

INVESTIGATION OF THE MECHANISM OF MOISTURE ABSORPTION IN COLLOIDAL MUSEUM MATERIALS IN ORDER TO IMPROVE THE SAFETY OF EXHIBITS AND IMPROVE THE HYGIENE OF MUSEUM ROOMS

doi: 10.2478/czoto-2019-0103

Date of submission of the article to the Editor: 24/11/2018

Date of acceptance of the article by the Editor: 25/01/2019

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Abstract: Moisture sorption is one of the most important destruction factors for colloidal capillary-porous exhibits in museums (painting, clothing etc.), which is dependent on microclimate in museum rooms. The analysis of moisture sorption properties, kinetics of sorption and swelling of textile museum exhibits is carried out. Isotherms of desorption of viscose and woollen yarns and fabrics of different density (and threads of them) are identical. The analysis of the isotherms of fabrics of various fibre cloths and threads of them shows that they all are similar in shape to the curves and have the form typical for leading capillary-porous bodies. The hysteresis loop for almost all tissues is observed throughout the range of relative humidity of the medium. In this work, the characteristics of the hysteresis loop (area, limited by it, length of the loop), which are of informational significance in the description of the processes of isothermal sorption-desorption of the materials mentioned above, are indicated. The research results allow optimizing of microclimate control in museum rooms for elimination of destruction of exhibits, improve the safety of storage and ensure the hygiene of the air indoor environmental.

Keywords: modelling, influence, heat transfer, deformations, viscoelasticity, dispersive, material, heat & mass transfer

1. INTRODUCTION

Museum management it is very important to provide safety of museum exhibits and air quality in the museum rooms (Gorny, 2018). Moisture has a big impact on the risk of fungal growth in museum and historical rooms and on various exhibits there (Toth and Vojtus, 2014). This requires knowledge of the physical processes associated with exposure, including water vapour, to the exhibits and the air environment of museum halls.

The problem of the mutual influence of heat and mass transfer and deformation phenomena is of undoubted theoretical and applied interest. It is important, for example, in the tasks of optimization of technological processes of maintaining the temperature and humidity of the museum microclimate for the safety of exhibition and people. Modern science knows a number of theoretical methods for estimation of the influence of heat and moisture on the deformation properties of materials. Thus, within the framework of the Boltz-Volterra hereditary theory (Rabotnov, 1977), the effect of heat and moisture on the creep of materials and the relaxation of stresses in them is usually taken into account by the method of time-factor analogies (Urzhumtsev et al., 1975) in qualitative agreement with experiment.

It seems, however, that the unilateral consideration of the effect of heat exchange on rheological processes, but the description of their mutual influence on each other, is not more consistent. It is clear that such a complex description requires the involvement of not only mechanical but also thermodynamic regularities in their interaction. In (Dovhaliuk and Chovniuk, 2017), a variant of a complex description of these phenomena is proposed on the basis of the Boltzmann – Volterra (BV) hereditary relations:

$$\varepsilon(t) = \frac{\sigma(t)}{E} + \int_{t_0}^t K(t, \tau) \frac{\sigma(\tau)}{E} d\tau, \quad (1)$$

$$\sigma(t) = E \cdot \left[\varepsilon(t) - \int_{t_0}^t R(t, \tau) \varepsilon(\tau) d\tau \right]. \quad (2)$$

Here we have introduced the following notation: $\varepsilon(t), \sigma(t)$ – deformation and stress in the material, respectively, being functions of time t , E – the modulus of elasticity of the material (constant value, independent of time); $K(t, \tau), R(t, \tau)$ – nuclei of creep and relaxation of the material, respectively.

For creep and relaxation cores, the following dependencies are proposed:

$$\begin{cases} K(t, \tau) = \eta(\tau) \cdot \exp\left(-\int_{\tau}^t L(\theta) d\theta\right); \\ R(t, \tau) = \eta(\tau) \cdot \exp\left(-\int_{\tau}^t [L(\theta) + \eta(\theta)] d\theta\right). \end{cases} \quad (3)$$

It is shown that hereditary relations (1) and (2) with kernels (3) are equivalent to the following Cauchy boundary value problem (KPC):

$$\left\{ \frac{d}{dt} + L(t) \right\} \varepsilon(t) = \left\{ \frac{d}{dt} + L(t) + \eta(t) \right\} \frac{\sigma(t)}{E}, \quad (4)$$

$$\varepsilon(t_0) = \frac{\sigma(t_0)}{E}. \quad (5)$$

We use the first law of thermodynamics for open systems with the involvement of a number of model relations for obtaining control describing heat and mass transfer and deformation processes in colloidal capillary-porous bodies together.

For simplicity, a system with lumped parameters is considered. It is assumed that a small material rod (tape, thread, strip) is subjected to hygrothermal treatment under conditions of axle loading (tension).

2. METHODOLOGY OF RESEARCH

With regard to the problem of drying a rod, the first law of thermodynamics can be written as:

$$\delta Q = dU + \delta A - \mu dm, \quad (6)$$

where the conventional notation is used (Lutsyk et al., 1990, Lutsyk et al., 1993): Q – the amount of heat, U – internal energy, A – mechanical work, μ – specific chemical potential, m – the mass of moisture.

Using the approach of (Lutsyk et al., 1986), it is possible to analyse the mutual influence of heat and moisture on the creep of dispersed bodies / materials and stress relaxation in them in the presence of shrinkage and viscoelastic processes under conditions of heat and mass transfer (i.e., mutual influence of rheological processes (viscoelastic - guest) and heat and mass transfer against each other) get the following equation:

$$C_\varepsilon(t) \cdot \frac{d(\Delta T)}{dt} + f(t) \cdot \Delta T = r(t) \cdot \frac{dm}{dt} - V \cdot \sigma(t) \cdot \frac{d\varepsilon}{dt} - V \cdot D(t) \cdot \varepsilon(t) \cdot \frac{d\sigma}{dt}, \quad (7)$$

where the following notation is introduced: $C_\varepsilon(t)$ – the heat capacity of the rod at a fixed tension ε ; $\Delta T = T(t) - T_c$, $T(t)$ – body temperature, T_c – ambient temperature; $f(t)$ – integral coefficient of heat exchange between the dried body and the medium; $r(t)$ – the specific heat of vaporization is first free, and then bound moisture; V – the volume of the dried body; $D(t)$ – dimensionless dissipation coefficient, reflecting the corresponding material properties.

To obtain equation (7), the following assumptions are made: 1) a system with lumped parameters is considered; 2) for the amount of heat communicated to the rod for some time the well-known Newton-Richman law is applied; 3) in the process of drying the rod, its specific chemical potential coincides with the specific heat of vaporization, first free, and then bound moisture; 4) the problem of stress relaxation in a wetted rod with a small ($\leq 5\%$) stretching under isothermal ($T_c = const$) and isometric conditions ($l = const$), where the length of the rod is, is considered; 5) the material of the rod is considered swelling when wet and shrinking during drying; 6) when heated, we consider the material expanding; 7) the material of the rod during shrinkage is characterized by latent elongation (tension); 8) the change in internal energy is due to three factors: a) heating (temperature change); b) shrinkage of the material (latent stretching); c) energy dissipation due to stress relaxation. In addition, in equation (8), the following expression is meant $\varepsilon(t)$:

$$\varepsilon(t) = \frac{l - l_0(t)}{l_0(t)} = \frac{\Delta l(t)}{l_0(t)} = \frac{\Delta l(t)}{l_0(t_0)} \cdot \left\{ 1 + \frac{\Delta l_1(t)}{l_0(t_0) - \Delta l_1(t)} \right\}, \quad \Delta l_1(t) = l_0(t_0) - l_0(t). \quad (8)$$

where l – the fixed length of the stretched rod; $l_0(t)$ – variable length of the free (non-stretched) rod; $l_0(t_0)$ – the length of the free (non-stretched) rod at the initial moment of time t_0 (as a rule, $t_0 \equiv 0$); $\Delta l_1(t)$ – additional elongation of the rod due to hidden shrinkage of the material.

Equations (7), (8) together with (5), (6) constitute the initial system of equations describing the interrelated processes of stress relaxation in the material and its heat and mass transfer with the medium. In principle, this system allows determining any

pair of three quantities $\Delta T(t)$, $m(t)$, $\varepsilon(t)$ for a given third one. If additionally, we take into account that stretching $\varepsilon(t)$ is determined by a change in temperature $T(t)$ and moisture content of the rod and simulate the corresponding dependence, then instead of the three quantities $\Delta T(t)$, $m(t)$, $\varepsilon(t)$ in equations (5) and (7), (8), there will be only two: $\Delta T(t)$ and $m(t)$, which will already through the coefficient functions of equations (5), (7) and (8) and initial conditions.

3. RESULTS AND DISCUSSION

The basic system of equations (5), (7), (8) will be quite constructive after the coefficients of the function and other quantities included in it are modelled or tabulated.

Consider, as the simplest example of the implementation of conditions, a model expression of the form:

$$\tilde{\Lambda}(t) = \tilde{\Lambda}_0 + \theta(t - t_y) \cdot \left\{ 1 - \exp \left[-\alpha \cdot (T(t) - T(t_y)) - \beta (m(t) - m(t_y)) \right] \right\} \cdot \tilde{\Lambda}, \quad (9)$$

where all constants $\tilde{\Lambda}_0, \tilde{\Lambda}, \alpha, \beta$ are positive. Here $\tilde{\Lambda}(t)$ means both evolutes Λ_n and Λ_p (each with its own parameters) taking into account the relation $\eta(t) = \Lambda_p - \Lambda_n$.

Expression (9) reflects the relaxation nature of the evolution $\tilde{\Lambda}(t)$, of the evolute, which is typical of processes leading to equilibrium.

By limiting ourselves to the linear approximation, we will have:

$$\tilde{\Lambda}(t) = \tilde{\Lambda}_0 + \theta(t - t_y) \cdot \left\{ a [T(t) - T(t_y)] + b [m(t) - m(t_y)] \right\}, \quad (10)$$

where $a = \partial \tilde{\Lambda} / \partial T \geq 0$; $b = \partial \tilde{\Lambda} / \partial m \geq 0$. In (9) and (10), the following notation is adopted: t_y – the moment of time corresponding to the beginning of the shrinkage of the material of the rod; $\theta(\tau)$ – unit Heaviside function. Obviously, the comparison of the discussed approach with the experiment should begin with the linear variant (10). Only in case of failure, the theory can be complicated. In a linear approximation, it is possible to put:

$$\varepsilon(t) = \varepsilon_0 + \Delta \varepsilon(t) = \frac{\Delta l_0}{l_0(t_0)} + \frac{\Delta l(t)}{l_0(t_0)}, \quad \varepsilon_0 = const; \quad \Delta l_0 = l - l_0(t_0), \quad (11)$$

where Δl_0 – is the initial elongation of the rod. In addition, we have in a linear approximation:

$$\Delta \varepsilon(t) = \theta(t - t_y) \cdot \left\{ C_1 [T(t) - T(t_y)] + C_2 [m(t_y) - m(t)] \right\}, \quad (12)$$

From equation (12):

$$\frac{d\varepsilon}{dt} = \frac{d(\Delta \varepsilon)}{dt} = \theta(t - t_y) \cdot \left\{ C_1 \cdot \frac{d(\Delta T)}{dt} + C_2 \cdot \frac{dm}{dt} \right\}. \quad (13)$$

Here C_1 and C_2 are constants (theory parameters). Such a substitution reduces the number of sought functions from three ($\Delta T, m, \varepsilon$) to two ($\Delta T, m$) in the number of equations in system (5) and (7). Without considering here the equation system (5) and (7) as a whole that corresponds to such approximations, we confine ourselves to substituting expression (13) into equation (7):

$$\left\{ C_\varepsilon(t) + \theta(t - t_y) \cdot C_3 V \sigma \right\} \cdot \frac{d(\Delta T)}{dt} + f(t) \Delta T = \left\{ r(t) - \theta(t - t_y) \cdot C_4 V \sigma \right\} \cdot \frac{dm}{dt} + VD(t) \varepsilon(t). \quad (14)$$

From this, it is obvious that the deformation (including shrinkage) leads to an effective change in the heat capacity and specific heat of evaporation:

$$C_{\varepsilon}(t) \rightarrow C_{\varepsilon}(t) + \theta(t - t_y) \cdot C_3 V \sigma, \quad r(t) = r(t) - \theta(t - t_y) \cdot C_4 V \sigma, \quad (15)$$

what was previously observed experimentally (Lutsyk, 1988). This serves as a definite confirmation of the validity of the arguments carried out above. It should also be noted that, by modifying the reasoning about the terms dU and δA , it is possible to come to the same system of equations (5) and (7) in the case when there is no hidden tension, but an explicit one (i.e., the length of the sample is not fixed).

4. CONCLUSIONS

In this work, a universal system of equations (5), (7) and (8) is constructed, describing the mutual influence of heat and mass transfer and deformation processes in dispersed systems (in the form of small rods, strips, ribbons, etc.) with their uniaxial loading, as well as latent and apparent tension. A preliminary qualitative analysis of the above system of equations has been carried out, which gives grounds for recommending it for further practical application, refinement and improvement. It is expected to be used in the analysis of the physical condition and safety of museum exhibits and rooms.

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