CONTACT HEAT TRANSFER AND EXTERNAL MASS TRANSFER IN CONTACT DRYING

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The heat transfer, compounded by a phase transformation, between the heater surface and the adjoining dried material is considered here as well as the mass transfer between the free surface of this material and surrounding medium (air or cloth) during the first stage and the second stage of the drying process.

In the theory of drying, which has been developed by Academician* A. V. Lykov and his school [1], the processes of heat and mass transfer are viewed inseparably connected and as one – which is of particular significance, specifically, in the analysis of conductive drying.

The essential mode of heat transfer in conductive drying (with the assumption that no heat is brought into the dried material through its free surface) is by conduction, the heat transfer by radiation from the heater surface to the surface of the moist material being insignificant and, for heater temperatures t_h up to 120°C, negligibly small.

The noticeable difference between the measured temperatures t_h and t_c (in a 0.08 mm thick contact layer l_c) is due to the thermal resistances of the contact layer and of the very contact between adjoining surfaces, as a consequence of the discrete character of the contact between pressed-together surfaces and as a consequence of the phase transformation taking place here.

When a rigid moist body (e.g., a ceramic plate) is in contact with a heater surface, small voids remain between the pressed-together surfaces and these become filled with a gaseous medium. When fibrous moist materials (e.g., cellulose) are in such a contact at low heater temperatures t_h and under low pressures, the contact becomes more solid. A contact between such materials and a heater surface is plastic in nature, made so by the moisture contained in it acting in the role of plasticizer. At high heater temperatures t_h, on the other hand, the evaporation mechanism takes effect in the contact layer. The size of the actual contact area is then considerably reduced and the volume filled with the vapor–gas medium increases, which results in a local "lifting" of the material. The "lifting" effect can be illustrated on a pressing iron, which "jumps" along a solid, rough surface. At a high t_h the roughness protrusions, which constitute the contact spots, comprise mostly adsorbed and adhering moisture.

The complexity of the phenomenon compounded by the phase transformation, by the contact between materials with different thermal properties, and by the plastic nature of the contact due to the moisture content, makes it impossible to separate the components of heat conduction (through the actual contact areas and through the vapor–air interlayer). It may, therefore, be worthwhile to assume that the thermal contact resistance results, so to speak, from an equivalent air interlayer of a mean effective thickness δ_a. This assumption is valid also because the thermal conductivity of the dried material is only a few times (not many times) greater than that of the medium and, consequently, the deflection of the heat flux across the actual contact areas and the corresponding increase of the temperature gradient are moderate.

In the most general case, the thermal resistance of a contact depends on t_h, g, and u of the contact layer, on the contact pressure, and on the surface microgeometry – as has been confirmed by experimental data.

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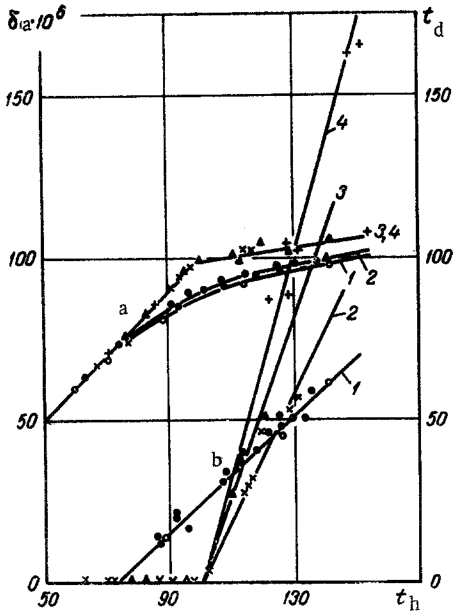

Fig. 1

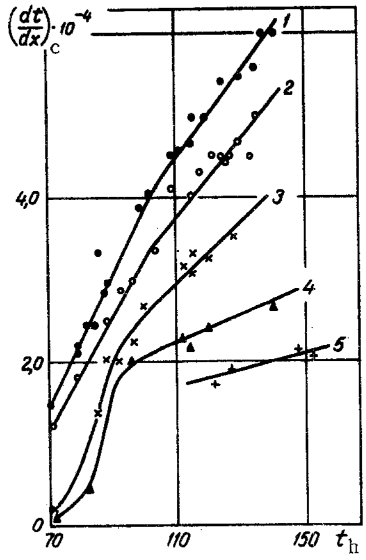

Fig. 2

Fig. 1. Temperature t_d°C (a) and thickness $\delta_a \cdot 10^6$ m (b) as functions of t_h°C for cellulose during the first stage of the drying process, g = 0.10 (1), 0.15 (2), 0.30 (3), 0.40 (4) kg/m^2.

Fig. 2. Temperature gradient in the contact layer $(dt/dx)_c \cdot 10^{-4}$ (°C/m) as a function of t_h (°C), for cellulose with various values of g: 0.10 (1), 0.15 (2), 0.30 (3), 0.50 (4), 0.95 (5) kg/m^2.

The resistance to heat transfer from a heater surface to a layer of moist material during stage I of the drying process is defined by the expression

$$R = \frac{t_h - t_c}{q} = \frac{t_h - t_c}{rm}, \tag{1}$$

where m is the drying rate at the end of the constant-rate stage.

We carefully measured the temperatures t_c and t_h during the drying of cellulose and other materials with different densities g, over a wide range of varying t_h at different contact pressures. As it turned out, the values of t_c agree well with data obtained by several other researchers who studied contact drying of various materials: cellulose, paper, cloths, milk, sunflower pith [2, 3, 4, 5], etc. Thus, the contact layer temperature during stage I in the conductive drying of different materials of equal thickness at the same heater temperature t_h is approximately the same.

Then taking (1) into consideration, we have

$$rmR = Rq = \text{const}, \tag{2}$$

or for two different materials

$$q_1R_1 = q_2R_2. \tag{3}$$

The thermal contact resistance during stage I of the drying process is calculated from the expression

$$R_c = \frac{R_{c,act}R_{av}}{R_{c,act} + R_{av}} = R - \frac{l_c}{\lambda}. \tag{4}$$

The mean effective thickness of the equivalent air interlayer is

$$\delta_a = \lambda_a R_c. \tag{5}$$

The temperature of the material t_d during stage I of the drying process is determined from the equation

$$t_d = t_h - qR_c. \tag{6}$$

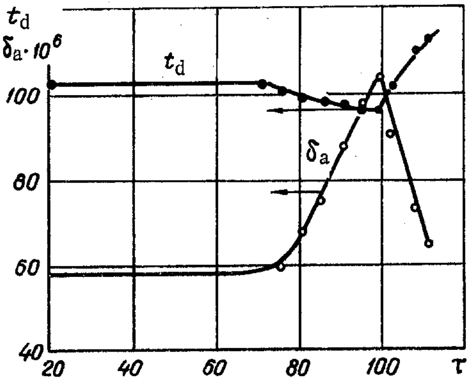

Fig. 3. Variation of t_d (°C) and $\delta_a \cdot 10^6$ (m) as functions of time τ (sec) in conductive drying of 0.3 kg/m^2 cellulose at t_h = 130°C.

Temperature t_d calculated from (6) is the maximum temperature of the material during stage I of the drying process. This is the temperature which, in fact, determines the feasibility of using a given drying method for the purpose of dehydrating one or another material and, therefore, the value of t_d and its dependence on t_h are of considerable interest (Fig. 1).

As Fig. 1 indicates, up to t_h = 73°C, t_d does not depend on g and is almost equal to t_h. A subsequent rise of t_h causes the curves to continue separately for different values of g, while the difference between t_h and t_d becomes significant and increases. As g is increased, t_d rises. From a density of 0.3 kg/m^2 up, almost no difference in t_d values is observed for different values of g and a single curve represents the empirical equation for t_d:

$$t_d = 99.00 + 0.13\,(t_h - 99.00). \tag{7}$$

This relation is also useful in approximate calculations of t_d for other materials.

According to the calculated data (Fig. 1), the mean effective thickness of the equivalent air interlayer during stage I depends strongly on t_h and also on the g value for a given material.

In the contact drying of fine materials (up to 0.25 kg/m^2), except colloids, the interlayer has already appeared at a rather low heater surface temperature (73°C) and becomes 50 μ thick at 130°C. In the contact drying of medium and thick materials, however, the interlayer only appears at t_h = 100°C but then its thickness δ_a increases considerably. The magnitude of δ_a at t_h = 140°C is 79.0, 109.0, and 135.0 μ respectively for g = 0.30, 0.50, and 0.95 kg/m^2.

The insignificant value of R_c at a low t_h indicates that a moist fibrous material, when the contact is of a plastic nature, touches the heater surface at many more points than when metallic surfaces are in contact, which is also confirmed by indirect measurements of the electrical contact resistance [6].

The formation of an interlayer becomes noticeable only at a temperature t_h which corresponds to a fully developed evaporation process within the contact zone. Vapor transfer from the contact zone has already begun at 59°C when g = 0.15 kg/m^2, while the interlayer appears at 73°C. At first, the rate of phase transformation is lower or corresponds to the rate of vapor transfer, and the vapor is removed from the contact zone. Then, as t_h rises, this correspondence becomes upset and, as all the generated vapor cannot leave the zone, it forms a vapor–air interlayer. This is characteristic especially at temperatures t_h above 100°C, at which boiling in the contact zone is possible. Furthermore, a certain "delay" in the interlayer formation may be due to the fact that evaporation occurs not only in the contact plane but also within the volume region of the contact layer, when the apparent evaporation surface is smaller than the actual evaporation surface.

The thermal conductance of a contact α ($\alpha = 1/R_c$) is very high and measures, on the average, from 2000 (at low t_h) to 400 (at high t_h) kcal/m^2·h·°C.

An evaluation of experimental data in terms of α as a function of t_h at various values of g for the material has shown that it is impossible to derive a single relation which would be convenient for calculations. In view of this, R_c was broken down into its factors (δ_a and $1/\lambda_a$) in accordance with the definition of R_c.

In this way, the scalar value of the thermal flux density from the heater surface during stage I of conductive drying can be calculated from the formula

$$q = \frac{\lambda_a}{\delta_a}(t_h - t_d). \tag{8}$$

Calculations based on (8) yield entirely satisfactory results with an error not exceeding ±5%. Knowing q from the mass-transfer data, one can also calculate δ_a from (8).

It is possible to calculate q at a high t_h from the surface temperature gradient in the material and from the magnitude of its thermal conductivity, according to the equation

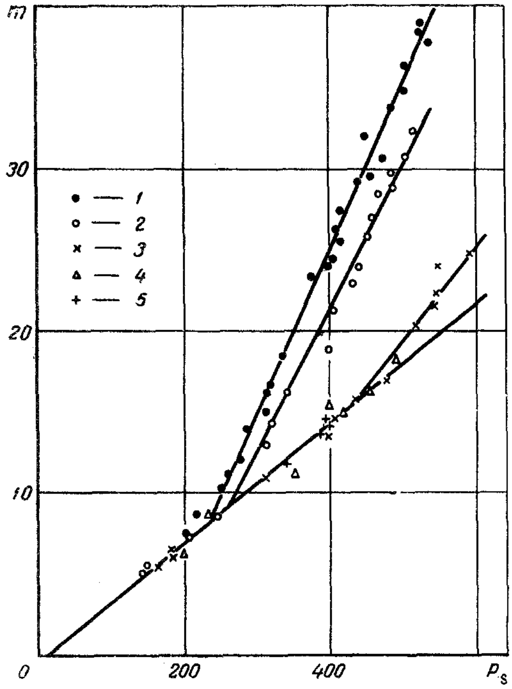

Fig. 4. Variation of t_d (°C) and $\delta_a \cdot 10^6$ (m) as functions of time τ (sec) in conductive drying of 0.3 kg/m^2 cellulose at t_h = 130°C.

$$q = \lambda_r \frac{t_d - t_c}{l_c} . \tag{9}$$

All quantities in (9) are known. Knowing λ_r of any moist material, one can approximately calculate q from Eq. (9) using the other data applicable to cellulose with a given value of g.

In Fig. 2 is plotted the empirical relation between the temperature gradient in the contact layer and the temperature t_h for cellulose of various densities g. Basically, the temperature gradient is determined by the phase transformation which takes place in the contact layer. The greater the temperature gradient becomes, the greater is the rate of internal evaporation. The temperature drop across the layer, which is due to conduction, amounts to about 0.2°C at a heater surface temperature of 70°C, while the total drop for a 0.1 kg/m^2 material, for example, is 1.5°C or 7.5 times greater at the same temperature. At a still higher t_h the temperature "jump" across the contact layer becomes still more significant. The onset of internal evaporation is noted on the temperature-gradient curves by their sharp rise (0.30 and 0.50 kg/m^2). At a temperature of approximately 100°C all curves inflect and then, as t_h rises further, the temperature gradient increases more slowly.

Equation (9) may also be used for directly determining λ_r and its dependence on t_h under industrial or laboratory conditions, as was actually done.

At a low t_h the value of q during stage I can be calculated approximately from the conductivity λ of the given material and from the experimentally found temperature drop across the material layers within a certain distance Δl. The value of q can, furthermore, be determined from mass-transfer data.

The magnitude of contact pressure under which the material sticks to the heater surface appears to have some effect on R_c.

Up to t_h = 60°C the temperature t_d does not depend on the pressure. Then, for cellulose with g ≈ 0.1 kg/m^2, t_d drops somewhat as the pressure decreases, but this effect is small. At t_h = 140°C and at pressures of 1570, 884, and 442 N/m^2, t_d has been found to be respectively 98.0, 96.5, and 95.5°C, i.e., thicker interlayers correspond to lower pressures. As t_h rises, the effect of pressure on the thickness δ_a weakens. While the maximum difference of thicknesses δ_a amounts to 10.0 μ at 73°C, it is only 4.0 μ when the pressure changes by a factor of 3.5 at 140°C.

The second stage of the drying process begins when the contact surface of a capillary-porous colloidal body "dries up" (down to 0.06-0.08 kg/kg) and, in the case of a capillary-porous body, this surface becomes dry. Initially in this stage the contact between a material and the heater surface becomes worse, which results in a sharply increased resistance to heat transfer from the energy source.

The magnitude of this resistance is altered in different ways depending on the structure of the moist material.

When the moist material is rigid and almost undeformable, like ceramic plates of varying porosity, as the contact layer is dried, R_c increases somewhat to a maximum value and remains constant throughout stage II. This is characteristic of thick colloidal and capillary-porous bodies (e.g., a layer of clay thicker than 20 mm).

In another case, when the moist porous material is plastic and subject to shrinkage (e.g., fibrous or other materials), R_c increases rapidly during the first part of stage II and decreases rapidly during the second part of this stage.

The manner in which R_c, i.e., the boundary conditions of heat transfer, vary affects the heat and mass transfer, above all in the shape of the curves which represent the kinetics of heating. In the first case, the temperature of the material layers remains constant or drops slowly during stage I, while a temperature rise shifted in time from layer to layer is observed in the layers beginning with the contact layer during stage II. In drying fibrous or similar materials the temperature of the layers drops during the first part of stage II and then rises during the second part of this stage [7].

As the moisture content in the contact layer decreases, the contact gradually transforms from a plastic to a rigid one and the actual contact area shrinks. The increasing "gap" between the heater surface and the material, as well as the volume of material behind the evaporation surface, become filled with the vapor–air phase and this greatly increases R_c above its value during stage I.

The evaporation rate in the inner evaporation zone remains quite high because of the favorable conditions, while the rate of vapor diffusion limits the exit of vapor from this zone (vapor cannot pass through a moist fiber skeleton) so that vapor and air expand toward the heater surface, which, with passage of time, results in an increased interlayer thickness during the first part of stage II.

The thermal contact resistance is, consequently, determined largely by the evaporation rate within the inner zone. If this rate is low (in microporous bodies, colloidal materials), then the magnitude of R_c may for all practical purposes be considered constant during stage II of the drying process, and the temperature of the material rises. As the vapor content reaches its second critical level, the resistance to vapor transfer begins to decrease markedly, the rate at which the evaporation zone deepens increases, and the vapor which forms the "buffer" zone represented by the vapor–air interlayer can be carried away through the material together with the vapor which is generated in the evaporation zone. As a result, with the passage of time the interlayer becomes thinner and the temperature of the material rises.

An analysis of the conductive drying process [8] has made it possible to determine the temperature field in the material during stage II of this process, specifically t_d, and also to calculate δ_a (Fig. 3). Evidently, during stage I, δ_a and t_d are constant. At the beginning of stage II, δ_a increases sharply (approximately twofold) while t_d drops. During the second part of this stage δ_a decreases sharply while t_d rises.

In this way, the heat transfer from the heater surface to a macroporous fibrous material during stage II of the drying process is effected by thermal conduction through the vapor–air interlayer of varying thickness.

The magnitude of q during stage II of the drying process can, accordingly, be calculated from the equation

$$q(\tau) = \frac{\lambda_a}{\delta_a(\tau)} [t_h - t_d(\tau)], \tag{10}$$

where $\delta_a(\tau)$ and $t_d(\tau)$ – the interlayer thickness and the temperature at a point where the material touches the heater surface – are functions of time.

Inasmuch as Eq. (10) contains quantities which vary during the process and which can be determined from experimental data under analogous conditions only, this equation is not recommended for calculating $q(\tau)$. The latter is more accurately calculated using the basic equations of heat and mass transfer during drying [1].

In engineering practice it is usually the difference between partial pressures of the vapor in the surface layer and the vapor in the surrounding medium which is considered the driving force effecting a mass transfer during evaporation of moisture into the air [9].

Test data on mass transfer during stage I of the conductive drying process have been evaluated in terms of a relation between m and P_s (Fig. 4), showing that the test points (except those corresponding to high heater surface temperatures t_h) for every value of g are distributed fairly regularly along a principal straight line which originates at a point on the abscissa's axis corresponding approximately to the saturated vapor pressure of 20 mm Hg, matching P_s in the surrounding medium during the experiment. Consequently, the basic equation of mass transfer, from which the rate of conductive drying during stage I can be calculated for thick materials, is

$$m = 0.0373(P_s - P_m). \tag{11}$$

Using this relation for drying thin materials will result in lower values of m, since Eq. (11) does not fully account for the vapor generation and transfer from the contact layer through the material.

According to test data, the mass-transfer coefficient in conductive drying is 5.73 times greater than the mass-transfer coefficient in convective drying. Such an increase of the mass-transfer coefficient in conductive drying is explained by the occurrence of bulk evaporation and a continuous expansion of the developed internal vapor-generating zone from which vapor is exuded from the capillaries through a system of discretely spaced and interacting jets.

For thick and medium-thick materials, the vapor generated directly on the free surface of the material during stage I amounts to about 18-20% of the total vapor mass m', while for thin materials it amounts to only 10-13%.

During stage II of the conductive drying process the rate of mass transfer is determined simply from data relating to the drying kinetics.

When the material is pressed against the heater surface through a screen or a cloth, the heat and mass transfer which occurs does not differ from the one described here. The use of cloth in conductive drying brings about some modifications in the process as a consequence of an additional resistance, mainly to the transfer of vapor. Vapor, entering the exceptionally well developed capillary system of the cloth, which offers resistance to vapor transfer and which is at a lower temperature, will condense and part of it, overcoming the system resistance, will exit into the surrounding medium. Vapor condensation occurs mainly within the layer, about 0.2 mm thick, directly adjoining the material surface (the total cloth thickness is about 8 mm). Part of the vapor, breaking through the condensation layer, will condense in various other layers of the cloth.

Cloth reduces the drying rate m during stage II considerably, while the drying rate m under a cloth and under a screen remain about the same during stage I. This effect of cloth on the drying rate during stage II is explained by the tremendous resistance to vapor diffusion, which is characteristic of stage II, into the cloth layer filled with condensate liquid. When the cloth is "dry," the drying rates m under it and under a screen do not differ much during stage II.

NOTATION

t	is the temperature, °C;
g	is the material density, kg/m^2;
u	is the moisture content, kg/kg;
δ	is the mean effective thickness, m;
q	is the heat flux density, kcal/m · h · °C;
r	is the specific heat of evaporation, kcal/kg;
R	is the thermal resistance, °C · m^2 · h/kcal;
λ	is the thermal conductivity, kcal/m · h · °C;
m	is the drying rate, kg/m^2 · h;
P	is the partial pressure of water vapor, mm Hg.

Subscripts

h	denotes the heater surface;
d	denotes the contact between material and heater surface;
a	denotes the air interlayer;
c	denotes the contact;
act	denotes actual contact;
av	denotes the vapor–air interlayer;
r	denotes true;
s	denotes saturated;
m	denotes the medium.

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