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# Moisture Adsorption with Capillary-Porous Textile Materials in Air Conditioning Systems

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**Annotation**

Analytical and regression dependences and methods for determination of physical and regression parameters that take place in the mathematical model of moisture adsorption with capillary-porous textile materials in air conditioned atmosphere. A comparison of the calculated and experimental dependences of equilibrium moisture of textile fibers on the relative humidity of the air is represented, their good compatibility is shown.

**Keywords**: textile fibers, capillary-porous medium, sorption isotherms, relative humidity, method of least squares, mathematical model

## INTRODUCTION

Nowadays, experimentally obtained sorption isotherms, i.e. dependences of fiber equilibrium moisture % on the relative humidity of the air $W_p$ % on the relative humidity of the air φ(x) at the constant temperature $t_i$, are used in determining the parameters of inside air: relative-humidity φ, % and temperature $t_i$, °C in industrial premises in order to provide high quality process of textile fiber processing.

Experiments require significant costs associated with the use of modern equipment and devices, as well as the high-precision measurement of required parameters.

To solve the problems mentioned, the Article offers analytical dependence $W_p=f(\varphi)$, for determining the parameters of internal microclimate existing in production facilities of textile enterprises.

## MATERIALS AND METHODS

Mathematical model for moisturizing of the material in the volume-porous medium [1] suggests the possibility to consider the dependence of equilibrium moisture $W_p(x)$, % at any point of pseudohomogeneous medium $x$ on the relative humidity of the air φ(x), %.

The modern theory of moisture adsorption does not provide any strict analytical dependence $W_p=f(\varphi)$ throughout the measurement φ (from 0 % to 100%). There are many under-approximations to the description of such dependence, for example, [2, 3, 4], but all formulae known in literature adequately describe the function $W_p=f(\varphi)$ only in rather close limits of changes in the relative humidity φ, %.

Fig.1 shows graph dependences of equilibrium moisture of the textile material $W_p$ on the relative humidity of the air φ, % available from experiments.

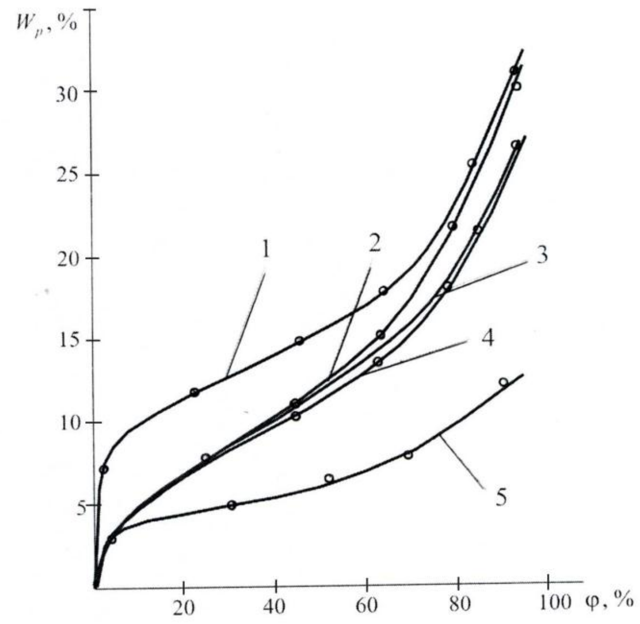



**Figure 1.** Experimental dependences $W_p=f(\varphi)$:
1 – Yarn, 2 – Viscose, 3 – Wool, 4 – Sliver, 5 – Nylon

As it is known, the shape of sorption isotherm is determined by the shape of moisture dependence on the moist material [5].

In the first segment, the isotherm sorption, at the relative humidity in accordance with the interval from 0% to 10%, has an upward convex curve, and characterizes the monomolecular adsorption.

In the second segment, the sorption curve, when changed from 10% to 60%, is straight-line and corresponds to the polymolecular adsorption.

In the third segment, the sorption curve, when φ(x) changed from 60% to 100%, changes its direction of convexity and corresponds to capillary condensation of moisture.

Analyzing the form of sorption curves (Fig. 1), it can be seen that it is reasonable to distinguish two segments of each curve in order to give a regression description of the experimental dependence: if $0<(x)<\varphi_s$ – upward convex segment of the curve, and if $\varphi_s<\varphi(x)<100\%$ – downward convex segment of the curve. Here, $\varphi_s$ is an averaged parameter (constant) from the interval 10% – 60% having a specific value for each type of textile material. Let's determine an analytical dependence of equilibrium moisture content on the air flow moisture in the first and second segments $W_p=f(\varphi)$, considering the following. In the first segment of adsorption curve, it is logical to assume that the growth rate of absorbed moisture volume is prosegmental to the volume of adsorbed moisture, firstly, to its value at the given humidity φ, since moisture molecules provide additional adsorption centers. In other words, the growth rate of moisture adsorption in keeping with the relative humidity of the air flow $\frac{dW_p}{d\varphi}$ is prosegmental to $W_p$. Then, the value of $\frac{dW_p}{d\varphi}$ must be prosegmental to the difference $(W_m$-$W_p)$**,** where $W_m$ – constant, characterizing the maximum moisture content of the porous material. Such value determines the potential growth of the equilibrium moisture content $W_p$.

Summing everything up, get the equation:

$$\frac{dW_p}{d\varphi} = k \cdot W_p \cdot \left(W_m - W_p\right), \qquad (1)$$

where k – prosegmentality coefficient.

The solution of the equation depends on a constant $W_n$, characterizing initial equilibrium moisture content of fibers:

$$W_p = \frac{W_n}{1+\left(\frac{W_n}{W_m}-1\right)e^{-k\varphi}}. \qquad (2)$$

Note that according to the model (2), the maximum rate of $W_p$ changing will take place, if $\frac{d^2W_p}{d\varphi^2}=0$, that is when

$$k^2 \cdot W_p \cdot \left(W_m - W_p\right)\cdot\left(W_m - 2W_p\right) = 0. \qquad (3)$$

And since $0< W_p < W_m$, then $W_p = \frac{W_m}{2}$. Wherein

$$\varphi = \frac{1}{W_m \cdot k}\cdot \ln\left(\frac{W_m}{W_n}-1\right). \qquad (4)$$

The last formula can be useful for solving issues connected with the optimization of capillary-porous textile fiber moisturizing, depending on the relative humidity of air conditioned atmosphere φ.

In the second segment of φ changes at $\varphi \geq \varphi_s$, another mechanism for capillary-porous medium moisturizing is activated, which has a monolayer, and then capillary character. It is natural to assume [6] that the increase of $W_p$ with the growth of φ has exponential character:

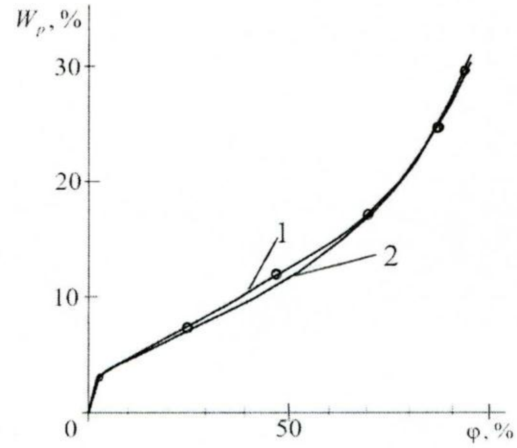
$$W_p = k_2 \cdot e^{k_1(\varphi-\varphi_s)}, \qquad (5)$$

where $k_1$, $k_2$ и are some "working" constants whose value can be selected through experiments by the method of least squares.

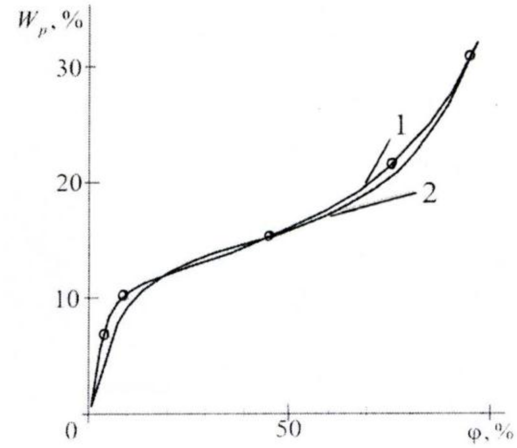
Summing up the described cases (2) and (5), we will get the general expression of dependence $W_p=f(\varphi)$:

$$W_p = k_2 \cdot e^{k_1(\varphi-\varphi_s)} + \frac{W_m}{1+\left(\frac{W_m}{W_n}-1\right)e^{-k\varphi}}. \qquad (6)$$

Fig. 2 (a-e) shows experimental – 1, corresponding to given in Fig.1, and theoretical – 2 moisture sorption isotherms for various capillary-porous materials (viscose, yarn, wool, nylon, sliver).




**(a)**

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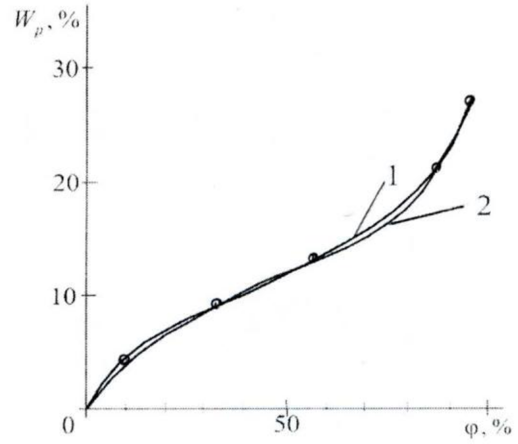


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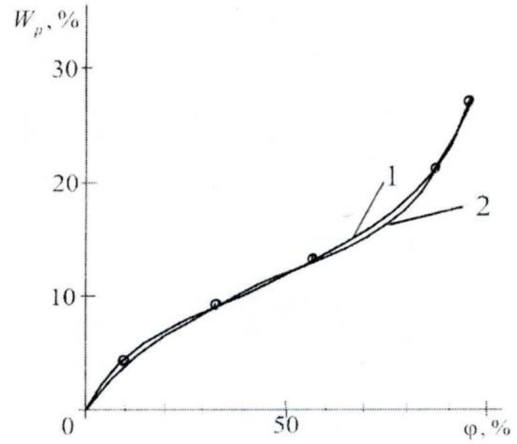


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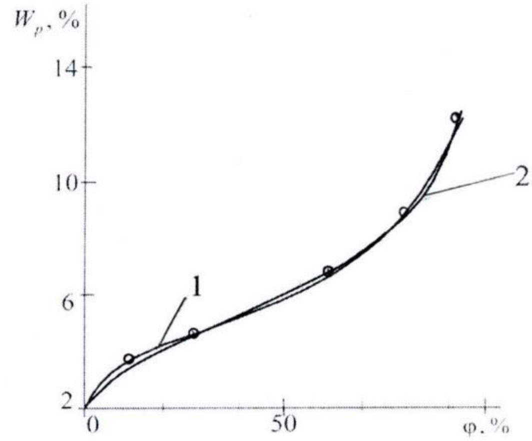


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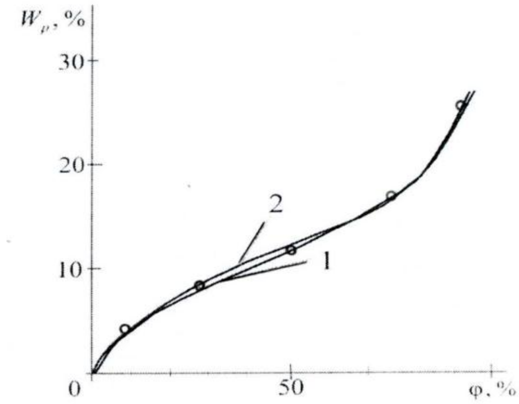


**(e)**

**Figure 2.** Experimental (1) and theoretical (2) dependences $W_p = f(\varphi)$:

a – Viscose; b – Yarn; c – Wool; d – Nylon; e – Sliver

The following Table 1 shows the parameters of the calculated curves (6) found by the method of least squares.

The proposed model for dependence of equilibrium moisturizing of capillary-porous material on the relative humidity of the air flow $W_p=f(\varphi)$ is the product of the two areas of mathematical modeling: computational and research, based on the use of physical prerequisites and description of processes, and experimental and statistics, when the kind of mathematical dependences is based solely on the mathematical processing of experimental data.

**Table 1:** Parameters for calculating adsorption isotherms of moisture for capillary-porous materials

| Type of material | $W_m$ | $W_n$ | $k_2$ | $k_1$ | k | $\varphi_s$ | Sum of squared deviations | Maximum deviation, % |
|---|---|---|---|---|---|---|---|---|
| Viscose | 14,9 | 3,5 | 3,0 | 4,4 | 3,3 | 0,55 | 2,5 | 7 |
| Yarn | 13,0 | 6,0 | 3,0 | 4,5 | 10,0 | 0,55 | 1.8 | 5 |
| Wool | 13,0 | 2,7 | 2,0 | 6,6 | 6,5 | 0,65 | 1,9 | 7 |
| Sliver | 13,0 | 2,7 | 2,0 | 6,5 | 7,0 | 0,65 | 2,4 | 7 |
| Nylon | 8,5 | 3,1 | 0,9 | 5,95 | 23,0 | 0,66 | 0,84 | 9 |

As for the methodology of determining other physical and effective constants, such constants are used in the mathematical model of moisturizing process for capillary-porous textile material obtained in the work [1], which dealt with the processes of conditioned air penetration into the compact medium, which is a bobbin with sliver, spindles with yarn, ribbon and so on.

## RESULTS AND DISCUSSION

Discussion of constant values present in the proposed [1] mathematical model starts with porosity ε pseudohomogeneous medium, components of which are textile fibers.

The porosity ε impacts the value of medium surface $F_{sp}$, $m^2/m^3$, movement rate of moisturizing air in the volume of medium w, *m/s*, value of $W_n$, characterizing the maximum moisture content and some other characteristic parameters of the medium and moisturizing process.

The porosity is determined based on the weight of the capillary-porous material G, *kg*, volume of the sample V, $m^3$ and density of fibers ρ, $kg/m^3$, forming the material:

$$\varepsilon = 1 - \frac{G}{V \cdot \rho}. \tag{7}$$

It should be noted that the porosity ε is always less than 1, or, in percentage terms, is less than 100%.

An important role in the effectiveness of the moisturizing process and mathematical model structure is played by a specific surface area of the porous medium $F_{sp}$, $m^2/m^3$. Obviously, the larger the value of $F_{sp}$ is, the greater amount of moisture can be adsorbed in the capillary-porous material, and therefore, the more efficient the process of moisture adsorption can be. The value of $F_{sp}$ is mainly determined by the radius of fibers r, *m*, material density ρ, $kg/m^3$ and material porosity ε.

It should also be noted that the paper [1] and the publication consider the average specific surface area of volume-porous medium $F_{sp}$ formed by compactly prepared textile material, rather than specific adsorption surface area mainly formed by the smallest pores, unevenness, roughness and so on, which must be considered in the study of adsorption properties of different materials.

In the simplest case, the specific surface area of porous medium can be calculated by the following formula on the assumption on regular structure of material fibers and not considering fiber roughness:

$$F_{sp} = \frac{2p_e}{\rho \cdot r}, \tag{8}$$

where $p_e$- mass of material volume unit, *kg* ;r – average fiber radius, m.

The formula (8) is obtained as follows.

The volume occupied by the threads (yarns) in the volume of the capillary-porous material is calculated in accordance with the formula:

$$V_e = \frac{p_e}{\rho}. \tag{9}$$

Square of cylindrical surface of the thread of unit length:

$$F_c = 2\pi \cdot r. \tag{10}$$

Volume of cylindrical thread of unit length:

$$V_c = \pi \cdot r^2. \quad (11)$$

Then the number of threads $k_n$ is equal to:

$$k_n = \frac{p_e}{\rho \cdot \pi \cdot r^2}. \quad (12)$$

Therefore,

$$F_{sp} = k_n \cdot 2 \cdot \pi \cdot r = \frac{2p_e}{\rho \cdot r}. \quad (13)$$

To determine all values of the specific surface area, being close to real values of $F_{sp}$ for different materials under consideration, it is necessary to perform the statistical processing of experimental data about the dependence of $F_{sp}$, $m^2/m^3$ on r, m and ε, % by the method of least squares:

$$F_{sp} = a_0 + a_1 r + a_2 \varepsilon + a_3 r\varepsilon. \quad (14)$$

Studies have shown that the following formula is true in the limit of 10 % of mistakes for sufficiently broad limits of changing r:

$$F_{sp} = 3066{,}9 \cdot 10^2 - 574{,}9 \cdot 10^6 r + 24{,}5\varepsilon. \quad (15)$$

It should be noted that considering the significance of regression model coefficients (14), it is enough to consider only linear relationships between $F_{sp}$, r, ε.

Regarding the rate of moisturizing air movement, the following should be noted.

If the volume rate of air flow $w_v$, *m³/s* is set in the moment of penetration to the porosity medium, then the linear rate w, *m/s*, being a part of the mathematical model [1], is easier to find in the following way:

$$w_v = \frac{w}{\varepsilon \cdot f}, \quad (16)$$

where *f* - cross-sectional area of the porous medium, $m^2$.

It is obvious that as the material becomes moist, the current linear flow rate $w_\tau$ can be reduced due to air flow stagnation in porous medium. The correction factor can be used in the calculations that require great precision for the consideration of changes in air flow rate:

$$P_k = \left( \frac{W_m - W_n}{W_m} \right)^m, \quad (17)$$

where m is a positive integer. Then

$$w_\tau = w \cdot P_k = w\left( \frac{W_m - W_n}{W_m} \right)^m. \quad (18)$$

The approximation accuracy (6) for dependence of equilibrium moisture content of the fibers $W_p$ on the relative humidity of air flow φ is significantly impacted by such coefficients, as k, $k_1$ and $k_2$. And the most important is k in the part of the equation, which is responsible for primary and middle segments of moisture adsorption curve (2).

Coefficient k can be calculated using experimental data and modified equation (2):

$$\ln\left(\frac{W_m}{W_p} - 1\right) - \ln\left( \frac{W_m}{W_n} - 1 \right) = -k\varphi. \quad (19)$$

Then, using the method of least squares, we find k:

$$k = \frac{\sum_{i=1}^{u} \varphi_i \ln\left( \frac{W_m}{W_p} - 1 \right) - \ln\left( \frac{W_m}{W_n} - 1 \right)}{\sum_{i=1}^{u} (\varphi_i)^2}. \quad (20)$$

Here, $\varphi_i$ and $W_n$ are values of the relative humidity of air φ, %, and equilibrium moisture of fibers $W_p$, % in case of i-th measurement.

Coefficients $k_1$ and $k_2$ can be calculated in the same way.

## CONCLUSIONS

1) Possible methodologies for determining effective physical and regression constants, allowing at sufficient degree of accuracy to simulate the processes associated with the movement of the air flow into the medium, as well as moisture adsorption in capillary-porous textile materials, are considered.
2) It is shown that to adequately describe real physical regularities in the changing of moisture content in the capillary-porous material by means of equations stated in the work [1], and equations (6)-(20) of the publication, often it is necessary to consequently correct the values of all model parameters and constants, achieving the required level of compliance between the calculated and experimental values.
3) Analysis of equations and graphic curves allows to conclude that the mathematical dependence (6) accurately describes the equilibrium process of textile fibers interaction with air conditioned atmosphere, with the maximum deviation of 5%... 9% of the calculated values from the experimental values. They can be used without additional experiments.

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