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DRYING AND MOISTENING OF THIN MATERIALS IN HUMID AIR

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This study is a survey devoted to research of heat-and-mass transfer between thin wet materials and humid air conducted at the department "Industrial thermal engineering" of MSTU named after A.N. Kosygin. Conception of thin material contemplates small values compared to the unit of heat and mass transfer Biot numbers. The first value of two is determined in a traditional manner, determination of the second one is given in [1]. Under these conditions, temperature fields and humidity content fields are uniform by thickness, which enables to neglect regularities of heat and humidity transfer inside the material.

Equations of energy and mass transfer, describing change of temperature and humidity content of wet materials, are formulated on the basis of balance relations:

$$M_c c_c \left(1 + W \frac{c_c}{c_ж}\right) \frac{dt}{d\tau} = \left(\alpha_к + \alpha_р\right)\left(t_в - t\right) F + r M_c \frac{dW}{d\tau}, \quad (1)$$

$$M_c \frac{dW}{d\tau} = \mu\beta \frac{\chi_в - \chi}{1 - \chi} F, \quad (2)$$

where M – mass; c – specific heat per unit mass; r – specific heat of phase transfer; μ – molar mass of water; τ – time; α and β – heat and mass-transfer coefficients; F – surface area of heat-and-mass-transfer; $\chi_в$ and χ – molar fractions of water steam in air and on the material surface. Indices "s, zh, v, k, r" belong to dry material, liquid, air, convection and heat-transfer factors. There are no special emitters, only radiation of environment is taken into consideration, with temperature that is equal to air temperature.

Denominator in the right part of the equation (1) takes into account correction for Stefan's flow in the course of masstransfer.

These equations are transformed as follows. Mass of dry material is determined using specific density m (mass of $1m^2$) and surface area. Convection heat-exchange coefficient is expressed through its value for low intensity of mass transfer and correction for final velocity of mass transfer according to film theory [2]. Mass-transfer coefficient is transformed in a similar way, moreover, value of the last one for low intensity mass transfer is expressed by heat-exchange coefficient for the same conditions $\tilde{\alpha}$ using the heat-and-mass transfer analogy. Besides, nondimensional time (nondimensional coordinate for a material moving with a constant velocity) X is entered.

As a result, equation system is transformed as follows:

$$\left(1 + \frac{c_ж}{c_c} W\right) \frac{dt}{dX} = B\left[\left(\frac{\ln(1+\psi)}{(1+\psi)^B} + \frac{\alpha_р}{\tilde{\alpha} B}\right)\left(t_в - t\right) - \frac{r}{c_п} \ln(1+\psi)\right], \quad (3)$$

$$\frac{dW}{dx} = -\frac{c_c}{c_п} B\ln(1+\psi), \qquad (4)$$

where

$$B = \frac{c_п \mu_п}{c\mu} Le^{1-n}; \quad X = \frac{\tilde{\alpha} x}{2c_c m_c w} = \frac{\tilde{\alpha}}{2c_c m_c \tau}; \quad \psi = \frac{\chi - \chi_в}{1-\chi}; \qquad (5)$$

Le =a/D – Lewis-Semenov number that is determined using temperature conductivity of air a and diffusion coefficient of vapor in air D.

Value of molar fraction on the surface of the material has been determined using atmospheric pressure p_{at}, saturated-vapor pressure at temperature of the material $p_s(t)$ and equivalent relative humidity φ on the surface of the material and it corresponds to $\varphi p_s(t)/p_{at}$. Value φ in the range of capillary-bound moisture corresponds to $\varphi \equiv 1$, and in the absorbing area, by $W < W_{md}$, is calculated based on the equations (3):

$$\ln\varphi = \frac{\varsigma}{\rho T^2} - \left(\frac{\nu}{W} - \frac{\rho\gamma}{W^2}\right)\exp\left(\frac{\alpha}{T}\right), \qquad 0{,}07 \le \varphi < 1, \qquad (6)$$

$$W = b\varphi/(a + \varphi), \quad 0 \le \varphi \le 0.07, \qquad (7)$$

where

$$a = \frac{b - W_*}{W_*}\exp\left[\frac{\zeta}{\rho T^2} - \left(\frac{\nu}{W_*} - \frac{\rho\gamma}{W_*^2}\right)\exp\left(\frac{\alpha}{T}\right)\right], \qquad (8)$$

$$b = W_*\left[1 - \frac{1}{1 - \left(\frac{\nu}{W_*} - \frac{2\rho\gamma}{W_*^2}\right)\exp\left(\frac{\alpha}{T}\right)}\right], \qquad (9)$$

with W_{md} calculated according to equation (6) by φ = 1. Values of material and energy constants in equations (6) ÷ (9) are given in Table 1 [3] for desorption cases that are characteristic for drying process, and sorption that is characteristic for moistening process.

Table 1

Types of fibers	α,K	Sorption			Desorption		
		ς·10⁻⁷, Pa·K	ν·10³	γ·10⁹ v³/kg	ς·10⁻⁷, Pa·K	ν·10³	γ·10⁹ m³/kg
Raw cotton	1050	4,29	2,37	5,46	4,29	3,07	7,41
Ginned cotton	1050	4,29	2,29	7,00	4,29	3,00	9,56
Mercerized cotton	1050	4,29	2,73	7,88	4,29	3,58	12,20
Raw silk	1230	6,28	2,27	2,48	6,28	2,78	5,36
Degummed silk	1230	5,24	1,81	7,60	5,24	2,18	5,54
Fine wool	1080	5,15	4,14	1,75	6,67	5,91	1,75
Harsh wool	1080	5,15	4,24	1,75	6,67	5,23	1,75
Viscose rayon fiber	740	4,74	13,7	55,8	4,74	10,5	17,3
Acetate cellulose fiber	640	2,42	5,32	7,60	2,42	7,45	21,1
Cupraammonium fiber	960	5,07	5,52	20,3	5,07	6,88	27,6

Reduced equation system was solved numerically at given values of temperature and pressure and relative air humidity and initial parameters of fiber t_0 and W_0. In Fig. 1 the following is given: change in parameters of fiber – moisture content W, temperature t, rate of drying, determined as $R_d = -dW/dX$, as well as air temperature $t_в$ in the process of drying, which continues until equilibration state is reached, during which rate of drying is transformed into zero, values of air and fabric temperature become equal, rate of drying is transformed into zero. The diagram demonstrates three characteristic stages of drying – initial period, periods of constant and decreasing rate of drying. During the initial period temperature of fabric can rise or drop depending on the relation between the initial temperature t_0 and temperature of wet-bulb thermometer $t_М$. With $t_0 < t_m$ temperature of fiber rises, in addition, if it is lower as dew-point temperature, i.e. rise of temperature, to a considerable degree, is caused by steam condensation from air. With $t_0 > t_М$ temperature of fabric decreases. During the period of constant rate of drying, temperature of the material is coincident with t_m. Period of decreasing rate of drying is caused by removal of hygroscopically bound moisture.

Comparison conducted with results of the experiment for a fine cotton fabric revealed satisfactory agreement at air temperatures up to 100°C.

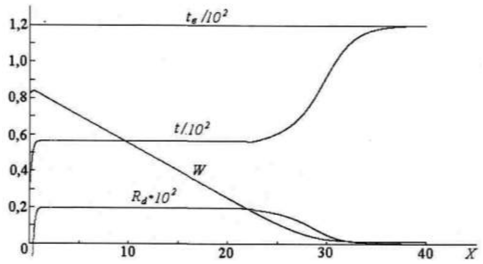

Fig. 1

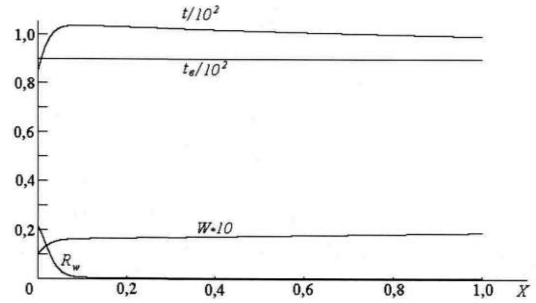

Fig. 2

The same equation system was used for description of fabric moistening processes at constant air parameters. In Fig. 2 initial stage of the moistening process and the same curves are given as in Fig. 1, except that the curve of rate of drying is replaced by a curve of rate of moistening determined as $R_w = dW/dX$. In this case, temperature of fabric can exceed air temperature due to heat emission of phase change, which includes also heat of sorption. This fact is known from technical literature and was established experimentally in earlier studies of other authors.

In order to describe processes of heat-and mass transfer at variable air parameters, the mentioned system should be accompanied by equations which determine the change of temperature of air and its moisture content. These equations take the following form [4]:

$$\pm g_в \frac{c_в}{c_т}\left(1+\frac{c_п}{c_в}D\right)\frac{dt_в}{dX} = B\left[\left(\frac{\ln(1+\psi)}{(1+\psi)^B}+\frac{\alpha_р}{\tilde{\alpha}B}\right)(t-t_в)\right] \mp \frac{c_п(t-t_в)}{c_f}\frac{dW}{dX}, \quad (10)$$

$$g_в dD = \mp dW, \quad (11)$$

in this case $g_в = G_в/G_т$. Indices "п, т" relate to vapor and fabric; D – moisture content of air.

In the equations (10), (11) in the terms with double sign, the upper one belongs to the case of direct flow, the lower one – to the case of counter flow.

System of differential equation system was solved numerically. In case of direct flow we obtain Cauchy problem – initial parameters of fabric t_0 and W_0 and air $t_{в0}$ and D_0 are set at the inlet to the dryer and give no rise to fundamental difficulties. With counter flow, initial parameters of fabric are set from one side of dryer, and those of air – from the opposite side, and during resolving the system we had to resort to iterative procedure according to secant method.

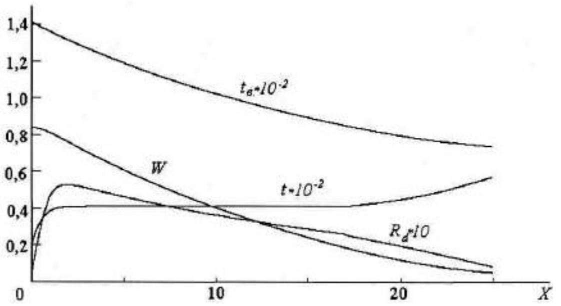

Fig. 3

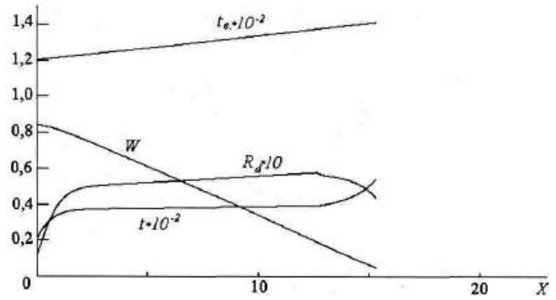

Fig. 4

Computing results are given in Fig. 3 for the case of direct flow, and in Fig. 4 for the case of counter flow. Designation of curves is the same as in Table 1. As we can see in both cases, sections of constant rate of drying are missing, though temperature of fabric changes insignificantly at the section of removal of capillary moisture (excluding initial period). The analysis revealed that this change is determined by dependence of thermal capacity on temperature. Removal of hygroscopically-bound moisture is followed by decrease of rate of drying and notable increase of temperature in the material.

Comparison of drying efficiency in the modes of direct and counter flow revealed that process duration and specific heat consumption in the last case are less. This difference is significantly bigger in case of relatively small air consumption.

Method for rating of a multisection dryer has been suggested. First of all, approximate method of rating [5] of distribution of suction devices along the length of the machine depending on the location of the point of release of waste air has been developed that enabled us to calculate air escape from one section into another one. On the basis of these data, equations of material balance on dry air and vapor, as well as heat balances have been formulated for a certain generalized section containing a section of fabric, section of safeguarding barrier, blower as a flow mixing unit and a heater [6], [7]. On the basis of such equations for separate sections, the whole drying machine was designed [8]. Design data are in satisfactory agreement with the data of industrial experiment which has been carried out by other authors.

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