of moisture by the body is not observed (Fig. 2), and the moisture redistributes itself along the thickness of the layer. This process is responsible for a considerable increase in the moisture of the inner layers (1. 1-1.3 times) as compared to the initial moisture. Removal of the

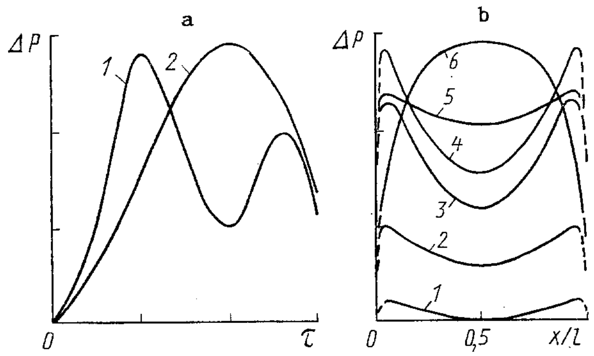

Fig. 3. Kinetics of variation (a) and characteristic fields of the excess pressure (b) in the layer of colloid capillary-porous materials under infrared irradiation (baking): (a) 1) for $x/\ell = 0.03$; 2) 0.5; (b) 1) initial stage; 2, 3, 4, 5) intermediate; 6) final.

moisture penetrating inside from the surface layers aids in broadening the vaporization zone and its deepening.

When densities of the penetrating flow of the long-wave ($\lambda > 2.8$ μm) radiation absorbed in the vaporization zone by moisture are high, the pressure of vapor-gas medium in the layer increases sharply (Fig. 3) resulting in the emergence of molar moisture transfer (baromoisture conduction). This is justified by the bulging of the layer or its breaking (baking, heat treatment).

It is found that the rate of deepening of the surfaces of "moist" and "dry" zones in the layer of the sample in infrared drying of materials varies with respect to time according to a complicated law. The vaporization zone is replaced by a conditional "vaporization surface" and the material is represented as a two-layer system: the "dry" layer and the "moist" layer.

In calculations of mass transfer under infrared irradiation in connection with the complexity and continuity of the course of irreversible biochemical processes in foodstuffs it is required to take account of the consumption of the absorbed radiant energy in dextrinization, denaturation, etc. [3, 4].

According to the methods proposed [4], the calculation of mass transfer under infrared irradiation is performed with regard to the features of regularities in radiant energy transfer under different conditions of irradiation and spectral composition of the radiant flow irradiating the products. Simultaneously with the consideration of depthwise absorption of infrared irradiation penetrating the material its effect on mass transfer and their mutual interaction in the process of irradiation are considered. The dependence of propagation and absorption of infrared radiation of different spectral composition in dried and moist zones on their optical properties allows one to intensify phase transitions and the advancement of the vaporization zone.

For most materials the radiation flow in calculations is divided according to spectral composition into short wave with $\lambda < 2.8$ μm, penetrating to a considerable depth ($\ell >$ 1.0 mm to 40 mm) and medium and long wave with $\lambda > 2.8$ μm, absorbed in the moist products practically in the surface layer ($\ell < 0.5$ μm). This allows one to define a function of distributed heat sources $w(x, \tau)$, which takes account of the absorption in the moist material of the penetrating infrared radiation with $\lambda < 2.8$ μm. The absorption of radiation with $\lambda > 2.8$ mm by the moist vapor is taken into account in this case in the form of concentrated sources in the zone (on the "boundary") of phase transitions.

Thus the problem is reduced to the simultaneous solution of the differential equations of heat and mass transfer and transfer of the radiant energy for dried and moist regions of the material, differing in their moist-thermophysical, opticothermoradiation characteristics and the presence of heat drains and sources in them.

NOTATION

u, moisture content, kg/kg; λ, radiation wave length, μm; w, amount of the absorbed flow of the radiant energy, W/m^3; x, coordinate, m; ℓ, layer thickness, m; Δp, excess pressure, Pa; t, temperature, °C; k_M, k_D, coefficients of molar/molecular and diffusive vapor transfer, kg/(m × sec × Pa); T, period of oscillation, sec; R, half of the slab thickness ℓ, m; a_m, coefficient of moisture diffusion, m^2/sec.

LITERATURE CITED

1. A. V. Lykov, Heat and Mass Exchange (Handbook) [in Russian], Moscow (1978).
2. V. V. Krasnikov, Conductive Drying [in Russian], Moscow (1973).
3. S. G. Il'yasov and V. V. Krasnikov, Physical Foundations of Infrared Irradiation of Foodstuffs [in Russian], Moscow (1978).
4. S. G. Il'yasov and V. V. Krasnikov, Heat and Mass Exchange VI, Vol. 7 [in Russian], Minsk (1980), p. 78.