

HEAT AND MASS TRANSFER DURING THE DRYING OF MOIST MATERIALS

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(Received 9 May 1960)

Abstract—This paper deals with heat and mass transfer inside a moist capillary porous body under conditions of an intensive heating process. It was found by the experiments that in the capillaries of a body a pressure of gas and vapour mixture occurs exceeding that of the surrounding air (barometric pressure). One of the main reasons stimulating moisture transfer inside a body in the process of drying is a decrease of this excessive pressure. The coefficients of moisture content are calculated and in analysis the mechanism of drying is given on the basis of the differential equation for heat and mass transfer in dispersed media.

Résumé—Cet article traite du transfert de chaleur et de masse à l'intérieur d'un corps humide à porosité capillaire soumis à un chauffage intensif. Les expériences ont montré que, dans les capillarités du corps la pression du mélange de gaz et de vapeur s'élève au-dessus de la pression ambiante (pression atmosphérique). L'un des principaux facteurs de l'accélération du transport de l'humidité à travers un corps au cours du séchage est la diminution de cette surpression. Les coefficients de teneur en eau sont calculés et une analyse du mécanisme du séchage est donnée, elle est basée sur l'équation différentielle du transport de masse et de chaleur dans un milieu dispersé.

Zusammenfassung—Diese Arbeit beschäftigt sich mit der Wärme- und Stoffübertragung im Inneren eines feuchten, kapillar-porösen Körpers bei intensiver Trocknung. Die Versuche ergaben in den Kapillaren einen Druck des Gas-Dampfgemisches, der über deren Umgebungsdruck (barometrischer Druck) lag. Eine der Hauptursachen für den Feuchtigkeitstransport innerhalb des Körpers während der Trocknung ist ein Abfall dieses Überdrucks. Die Koeffizienten des Feuchtigkeitsgehaltes werden berechnet und eine Analyse des Trocknungsmechanismus gegeben auf der Grundlage der Differentialgleichung für den Wärme- und Stofftransport in dispersen Medien.

Аннотация—В статье рассматривается перенос тепла и вещества внутри влажного капиллярно-пористого тела в процессе интенсивного нагрева. Экспериментами установлено, что в капиллярах тела возникает давление парогазовой смеси, превышающее давление окружающего воздуха (барометрическое давление). Перепад этого избыточного давления является одной из основных причин переноса влаги внутри тела в процессе сушки. На основе дифференциального уравнения тепломассопереноса в дисперсных средах подсчитаны коэффициенты переноса влаги и дан анализ механизма сушки.

It is known that the process of drying materials consists both of the transfer of moisture within the material and of the evaporation of it from the surface of the material into the surrounding medium. In most cases the rate of drying depends on the intensity of moisture transfer from within the material towards its surface.

In earlier works the heat and mass transfer processes were considered as analogous. Therefore the equation of mass conduction was written analogically to the Fourier heat conduction equation:

$$q' = - a' \gamma_0 \nabla u \quad (1)$$

where q' is the density of mass flow, $\text{kg}/\text{m}^2\text{hr}$,
 ∇u is the moisture content gradient,
 a' is the moisture potential conductivity coefficient of material,
 γ_0 is the density of dry material kg/m^3 .

Accordingly the differential equation of mass conduction had the form:

$$\frac{\partial u}{\partial \tau} = a' \nabla^2 u$$

where τ is the time in hr.

1923–30 the American scientists Sherwood and Lewis published their works where analytical dependences for some particular cases of the kinetics of the drying process described by the above equation were given.

The experimental investigations carried out by the Soviet scientists A. M. Fedorov, B. A. Posnov, J. I. Minjovich, I. I. Paleev, A. A. Shumilin and others determined that moisture transfer does not correspond to the molecular diffusion but occurs under the influence of some other causes and that the coefficient a depends on the moisture content of the material.

In 1934, A. V. Luikov discovered the phenomenon of moisture thermal diffusion and established a new factor causing moisture transfer in materials—the temperature gradient and, corresponding to it, the thermal gradient coefficient.

At first this factor was considered insignificant, since it does not influence considerably the low temperature convective drying of various materials. The intensification of heat and mass transfer processes in general and the application of high-frequency to drying material in particular showed the enormous significance of this factor.

In this case the mass transfer equation will be of the following form:

$$q' = -q'_u + q'_i = -a'\gamma_0 \nabla u - a'\gamma_0 \delta \nabla t \quad (3)$$

where δ is the thermal gradient coefficient $1/^\circ\text{C}$, q'_u and q'_i are the flows of mass provoked by moisture conductivity and the thermal diffusion of moisture, ∇t is the temperature gradient $^\circ\text{C}/m$.

In this case the mass conduction differential equation will be of the following form:

$$\frac{\partial u}{\partial \tau} = a' \nabla^2 u + a' \delta \nabla^2 t \quad (4)$$

and the heat conduction differential equation of the form:

$$\frac{\partial t}{\partial \tau} = a \nabla^2 t + \frac{\epsilon r}{c} \frac{\partial u}{\partial \tau} \quad (5)$$

the second term of which takes into account the influence of the moisture evaporation within the body on the temperature field change. ϵ is the

coefficient of moisture internal evaporation; at $\epsilon = 0$ the total mass of moisture is transferred in a liquid form and at $\epsilon = 1$ only in the form of vapour. r is the heat of evaporation, kcal/kg, c is the specific heat of an absolutely dry material, a is the thermal diffusivity coefficient, kcal/kg $^\circ\text{C}$.

The coefficients a' and δ depend on the temperature and moisture content of the material. The coefficient a' remains constant both when the material has a high moisture content and when it is at a constant temperature; in this state a' corresponds to the transfer of osmotically bounded and of capillary moisture in liquid form. On further removal of moisture from the smaller capillaries, it can be transferred not only in the form of liquid but partially also in the vaporous state; in this case the coefficient a' is decreasing. Still greater decrease of a' may be observed when the moisture content of the material is very low. The moisture bound by the polymolecular absorption is then being removed as steam.

The coefficient δ varies in rather a different way with the variation of the moisture content and of the temperature. It decreases with the increase in temperature. The coefficient δ will increase and reach its maximum value with the decrease of the average moisture content of the material, for when there are larger amounts of capillary moisture in the material there is a favourable influence of the trapped air upon the transfer of moisture. Further, a part of the moisture can be transferred as vapour with a decrease of the moisture content (when it approaches the critical moisture level), and δ decreases in consequence of the relative thermal diffusion of vapour and air. When there is only the sorbite moisture in the material, then δ becomes negative since the vapour tends to be transferred in the opposite direction towards the heat flux.

It was established by experiment that an increase in the difference of temperature, moisture concentration and vapour pressure in the interior of the material and at the surface of the material respectively causes an adequate increase in the rate at which it dries.

If the temperature or the moisture content of the surface layers of the material are greater than those of the internal ones, this may either

slow down the transfer of moisture towards the surface of the material or even provoke a reverse transfer of moisture into the internal layers of the material.

Accordingly the moisture, temperature and pressure gradients may have both negative and positive signs. The negative sign shows a lack of agreement between the direction of the moisture-flow vector and the direction of the gradient and corresponds to a transfer of moisture from the internal layers of the material towards its surface.

The application of equation (3) to the analysis of various drying processes shows that the transfer of moisture towards the surface occurs at the convective drying (Fig. 1) owing to the moisture content gradient; on the contrary the temperature gradient makes the transfer of moisture slow down. In this case $q' = q'_u - q'_t$.

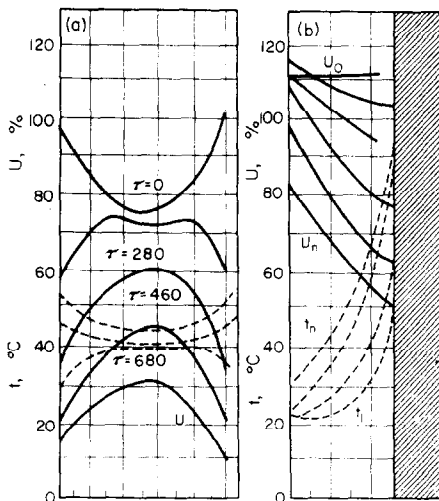


FIG. 1. Typical curves of moisture content and temperature distribution in the material:
(a) For convective drying,
(b) For conductive drying.

The greater the temperature difference between the centre and the surface of a material and the higher the value of the thermal gradient the larger the value of q'_t . The effect of a change of the temperature field on the intensity of the moisture transfer can be neglected only in the case of low-temperature drying. The transfer of moisture towards the surface (Fig. 1(b)) is

determined at the contact drying in the same way as in most cases of drying (Fig. 2(b)) i.e. by the temperature gradient; on the contrary the gradient of moisture content slows down the process of drying.

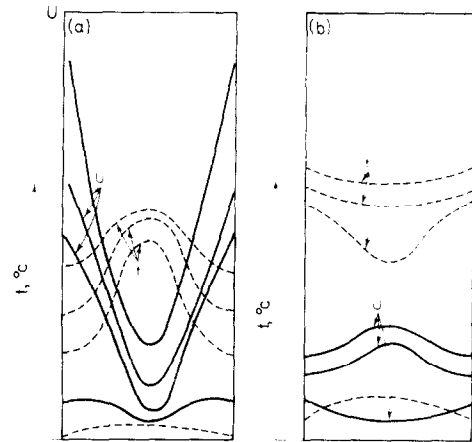


FIG. 2. Curves of moisture content and temperature distributions for high frequency drying of wood.

For instance, forced circulation of air is applied in order to intensify the process of contact fabric drying. In most cases the application of air circulation to the process of high frequency drying also gives positive results. The anomalous fields of temperature and of moisture content can be observed, as shown in Fig. 2(b), at high frequency drying of a piece of wood, the central part of which has a higher moisture content and absorbs more heat. In this case the process of drying goes on sluggishly and an application of the high frequency method makes no sense at all. The main drawback of the convective drying method lies in its duration. All attempts to intensify this method of drying end in failure as they require an increase of the moisture content gradient; this is inadmissible for many materials as it makes them to crack, and thus results in wastage.

Numerous attempts were made, therefore to apply oscillating regimes which allow the influence of the temperature gradient to be operative at least momentarily. The application of high frequency current made it possible to obtain a large temperature gradient. However, this

method has no utilization in engineering practice because of the low efficiency of the high frequency drying installation.

Still this method of drying may find an economic and rational application in combination with other methods. Posnov and Pershanov suggested a combined high frequency and convective method of wood drying, where electrical energy is spent only to create a negligible decrease of positive temperature in dried boards and the moisture evaporation goes on in a usual way, i.e. with the help of recirculating air heated by the steam air heater. In this case the intensity of the combined drying is double that of the convective one and the expenditure of electrical energy is reduced by ten times compared to pure high frequency drying.

However, the drying processes can be intensified not only by creating a temperature gradient, since some materials are able to endure momentary and sometimes even prolonged heating up to 100°C and higher. In this case the evaporation of moisture can occur within the material. In 1952 a new factor determining the transfer of moisture from within the material towards its surface was discovered and the corresponding coefficient of molar transfer was derived through our investigations on high temperature methods of drying materials using different kinds of heat supply when the material is heated up to 100°C and more, or when the temperature of the material exceeds the saturation temperature at a given pressure. This factor is referred to as the total pressure gradient.

By our preliminary experiments we determined the values of the potential conductivity coefficient and the thermal gradient coefficient at different temperatures and for different moisture contents of the dried material. The corresponding temperature and moisture content gradients were determined directly from the experimental data, by measuring the temperature fields and the moisture content. All this made it possible to build the corresponding mass transfer balances. The analysis of mass transfer balances showed that the law of moisture transfer for a dried material is fully described by equation (3) only for temperatures lower than 100°C .

In cases when the temperature of separate zones within the material exceeds 100°C , one

can find a lack of co-ordination in the mass transfer balance calculated on the basis of equation (3) and this divergence is greater, the more the temperature inside the material exceeds 100°C . In these cases a noncompensated field appears in the mass transfer balance. (In Fig. 3

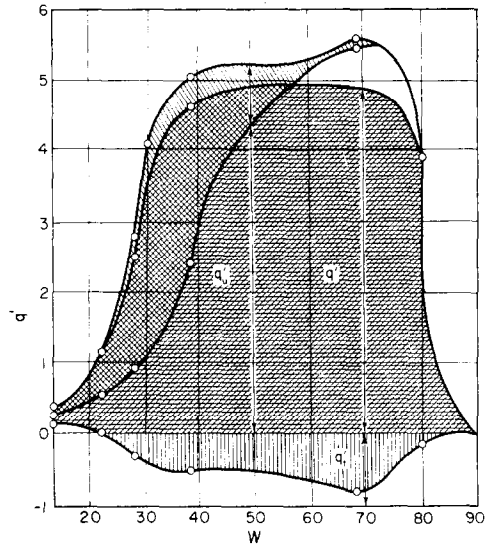


FIG. 3. The dynamics of the flow of moisture for the high radiation frequency method of drying wood.
 $E = 30 \text{ V/sm}; t = 190^{\circ}\text{C}$.

it is shaded in.) It is interesting to note that the intensity of drying and, consequently, the density of moisture flow have extremely high values in some cases of combined high frequency radiative drying in spite of the fact that at some moments there exist extremely small values both for the moisture content and for the temperature gradients (Fig. 4(c)). But the intensity of drying here should be almost equal to zero according to equation (3).

All this makes it possible to suppose that the gradient of excessive vapour pressure is the main motive force of moisture flow at temperatures exceeding 100°C in the interior of the material.

The nearer the location of a point to the surface, the less the resistance of the whole capillary system through which the vapour passes in its motion towards the surface.

Due to this we had every reason to suppose that

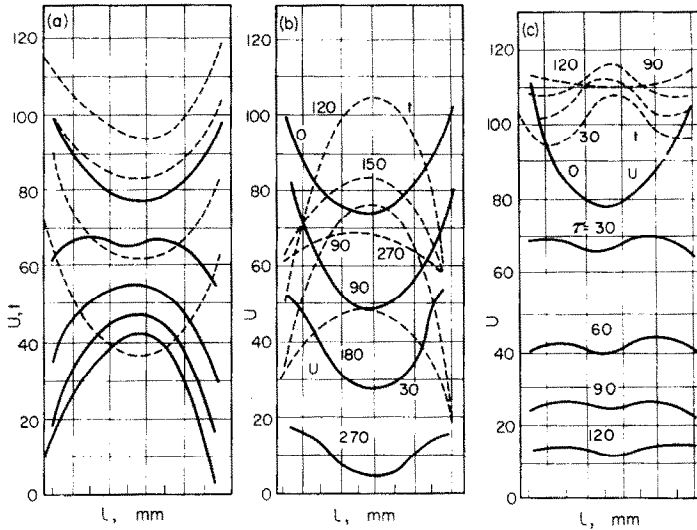


FIG. 4. Curves of moisture content and temperature distributions for different methods of heat supply: (a) For the radiation method, (b) For the high frequency method, (c) For the combined high frequency and radiation method.

in every case the value of the gradient $\partial p_B / \partial x$ has a positive value, i.e. it favours the molar motion of the vapour from the central layers to the periphery. There may exist the possibility that during this motion the vapour carries away the particles of liquid thus increasing the total flow of moisture.

The character of moisture motion under the influence of the excess pressure gradient given $\partial p_B / \partial x$, does not exclude movement under the simultaneous influence both of the moisture content and of the temperature gradients, but the role of moisture transfer owing to the thermal diffusion of moisture is very small because of the small values of δ and can be neglected.

Analysis of the mass transfer balance or of flow dynamics for high temperature drying of different materials (sand, clay, wood, etc.) showed that it is necessary to insert the third term q'_p into equation (3) which takes into account the molar transfer of vapour and moisture at the expense of the excess vapour pressure arising in the material at temperatures exceeding 100°C, i.e.

$$q' = q'_u + q'_t + q'_p = -a'\gamma_0 \nabla u - a'\gamma_0 \delta \nabla t - a_p \gamma_0 \nabla p_B \quad (6)$$

The last term on the right side of the equation represents the density of the moisture flow due to the excess pressure gradient ∇p_B .

The coefficient a_p in equation (6) may be called the coefficient of molar vapour transfer in contrast to a' which is the complex coefficient of vapour diffusion and liquid transfer under the influence of capillary and osmotic forces.

At the beginning of the drying process, when the moisture content of the material is considerable and all the capillaries are filled with moisture, the coefficient of molar vapour transfer a_p remains constant but it decreases when the moisture falls below the hygroscopic one. This coefficient also depends on the structure of the dried material (porosity and capillary radii). Fig. 5 shows the change of the vapour molar-transfer coefficient a_p at high temperature radiative high frequency drying of wood.

The differential mass conduction equation taking into account the excessive pressure gradient may be represented in the following form:

$$\frac{\partial u}{\partial \tau} = a' \nabla^2 u + a' \delta \nabla^2 t + a_p \nabla^2 p_B \quad (7)$$

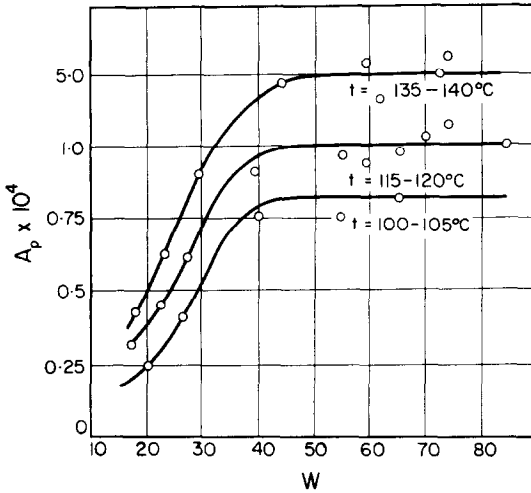


FIG. 5. The change of the molar transfer coefficient a_p for the high frequency radiation method of drying wood depending on the moisture content for different values, given the average temperature of wood.

For internal temperatures below 100°C ($p_B = 0$) or at $\nabla^2 p_B = 0$ equation (9) becomes the ordinary equation (4).

In our previous works the pressure gradient was determined in an indirect manner, but during our further investigations on the processes of wood drying in liquid media we managed to measure the pressure arising inside the wood at different temperatures applying the method of medical needles suggested by G. A. Maximov.

It should be pointed out that in our experiments we measured the excess pressure inside the material. For this purpose two capillary needles were placed at the tested depth. One capillary was soldered and measured the pressure arising from the expansion of the heated air in the capillary, while the second one measured the total pressure including that of the water vapour pressure.

The difference corresponded to the excess pressure of water vapour. It was shown by the experiments that the excess pressure on drying materials in liquid media may be observed only at temperatures above 100°C . In the experiments of Maximov the existence of considerable pressures at temperatures below 100°C was discovered by measurements with the help of

unsoldered capillaries by rapid heating with high frequency currents. Maximov explains the existence of excess pressures in some porous materials drying at $70^\circ\text{--}80^\circ\text{C}$ by air effusion through the microcapillaries from the surrounding medium into the interior of the material.

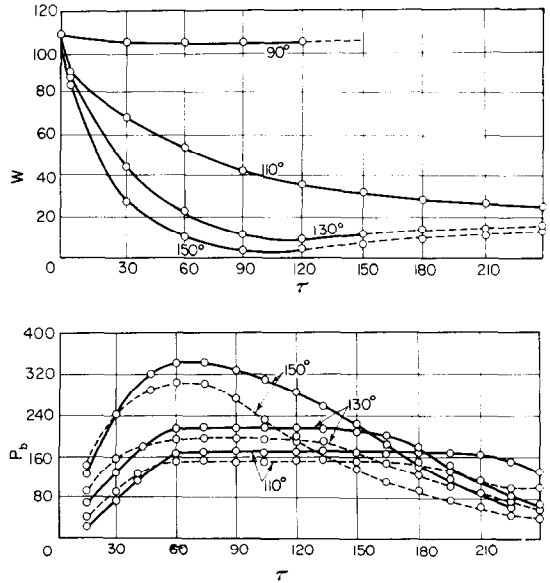


FIG. 6. The drying and pressure curves at the centre and near the surface of a block of wood at different temperatures of a liquid medium (molten paraffin).

Fig. 6 gives the diagrams for wood drying at the initial stage when it has a uniform distribution of moisture in it. The effects were observed at various temperatures of a liquid medium (melted paraffin) into which a wooden cube $50 \times 50 \times 60$ mm was placed.

The direct measurements showed that

$$\nabla p = f(t, \omega, m) \tag{8}$$

where m gives the value of the porosity of the material.

Fig. 7 shows the curves of moisture, temperature and pressure distributions along the thickness of the wood sample at the liquid temperature of 150°C .

The conclusion of some investigators that the excess pressure has to correspond to the saturation temperature is wrong. Thus, when

the moisture content is greater than the hygroscopic one ($\omega = 60$ per cent) the pressure in the centre is only 340 mm of mercury column when the temperature of the material is 150°C (Fig. 7).

The application of the wood drying method in liquids at the expense of ∇p_B gives an acceleration 8–10 times greater than for convective drying.

A more clear understanding of the mechanism of moisture transfer obtained if the complex potential conductivity coefficient a' in the differential transfer equations is replaced by the coefficient of moisture transfer a_l in a liquid phase under the action of the moisture content gradient action provided the molar and molecular transfer of vapour is taken into

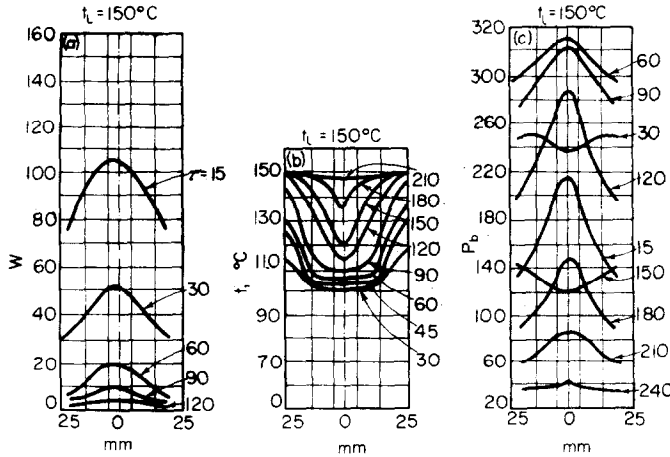


FIG. 7. The moisture, temperature and pressure distribution curves along the thickness of a sample of wood on drying it in molten paraffin at a temperature of 150°C .

The various phenomena and processes associated with materials which are being dried can be explained by the effect of the pressure gradient. Only the action of the pressure gradient can explain in the most simple way, the regularities observed in the drying of materials in organic liquids and in autoclaves with a sharp or gradual decrease of pressure, as well as the sharp increase in volume of particles at high temperature pneumatic drying of materials or of material dried in a boiling layer.

The periodical accelerations and decelerations of pastes drying on a heated surface and many other phenomena inexplicable in any other way can be explained only by the presence of internal pressure. But most important is the fact, that the pressure gradient is a powerful factor which intensifies moisture transfer at the high temperature drying of materials.

We should dwell now upon the interconnexion of the forces of moisture transfer acting within the material.

account separately. In this case the mass conduction differential equations may be presented in the following general form. The condition of drying when there is no excess pressures in the material (at low temperature drying) is

$$\frac{\partial u}{\partial \tau} = a'_i \nabla^2 u + a'_i \delta \nabla^2 t + \epsilon \frac{\partial u}{\partial \tau} \quad (9)$$

The last term of this equation takes into account molecular vapour transfer; for these conditions it is of the order of 3–5 per cent and therefore may be neglected in engineering calculations. The conditions for drying when there is excess pressure in the material (at high temperature drying) is

$$\frac{\partial u}{\partial \tau} = a_p \nabla^2 u + \epsilon \frac{\partial u}{\partial \tau} \quad (10)$$

It should be also noted, that moisture can be transferred under the action of the pressure gradient both as vapour and as liquid.

When the temperature of the material is

above 100°C and evaporation instead of drying is going on, moisture transfer in the liquid phase is small; it is possible only at the beginning when there is a considerable moisture content (higher than the hygroscopic one).

The differential equations given show their complete interconnexion. For example, at low temperature drying the transfer moisture in the material goes on only in the liquid phase and is due to the moisture gradient or the temperature gradient as well as the transfer of moisture in the form of vapour being small. But at high temperature drying the moisture transfer in the material goes on mainly in the form of vapour and the active force is the pressure gradient; the influence both of the moisture content gradient and of the temperature gradient is very small and the moisture transfer in a liquid form is also negligible.

In conclusion we shall give the heat transfer differential equation with the corresponding boundary conditions. The heat conduction differential equation which is valid for the conditions of high and low temperature drying for the various methods of heat supply to the material is:

$$\frac{\partial t}{\partial \tau} = a \nabla^2 t + \frac{\epsilon r}{c} \frac{\partial u}{\partial \tau} + \frac{q}{c\gamma} \quad (11)$$

and the boundary conditions are

$$-\lambda \nabla t_w + a(t_a - t_w) - r(1 - \epsilon)q' = 0 \quad (12)$$

For the convective and conductive methods of heat supply the third term of equation (11) is equal to zero, the second term being taken into account only for intensive methods of drying materials.

t_a and t_w are the medium and material surface temperatures respectively.

In conclusion it should be pointed out that the equations given explain the mechanism of moisture transfer and may be applied to analytical calculations and for the establishment of criteria when discussing the experimental results. The rational method of drying has to be determined on the basis of the available technology considerations and economy in drying the material.

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