



KINETIC MODELS OF DRYING OF TEXTILE PRODUCTS

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Abstract: Examined are the rate of evaporation of moisture from the clothing items. An attempt was made to find solutions based on the equations for the transfer of moisture in the form of liquid and vapor in the vapor space of the different food materials. The results were processed and presented in graphical form.

Keywords: drying of textile, capillarity model

I. Introduction

Moisture heat treatment is widely applied in technological processes in the production of clothing items and largely determines the quality and appearance of the product. The aim is to obtain a stable deformation of the device, Wilson (2001). According to Carr and others. (2006) in making outerwear on MHT falls to 25% of the total technological time, and in the manufacture of underwear (5-7) %.

For proper operation of this process it is necessary the right combination of the parameters temperature, humidity, pressure, and duration of the process, so as to obtain the desired shape and strength of the device. Incorrect formulation of these values leads to a distortion of the production cycle and the occurrence of defects in the product. Moisture-heat treatment consists of three stages:

First stage of MHT-steaming (preparation of material deformation);

Second stage of MHT-deformation of the material drying;

Third stage of MHT-fixation of deformation.

II. Exposure

Proposed models and experimental results are based on theory and Nerpin Churaev (1966) that at a constant relative humidity, moisture evaporation starts from the surface of the capillaries of the material and form concave meniscus. If the value of φ_0 is smaller than the value φ_1 over meniscus limit curvature of the largest capillaries, the further evaporation of moisture leads to a fall in their level of the meniscus, that is characterized by the coordinate X. This theory much later was expanded from Penchev and others. (2011) and Angelov and others. (2012) and gives good results.

At isothermal conditions, the amount of moisture that evaporates from the larger capillaries is determined by

$$\dot{m}_1 = \frac{D p_s M A_1 (\varphi_1 - \varphi_0)}{RT(X + x_0)} \quad (1)$$

wherein A_1 the total area of the large capillaries, D coefficient of diffusion of the vapor in the air, x_0 - bent border thickness of the surface layer, p_s - partial pressure of saturated steam at a temperature T , M - molecular mass of water, and R - the universal gas constant.

The relative humidity above the meniscus of large capillaries is determined by the relationship

$$\varphi_1 = \exp\left(-\frac{2\sigma M}{\rho R T r_1}\right), \quad (2)$$

wherein ρ - density and σ - surface tension of water.

The model assumed that the walls of the capillaries are completely moistened with water and large amounts of capillaries is such that the influence of the layered transmission of moisture therein can be ignored.

When the difference between capillarity pressures in the meniscus of the small and large capillary is sufficient to raise the distance X of a quantity of water which can evaporate from the small capillaries, the position of the meniscus in them (gradually increasing its curvature) will not be modified. The amount of moisture that evaporates from the narrow capillaries in this case will be

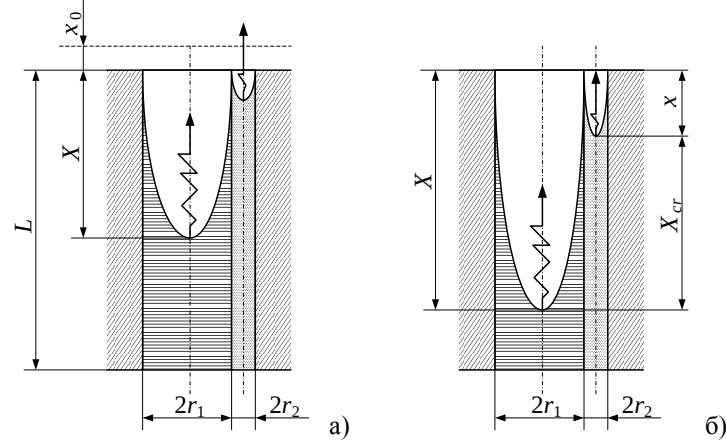
$$\dot{m}_2 = \frac{D p_s M A_2 (\varphi_a - \varphi_0)}{R T x_0}, \quad (3)$$

where: A_2 the total area of the sections of the small capillaries; φ_a - relative humidity of the air above her meniscus while $\varphi_1 > \varphi_a > \varphi_2$. Here φ_2 is the relative humidity of the air above the meniscus of tiny capillaries

at the maximum curvature:

$$\varphi_2 = \exp\left(-\frac{2\sigma M}{\rho R T r_2}\right). \quad (4)$$

Figure 1 Capillarity model of the porous body



Mass flow of the fluid flowing through small capillaries can be represented using the law of Puaziel in the following form

$$\dot{m}_2 = \frac{A_2 r_2^2}{8\eta X} (\Delta p - \rho g x), \quad (5)$$

Here η is the viscosity of the water, and Δp is the difference in the capillarity pressures causing movement

$$\Delta p = 2\sigma \left(\frac{1}{r_0} - \frac{1}{r_1} \right), \quad (6)$$

where r_0 is the radius of curvature of the meniscus in the small capillaries of the surface of the model body. Limit value of Δp , which will hereafter be marked with Δp_{cr} , will obviously be determined by the condition.

$r_0 = r_2$.

From dependencies of Eq. (2) and Eq. (6) is found the value φ_a .

$$\varphi_a = \varphi_1 \exp\left(-\frac{\Delta p M}{\rho R T}\right). \quad (7)$$

Using the obtained expression can be found from the dependence of φ_a from X , excluding m_2 from Eq. (3) and Eq. (5)

$$X = \frac{\rho \left(\frac{RT}{M} \right) \ln \frac{\varphi_1}{\varphi_a}}{\left(\frac{8\eta}{r_2^2} \right) \frac{D p_s M (\varphi_a - \varphi_0)}{RT x_0} + \rho g}. \quad (8)$$

The condition in which the narrow capillaries does not drop the meniscus can be written as $\varphi_a \geq \varphi_2$ or $\Delta p \leq \Delta p_{cr}$.

The position of the meniscus in the large capillaries X_{cr} , in which began the dropping of the meniscus in the small ones is found from Eq. (8), assuming $\varphi_a = \varphi_2$:

$$X_{cr} = \frac{2\sigma \left(\frac{1}{r_2} - \frac{1}{r_1} \right)}{\left(\frac{8\eta}{r_2^2} \right) \frac{\dot{m}_2}{A_2} + \rho g}. \quad (9)$$

When $X \leq X_{cr}$ position of the meniscus in the small capillaries fully coincides with the surface of the pores body, and when $X > X_{cr}$ starts their displacement in depth of the specimen.

The intensity of the evaporation of moisture from the body model in the first stage of drying is characterized by the conditions $X < L < X_{cr}$ и $X < X_{cr} < L$ and is determined by the dependence:

$$i = \frac{\dot{m}_1 + \dot{m}_2}{A} = i_0 \left[\frac{A_s x_0 (\varphi_1 - \varphi_0)}{(X + x_0)(1 - \varphi_0)} + \frac{(1 - A_s)(\varphi_a - \varphi_0)}{1 - \varphi_0} \right], \quad (10)$$

where

$$i_0 = \frac{Dp_s M(1-\varphi_0)}{RTx_0} \quad (11)$$

is the intensity of evaporation from the free surface of the water in the test conditions. The magnitude $A_* = A_1/A$, wherein $A = A_1 + A_2$ accounts the ratio between the number of large and small capillaries in the model body.

For macroporous bodies [$r_2 \geq 10^{-5} \text{ cm}^2$] values for φ_a and φ_1 are slightly different from 1. Then

$$\frac{i}{i_0} \approx 1 - \frac{A_* X}{X + x_0}. \quad (12)$$

As seen from the dependence Eq. (12), evaporation rate in the drying process falls to $i = i_0$ at $X = 0$ to $i/i_0 \approx 1 - A_* = \text{const}$ at $X \gg x_0$. The value has to be established in the first period of drying at a constant evaporation rate *ceteris paribus* depends only on the ratio between the quantity of large and small capillaries, i.e. the structure of the model body.

By entering the value of the average moisture content corresponding to the degree of filling the steam space with water

$$\omega = 1 - A_* \frac{X}{L}, \quad (13)$$

Switching from equation type $i = f(X)$ into dependence of the type $i = f(\omega)$. To obtain the value for i as a function of time for performing the test τ in the drying equation

$$i = \rho A_* \frac{dX}{d\tau} \quad (14)$$

has to be replaced i from Eq. (10) or (12) and to solve the resulting differential equation. If equation (12) is used the decision will have the type

$$\tau = \frac{\rho A_*}{(1 - A_*)i_0} \left\{ X + x_0 + \frac{A_* x_0}{1 - A_*} \ln[X(1 - A_*) + x_0] \right\}. \quad (15)$$

At $X \gg x_0$ Eq. (15) will switch to equation with a constant evaporation rate, where τ and X are related linearly

$$\tau = \frac{\rho A_* X}{(1 - A_*)i_0}. \quad (16)$$

For microporous bodies [$r_2 \leq 10^{-6} \text{ cm}^2$] from Eq. (6) and (7) the terms for the influence of the force of gravity can be ignored, i.e. to allow random orientation of the capillaries of the model. The decision on the intensity of the evaporation in the first period of drying can be obtained as in Eq. (10) the value of φ_a has been replaced from Eq. (9), applying $\rho g = 0$. After remitting the following is obtained:

$$\frac{i}{i_0} = \frac{A_* x_0 (\varphi_1 - \varphi_0)}{(X + x_0)(1 - \varphi_0)} + \frac{1 - A_*}{\frac{8\eta D p_s M^2}{\rho R^2 T^2 r_2^2} \left(\frac{X}{x_0} \right) + 1}. \quad (17)$$

At $\varphi_1 \approx 1$ и $X \gg x_0$ equation (17) turns into $i/i_0 \approx 1 - A_*$. Accordingly, the first period of drying the model body is always characterized by a section with a relatively constant rate of evaporation.

If the height of the model $L < X_{cr}$, then after the evaporation of the water from the largest pores begins evaporation of the water from the small capillaries. The second stage of drying is determined by the values of $\tau = \tau'$ и $\omega = \omega'$, which are determined by Eq. (13) and Eq.(16), where $X = L$.

When analyzing the second drying step introducing magnitude linear rate of evaporation of moisture from the capillaries, $u, \text{ cm}^2 / \text{ s}$, Deryagin and others (1964). Then the position of the meniscus in the capillaries of small size, further noted with x will be

$$x = \frac{\rho u (1 - A_*)}{i}. \quad (18)$$

Differentiating both sides of Eq. (18) by the time τ will obtain

$$\frac{dx}{d\tau} = - \frac{\rho u (1 - A_*)}{i^2} \frac{di}{d\tau} \quad (19)$$

So for the second drying step the intensity of evaporation, by analogy with Eq. (14) will be rewritten in the form

$$i = \rho (1 - A_*) \frac{dx}{d\tau}. \quad (20)$$

Taking the dependence of $dx/d\tau$ from Eq. (20) in Eq. (19), finally for the intensity of evaporation in the second period of the drying will be obtained

$$i = \frac{i'}{\sqrt{\frac{i'^2(\tau - \tau')}{2u\rho^2(1 - A_*)^2} + 1}}. \quad (21)$$

Here i' is the intensity of evaporation at the end of the first drying step and may be considered equal to $i_0(1 - A_*)$.

Solving together equations (18) and (20) we can write

$$x = \sqrt{2u(\tau - \tau')}. \quad (22)$$

Replacing in Eq. (21) $\tau - \tau'$ with its meaning from Eq. (22) and entering $i_0 = u_0\rho/x_0$, where u_0 is linear evaporation rate without taking into account layered transmission, we get the final expression for the intensity of drying during the second period of drying

$$i = \frac{i_0(1 - A_*)}{\sqrt{\left(\frac{x}{2x_0} \frac{u_0}{u}\right)^2 + 1}}. \quad (23)$$

The values for u/u_0 for some model materials can be found in Lykov (1950, 1968). Here instead x in the equation can be entered in the average moisture content values, which are equal in the second drying step:

$$\omega = (1 - A_*) \left(1 - \frac{x}{L}\right). \quad (24)$$

In cases where the height of the model $L > X_{cr}$, is possible a transitional regime, characterized by the simultaneous reduction of the meniscus in the large and small capillaries. In this way the distance between the position of the meniscus, Fig. 1b is not constant and is equal to X_{cr} . The values for X_{cr} can be found from

Eq. 9, in which instead $\dot{m}_2$ should be placed overflow mass discharge

$$\Delta \dot{m} = \dot{m}_2 - (1 - A_*)(\dot{m}_1 + \dot{m}_2). \quad (25)$$

Beginning of the transition regime is determined by the condition $X = X_{cr}$, and the end with the condition $X = L$. Amount of moisture evaporation at this stage of the large capillaries is determined by

$$\dot{m}_1 = \frac{Dp_s M A_1 (\varphi_1 - \varphi_0)}{RTX}. \quad (26)$$

The corresponding moisture flow from the small capillaries considering the layered transfer Churaev (1966) and Deryagin *et al.* (1964) will be

$$\dot{m}_2 = \frac{\rho u A_2}{x} = \frac{\rho u A_2}{X - X_{cr}}. \quad (27)$$

Considering that $\varphi_1 \approx 1$ for the intensity of evaporation of moisture from the capillary model in the transition regime is obtained

$$\frac{i}{i_0} = \frac{A_* x_0}{X} + \frac{(1 - A_*) x_0}{X - X_{cr}} \left(\frac{u}{u_0}\right). \quad (28)$$

Substituting in the case with the expression $X_{cr} = \frac{2\sigma \left(\frac{1}{r_2} - \frac{1}{r_1}\right)}{\frac{8\eta A_* i_0}{(1 - A_*) r_2^2} \left(\frac{i}{i_0} - \frac{x}{X}\right) + \rho g}$, can easily find a precise expression ratio i/i_0 .

It should be noted that the value for the macroporous bodies of hydraulic losses in the expression for X_{cr} from Eq. (9) is significantly smaller than the value ρg . Therefore, further calculations can be considered

$$X_{cr} = \frac{2\sigma \left(\frac{1}{r_2} - \frac{1}{r_1}\right)}{\rho g} = const, \quad (29)$$

which significantly simplifies them. Ignoring the hydraulic losses may be allowed only $r_2 \geq 10^{-3} \text{ cm}$ for $\varphi_0 \approx 0$ and $r_2 \geq 10^{-4} \text{ cm}$ at $\varphi_0 \approx 0.9$.

III. Experimental results

Test material is textile with thickness 480 μm . The feed rate of the needle is taken for the speed of drying of the fabric - 0.1 m/s. The temperature during the drying has changed in a range - 105-109° C. The measured diameter of the macropores is 240 μm and the diameter of the micropores - 5 μm . The results of the tests are shown in Fig.2-6

Figure 2. Alteration of the amount of moisture evaporated from large capillaries, depending on the drying temperature

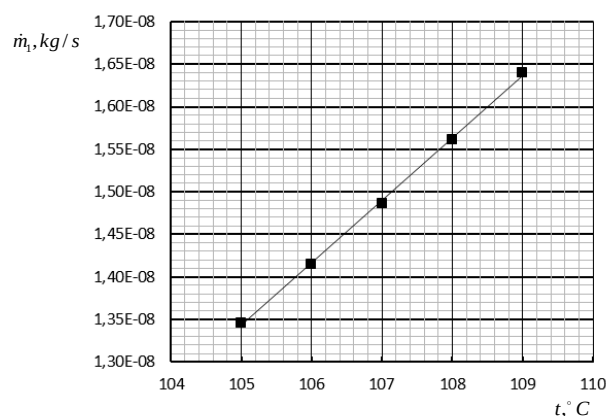


Figure.3. Alteration of the amount of moisture evaporated from the small capillaries depending on the drying temperature

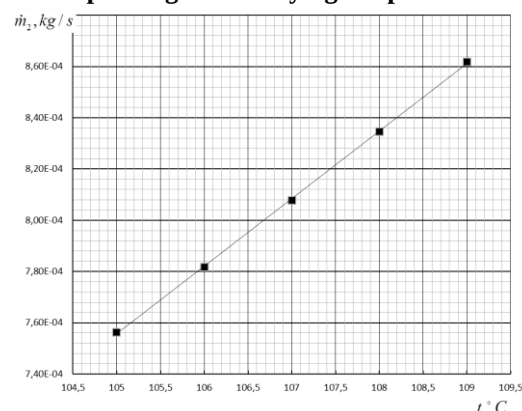


Figure.4. Variation of the intensity of evaporation in the second drying period depending on the temperature

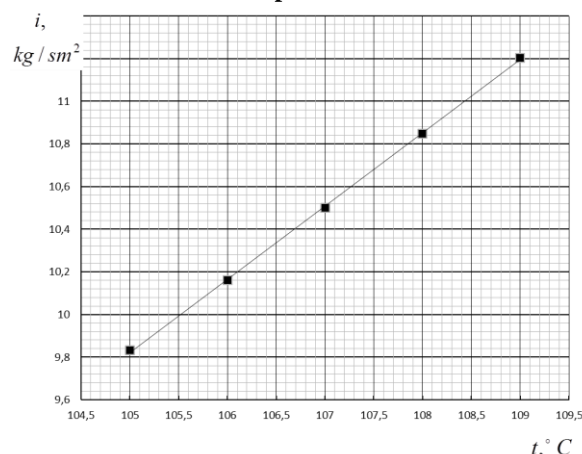


Figure.5. Variation of the intensity of evaporation in the first period of drying depending on temperature

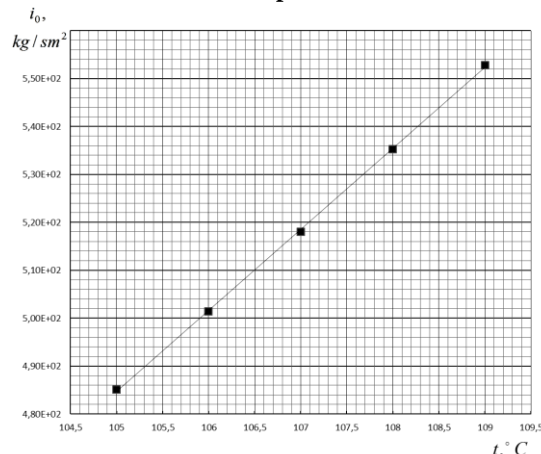
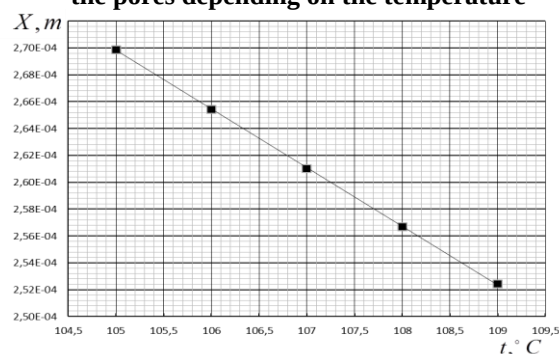


Figure 6 Modification of the height of the meniscus of the pores depending on the temperature



As can be seen from the figures, with an increase of the drying temperature of the evaporated moisture for the macro - and micropores increases linearly. The same is true for the intensity of drying the first and second period.

Vice versa height of the meniscus of the macrocapillaries decreased with increasing the temperature.

Although capillary model is not considered universal because it does not take into account a number of factors, such as the possible shrinkage of the samples and more. It gives a real idea of variations in the parameters of the material during drying.

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