

DETERMINATION OF STATE VARIABLES IN TEXTILE COMPOSITE WITH MEMBRANE DURING COMPLEX HEAT AND MOISTURE TRANSPORT

Ryszard Korycki*

Department of Mechanical Engineering, Informatics and Chemistry of Polymer Materials, Faculty of Material Technologies and Textile Design, Lodz University of Technology, Lodz, Poland

*Corresponding author. E-mail: ryszard.korycki@p.lodz.pl

Abstract:

The cotton-based composite is equipped with a single/double semipermeable membrane made of polyurethane (PU) (100%), which blocks liquid transport to the surrounding environment. The complex problem analyzed involves the coupled transport of water vapor within the textile material, transport of liquid water in capillaries, as well as heat transport with vapor and liquid water. The problem can be described using the mass transport equation for water vapor, heat transport equation, and mass transport equation for liquid moisture, accompanied by the set of corresponding boundary and initial conditions. State variables are determined using a complex multistage solution procedure within the selected points for each layer. The distributions of state variables are determined for different configurations of membranes.

Keywords:

Textile composite, membrane, coupled heat and moisture transport

Nomenclature

A – thermal conduction coefficient of the fabric in the x -direction, $W/(m \cdot K)$;

c – volumetric heat capacity, $J/(kg \cdot K)$;

D_a – water vapor transport coefficient, m^2/s ;

D_l – liquid moisture transport coefficient, m^2/s ;

h, h_w – heat and mass convection coefficient, $W/(m^2 \cdot K)$, m/s , respectively;

h_e, h_{we} – heat and mass convection coefficient for membrane, $W/(m^2 \cdot K)$, m/s , respectively;

h_m – mass transport coefficient, m/s ;

R_1, R_2 – sorption rates during the first and second stages of sorption, $kg/(m^3 \cdot s)$, $kg/(m^3 \cdot s)$, respectively;

R_f – mean radius of fibers, m ;

S_v – specific volume of fabric, $1/m$;

T – temperature, $K/^\circ C$;

t – real time in structure, s ;

t_{eq} – time to reach quasi equilibrium during the sorption process, s ;

w_1 – proportion of sorption of water vapor by the fibers;

w_2 – proportion of sorption of liquid water by the fibers;

w_a – water vapor concentration in the air filling the interfiber void space, kg/m^3 ;

w_f – water vapor concentration within the fibers, kg/m^3 ;

w_∞ – water vapor concentration in the surroundings, kg/m^3 ;

w^* – saturated water vapor concentration, kg/m^3 ;

W_C – fractional water content on the fiber surface;

x – coordinate of crucial geometrical points, m ;

Γ – external boundary of structure;

$\sigma = 5.6704 \times 10^{-8}$ Stefan–Boltzmann constant, $W/(m^2 \cdot K^4)$;

ε – effective porosity of textile material;

ε_a – volume fraction of water vapor;

ε_f – volume fraction of fibrous material;

ε_l – volume fraction of liquid phase;



λ – latent heat of evaporation of water, kJ/kg;

λ_l – heat of sorption/desorption of liquid water in the fibers, kJ/kg;

λ_v – heat of sorption/desorption of water vapor in the fibers, kJ/kg;

ρ – density of the fibers, kg/m³;

ρ_l – density of liquid water, kg/m³;

ξ_a – effective tortuosity of fabric by diffusion of water vapor;

ξ_l – effective tortuosity of fabric by diffusion of liquid water;

β – average angle of capillaries within fabric, rad.

Introduction

Composites made of natural fibers are frequently subjected to a complex process of transport of heat and moisture. The problem is significant because of (i) the thermal comfort of the user in normal conditions and (ii) the adequacy of working conditions in clothing exposed to the heat flux of prescribed density. The semipermeable membrane made of polyurethane (PU) (100%) ensures the diffusion of water vapor to the surroundings, while simultaneously blocking the transport of liquid moisture outside (the sweat from the skin) and inside (the precipitation). The second membrane between the textile layers helps to secure the prescribed conditions in a cotton-based composite.

The effect of coupled transport on the protective performance of a garment has been investigated previously [1], with the model being developed using the balance concept and enthalpy formulation. The energy approach accompanied by adequate boundary conditions and Pennes's approach of heat conduction in human skin have been presented by Song et al. [2]. The problem can be also analyzed by means of the only state variable, viz., the temperature [3], and water vapor concentration [4].

The model of coupled heat and water vapor transport and the interaction with human comfort have been investigated by Li [5]. Additional air layers are introduced inside the garment, which are determined by the active elements. A mathematical model that takes into account the water vapor sorption of fibers has been developed [6] to describe and predict the coupled heat and moisture transport in wool fabrics. The two-stage moisture sorption has been analyzed using the Fick's diffusion and David–Nordon models. A mathematical simulation of the perception of thermal and moisture sensations also has been developed [7] using the physical mechanisms of heat and vapor transport, the neurophysiological responses, and the psychoneurophysiological relationships from experiments. On the basis of a mathematical model describing the coupled heat and moisture transfer in wool fabric, Haghi [8] has investigated the moisture sorption mechanisms in fabrics made from

fibers with different degrees of hygroscopicity. For weakly hygroscopic fibers, such as polypropylene fiber, the moisture sorption can be described by a single Fickian diffusion with a constant diffusion coefficient.

Li et al. [9] have investigated the coupling mechanism of heat transfer and liquid moisture diffusion in porous textiles. An equation describing liquid diffusion is incorporated into the energy conservation equation and the mass conservation equations of water vapor and liquid moisture transfer, which include vapor diffusion, evaporation, and sorption of moisture by fibers. A dynamic model of liquid water transfer, coupled with moisture sorption, condensation, and heat transfer, in porous textiles has been developed by incorporating the physical mechanism of liquid diffusion in porous textiles [10]. The same mathematical model of heat and mass transfer is coupled with the phase change of materials in porous textiles [11]. The study of water vapor permeability of wet fabrics and the effect of air gaps between the skin and the fabric on the total relative cooling heat flow is analyzed by Hes and Araujo [12].

Puszkarcz and Krucińska [13] investigate the comfort of double-layered knitted fabrics with applications addressed for specific users. Textiles with a comparable structure are tested for air permeability, and the results are compared with numerical calculations. Different aspects of textile materials in the microscale are analyzed by Grabowska and Ciesielska-Wróbel [14]. The uncovered head causes significant heat and moisture loss from a newborn's skin. The thickness of a composite textile bonnet that retains optimal skin parameters has also been analyzed [15]. The study [16] presents the tests of heat insulation obtained for the newly developed garment compared with that of commercially available garments for babies, under different climatic conditions.

This paper is a continuation of previous investigations concerning the determination of state variables in complex composites [15, 17–21]. The main goal is to determine the distribution of state variables in the cotton-based composite subjected to complex heat, water vapor, and liquid water transport. The structure is equipped with a single membrane made of 100% PU (on the external boundary) and two membranes made of 100% PU (on the external boundary and between the textile layers), which can improve the user's working conditions. The numerical simulation is always cheaper and gives more general results than the practical tests with measurable numerical and economic benefits.

The novel elements are the following. (i) Introduction of two cotton layers characterized by different material characteristics (cotton + Kevlar; acryl + cotton). (ii) Determination of state variables for cotton-based composite with single and double membranes to improve the thermal comfort and working conditions of the user.

Problem Formulation

Let us determine the problem of simultaneous transport of liquid moisture and water vapor within a capillary-porous textile

material, combined with the heat transfer. The transport is unidirectional and is reduced to an optional cross section of the textile material determined within the 2D Cartesian coordinate system. The coordinate $x = 0$ denotes the lower part, whereas $x = L$ represents the upper part of the material (Figure 1). The fibrous material is interleaved by capillaries, which transport the water vapor and liquid moisture (e.g., the sweat) from the skin to the surroundings. These capillaries are directed at a dominant angle of β .

The assumptions characterizing the physical model are the following [5, 6, 9, 10]: (i) Water vapor diffuses within the fibers and the interfiber void spaces. Liquid is transported by surface tension to the regions of lesser concentrations. Heat is transported by conduction within fibers and by convection from the outer surfaces to the void spaces as well as within these spaces. (ii) The volume increase caused by mass diffusion and liquid transport can be neglected. (iii) Orientation of the fibers can be significant, although the diameters are small, and water vapor is transported through the interfiber spaces faster than within the fibers. The internal structure is different in woven fabrics, knitted fabrics, and nonwovens, and it should be always deeply analyzed. (iv) Though the combined transport is a disequilibrium process, instantaneous thermodynamic equilibrium can be introduced between the textile material and the fluid in the free spaces and capillaries irrespective of time characteristics. Textile fibers have small diameters and large surface/volume ratio. (v) The inertial force is neglected considering the low velocities. (vi) The air/vapor mixture is at saturation point in the presence of the liquid phase. (vii) Capillaries are assumed to be of the same diameter and ensure the continuous flow, i.e., the liquid transport is assumed to satisfy the cumulative frequency and linear distribution.

Introducing the balance concept, we can determine the following: (i) the mass transport equation for water vapor – Eq. (1); (ii) the heat transport equation – Eq. (2); (iii) the mass transport equation for liquid moisture – Eq. (3).

$$\frac{\partial(w_a \varepsilon_a)}{\partial t} + w_1 \frac{\partial(w_f \varepsilon_f)}{\partial x} - \varepsilon_a h_m S_v (w^* - w_a) = -\frac{1}{\xi_a} \frac{\partial}{\partial x} \left[D_a \frac{\partial(w_a \varepsilon_a)}{\partial x} \right] \quad (1)$$

$$\rho c \frac{\partial T}{\partial t} - w_1 \lambda_v \frac{\partial(w_f \varepsilon_f)}{\partial t} - w_2 \lambda_l \frac{\partial(w_f \varepsilon_f)}{\partial t} + \varepsilon_a \lambda h_m S_v (w^* - w_a) = -\frac{\partial}{\partial x} \left[A \frac{\partial T}{\partial x} \right] \quad (2)$$

$$\frac{\partial(\rho_f \varepsilon_l)}{\partial t} + w_2 \frac{\partial(w_f \varepsilon_f)}{\partial t} + \varepsilon_a h_m S_v (w^* - w_a) = -\frac{1}{\xi_l} \frac{\partial}{\partial x} \left[D_l \frac{\partial(\rho_f \varepsilon_l)}{\partial x} \right] \quad (3)$$

$$\text{where } w_1 = \frac{\varepsilon_a}{\varepsilon_a + \varepsilon_l}; \quad w_2 = \frac{\varepsilon_l}{\varepsilon_a + \varepsilon_l}; \quad w_1 + w_2 = 1.$$

The mass transfer equation, i.e., Eq. (1), determines the transport of water vapor as follows: (i) within the void spaces between the fibers in time – the first term on the left-hand side; (ii) in the fibers from the skin to the surroundings – the second term; (iii) from the current concentration to the saturation conditions that cause vapor condensation – the third term. The heat transport equation, i.e., Eq. (2), describes the following: (i) the heat transported with liquid water – the first term on

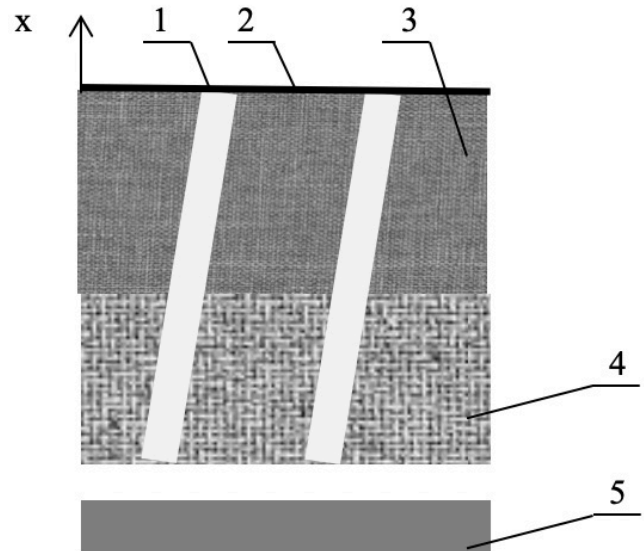


Figure 1. Model of analyzed cotton-composite.
1 – capillaries; 2 – membrane; 3 – external textile layer (acryl + cotton);
4 – internal textile layer (cotton + Kevlar); 5 – skin

the left-hand side; (ii) the heat transported during sorption/desorption of water vapor and liquid moisture in fibers – the second and third terms; (iii) the latent heat of condensation – the fourth term. The mass transport equation for liquid, i.e., Eq. (3), defines the transport of moisture as follows: (i) along the capillaries in time – the first term on the left-hand side; (ii) in the fibers with respect to time – the second term; (iii) the current transport of liquid water to attain the saturation condensation – the third term.

The sum of the volume fractions is represented as follows.

$$\varepsilon_a + \varepsilon_l + \varepsilon_f = 1 \Rightarrow \varepsilon_a + \varepsilon_l = 1 - \varepsilon_f \quad (4)$$

The sorption/desorption of water vapor between the fibers and the interfiber spaces is a complex process [5, 6]. The first stage of sorption is described by Fick's law and the constant diffusion coefficient of the material. The sorption/desorption process within some materials possessing strongly hygroscopic properties (cf., wool) is determined by Fick's law during the entire process [5, 6, 9, 10]. Assuming a short duration of time, the problem is described by the first phase of sorption. The discrete relations have the following form.

$$\frac{dw_f}{dt} = R_1 \quad \text{for } W_C < 0.185 \quad \text{and } t < t_{eq};$$

$$\frac{dw_f}{dt} = \frac{1}{2} R_1 + \frac{1}{2} R_2 \quad \text{for } W_C \geq 0.185 \quad \text{and } t < t_{eq}; \quad (5)$$

$$\frac{dw_f}{dt} = R_2 \quad \text{for } t > t_{eq}$$

$$W_C = \frac{w_f(x, R_f, t)}{\rho_f} \quad (6)$$

The equilibrium time, t_{eq} , is determined experimentally, which depends on the textile material and is in the range of 540–600 s [5, 6, 8]. For weakly hygroscopic fibers such as polypropylene, the moisture sorption is described by a single Fickian diffusion with a constant diffusion coefficient. The sorption rate during the first stage, R_f , is defined by the water vapor transport in dry cylindrical fibers [9, 10] according to Fick's diffusion.

$$\frac{dw_f}{dt} = R_f(x, t) = \frac{1}{R_f} \frac{\partial}{\partial R_f} \left[R_f D_a(x, t) \frac{\partial w_f(x, R_f, t)}{\partial R_f} \right] \quad (7)$$

The boundary conditions at the skin ($x = 0$) determine the concentration of saturated water vapor, the specified temperature, and the constant volume fraction of fibrous material in the following form.

$$w_a(0, t) = w^*; T(0, t) = T_0; \varepsilon_f(0, t) = \text{const} \quad (8)$$

Let us assume that the external boundary $x = L$ is unprotected against disadvantageous working conditions. It is subjected to water vapor convection from the void spaces, as shown in Eq. (9). Heat is transferred by radiation, convection, and latent heat of evaporation, as in Eq. (10). Liquid moisture is transferred by convection, shown in Eq. (11). The appropriate conditions are expressed below.

$$D_a \frac{\partial [w_a(L, t) \varepsilon_a(L, t)]}{\partial x} = \frac{\varepsilon_a}{\varepsilon_a + \varepsilon_l} h_w (w_a - w_\infty) \quad (9)$$

$$A \frac{\partial T(L, t)}{\partial x} = \sigma T^4 + h(T - T_\infty) + \frac{\varepsilon_l}{\varepsilon_a + \varepsilon_l} h_m \lambda (w^* - w_\infty) \quad (10)$$

$$D_l \frac{\partial [\rho_l(L, t) \varepsilon_l(L, t)]}{\partial x} = \frac{\varepsilon_l}{\varepsilon_a + \varepsilon_l} h_m (w^* - w_\infty) \quad (11)$$

The external boundary can be alternatively protected by the semipermeable membrane. The membrane ensures the partial convection of water vapor from the void spaces by the reduced mass convection coefficient h_{we} , represented by Eq. (12). Heat is transported to the surroundings by radiation and convection [Eq. (13)]. Liquid is not transported to the surroundings because the pore dimensions prevent drop-wise penetration, as shown in Eq. (14).

$$D_a \frac{\partial [w_a(L, t) \varepsilon_a(L, t)]}{\partial x} = \frac{\varepsilon_a}{\varepsilon_a + \varepsilon_l} h_{we} (w_a - w_\infty) \quad (12)$$

$$A \frac{\partial T(L, t)}{\partial x} = \sigma T^4 + h_e (T - T_\infty) \quad (13)$$

$$D_l \frac{\partial [\rho_l(L, t) \varepsilon_l(L, t)]}{\partial x} = 0 \quad (14)$$

Let us next introduce the two-layered textile structure. The internal layer is made of cotton (80%) and Kevlar (20%) of

thickness 7×10^{-3} m. The external layer is made of acrylic fiber (80%) and cotton (20%) of thickness 8×10^{-3} m. The surface mass is equal to 0.500 kg/m² for Kevlar, 0.300 kg/m² for cotton, and 0.350 kg/m² for acrylic fiber. The working time in the test clothing is limited and does not exceed $t_{eq} = 540$ s; the diffusion in the fibers is determined by the first stage of sorption.

The material shows unidirectional transport of moisture and heat. The diffusion coefficients within the fibers are assumed according to previous reports [8].

$$\begin{aligned} \text{cotton: } D_{a \text{ fiber}} &= \left[0.8481 + 50.6 \frac{w_f}{\rho} - 1100 \left(\frac{w_f}{\rho} \right)^2 \right] \cdot 10^{-14}; \\ \text{acryl: } D_{a \text{ fiber}} &= \left[1.1200 - 410 \frac{w_f}{\rho} - 8200 \left(\frac{w_f}{\rho} \right)^2 \right] \cdot 10^{-13}; \end{aligned} \quad (15)$$

$$\text{Kevlar } D_{a \text{ fiber}} = 1.4 e^{-13}.$$

The diffusion coefficient of water vapor in the air is $D_a = 2.5e^{-5}$. The “internal” material porosities within the fibers are constant and are equal to the following values:

$$\text{Kevlar + cotton: } \varepsilon = 0.350; \text{ acryl + cotton: } \varepsilon = 0.200 \quad (16)$$

Of course, the global value of the diffusion coefficient within the fibers is determined using any homogenization method, e.g., the simplest “rule of mixture”.

The heat transport coefficients in textile fibers have the following values [8]:

$$\text{cotton: } A_{\text{fiber}} = \left[44.10 + 63.00 \frac{w_f}{\rho} \right] \cdot 10^{-3} \quad (17)$$

$$\text{acryl: } A_{\text{fiber}} = 28.80 \times 10^{-3}; \text{ Kevlar: } A_{\text{fiber}} = 51.80 \times 10^{-3}.$$

The heat of sorption of water vapor in the fibers, λ_v , determines the part of heat transported with moisture during sorption on the external surface of the fibers. The volumetric heat capacity c is the heat transferred to increase the temperature.

$$\begin{aligned} \text{cotton: } \lambda_{v \text{ fiber}} &= 1030.9 \exp \left[-22.30 \frac{w_f}{\rho} \right] + 2522.00; \\ \text{acryl: } \lambda_{v \text{ fiber}} &= 2522.00; \text{ Kevlar: } \lambda_{v \text{ fiber}} = 2522.00 \end{aligned} \quad (18)$$

$$\text{cotton: } c_{\text{fiber}} = \left(1663.00 + 4184.00 \frac{w_f}{\rho} \right) \left[1610.90 \left(1 + \frac{w_f}{\rho} \right) \right]^{-1}$$

$$\text{acryl: } c_{\text{fiber}} = 1610.90; \text{ Kevlar: } c_{\text{fiber}} = 1715.00$$

The volume fraction of the fibrous material is equal to $e_f = 0.80$ for the internal layer and $e_f = 0.85$ for the external layer. The initial parameters are the same for the structure and the surroundings: $T_0 = T_\infty = 21^\circ\text{C}$; $w_0 = w_\infty = 0.65$. The composite

is subjected at $t = 0$ to the following conditions at the skin: $T = 19^\circ\text{C}$; $w = 1.0$.

The radii of monofilaments are assumed as follows: cotton $R_f = 0.9 \times 10^{-5}$ m; acryl $R_f = 10^{-5}$ m; and Kevlar $R_f = 10^{-5}$ m. The corresponding fiber densities are as follows: cotton $r = 1.35 \times 10^3$ m; acryl $r = 1.40 \times 10^3$ m; and Kevlar $r = 1.45 \times 10^3$ m.

The heat and mass transport coefficients from the external surface are assumed as follows: $h = 8 \text{ W}/(\text{m}^2 \cdot \text{K})$; $h_e = 4 \text{ W}/(\text{m}^2 \cdot \text{K})$; $h_w = 0.2 \text{ m/s}$; $h_{we} = 0.05 \text{ m/s}$; the mass transport coefficient within the fabric is $h_m = 0.015 \text{ m/s}$. For simplicity, let us assume that $D_l = D_a$ and $\lambda_l = \lambda_a$. The effective tortuosity of the fabric by diffusion of water vapor and liquid phase is $\xi_l = \xi_a = 1.2$; the effective porosity of the fabric is $\varepsilon = 0.8$. The latent heat of evaporation of water $\lambda =$ is 2256 kJ/kg .

Numerical Solution

The problem is solved numerically using an iterative procedure of the following operational sequence.

1. Water vapor concentration within the fibers w_f is determined from Eq. (4), i.e., Fick's diffusion within a fibrous material.
2. Two-factor formula ($\varepsilon_a w_a$) is calculated from the mass transfer equation for water vapor, i.e., Eq. (1).
3. Volume fraction of the liquid phase ε_l can be determined from the mass transport equation for liquid moisture, i.e., Eq. (3).
4. Volume fraction of water vapor ε_a is computed from the sum of the volume fractions, viz., Eq. (4).
5. Water vapor concentration in the air filling the interfiber void space w_a is consequently defined by a simple division: $(\varepsilon_a w_a)/\varepsilon_a$.
6. Temperature T is calculated from the heat transport equation, i.e., Eq. (2).

The textile structure with material characteristics as in Eq. (18) is exposed to coupled transport for 400 s; the problem can be solved numerically from $t = 0$ to the final value $t = 400$ s with a time step equal to 25 s.

Let us first analyze the textile structure made of two textile layers without any membrane. The location of the calculation points is shown in Figure 2a. The distributions of the vapor concentrations in the air filling the interfiber void space w_a versus time are depicted by Figure 2b. The concentration w_a increases rapidly with time to the maximal value irrespective of the calculation point. Next, the concentrations decrease slightly (3–3.5%) to a constant level. The vapor concentrations at the points located further toward the external boundary are reduced in relation to the values at the points located closer. The reason

is convection of both vapor and fluid from the external surface to the surroundings.

The water vapor concentration within the fibers w_f versus time is shown in Figure 3. The curves increase fast in time and reach concentration values close to maximum at time $t = 200$ – 250 s, and then, the values increase insignificantly to the maximal value at the final time point. The water vapor concentration depends on the location within the material. The values within the points $x = 0.0035$ m and $x = 0.007$ m are considerably greater than the values at other points. Different courses are seen for various materials (cotton and Kevlar; acryl + cotton), which show different characteristics of water vapor penetration.

The course of temperature versus time is shown in Figure 4. The temperature at the calculation points situated closer to the skin is higher, and the courses are different depending on the location. The points located closer to the skin are characterized by a rapidly reduced course at the beginning of the calculation time. In contrast, the temperature at the points located further from the skin decreases softly at the beginning of the test period. Next, the temperature reduction is substantial. The maximal difference in temperature at the end of the time range is 0.3°C (about 1.8%). The temperatures for $x = 0.0035$ m and $x = 0.007$ m are reduced in relation to the other two values.

Generally speaking, the computed distributions of the state variables are concomitant to those obtained by other authors [9, 10].

The external boundary can be also protected by a semipermeable membrane made of polymer/polypropylene of thickness 0.25×10^{-3} m. The water vapor is now transported to the surroundings, whereas the liquid water outside and inside is blocked because of the pore dimensions. The layers are

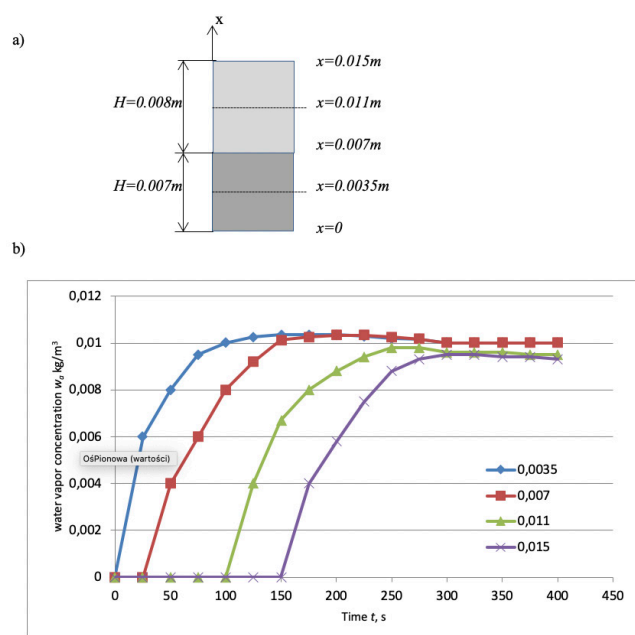


Figure 2. a) Location of calculation points; b) Water vapor concentration in air filling interfiber void space w_a versus time for different coordinates x of simple cotton-composite

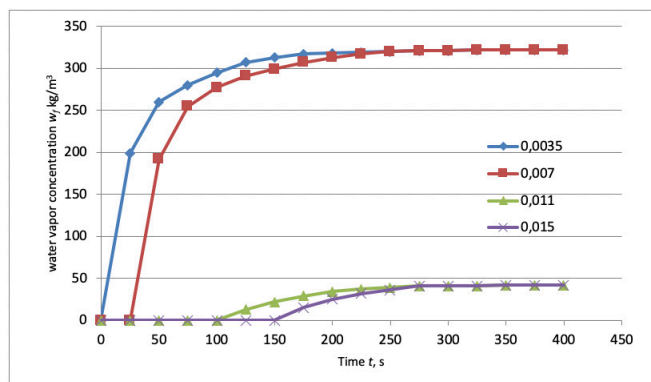


Figure 3. Water vapor concentration within fibers w_f versus time for different coordinates x of simple cotton-composite

made of the same materials (cotton + Kevlar, acryl + cotton). The solution is typical for personal protective equipment, firefighter clothing, and so on. The water vapor concentration in the air filling the interfiber space (w_a) versus time is depicted in Figure 5. The courses in Figures 2b and 5 are similar in the first part of the time range. The final concentrations are different, as shown in Figure 2b, irrespective of time and location. It is caused by the membrane, which blocks the transport of vapor to the surroundings and equalizes the values irrespective of location point. The curves are asymptotic, but the maximal concentrations are reached at different times, which in turn depend on the location of the point, i.e., from $t = 150$ s for $x = 0.0035$ m to $t = 325$ s for $x = 0.015$ m.

The water vapor concentrations within the fibers, w_f , are depicted in Figure 6. The membrane on the external surface of the cotton-based composite protects against vapor loss to the surroundings. Therefore, the values of vapor concentrations in the fibers increase continually irrespective of the time to the saturation value at the maximal time. The difference in the values at different calculation points is caused by the diverse nature of the materials in the layers. The course of temperature versus time is similar to that shown in Figure 4.

The next composite is equipped with two membranes, the first is between two cotton layers, and the second is on the external boundary. The structure can be implemented into the personal protective equipment for firemen subjected to thermal radiation from the fire source. The vapor transport to the surroundings is blocked, which results in an increased level of water within the internal layer and a constant skin temperature due to contact with the coolant. The water vapor concentration within the interfiber space, w_a , versus time is shown in Figure 7. The initial values of vapor concentrations increase rapidly for $x = 0.0035$ m and $x = 0.007$ m; the courses are similar to the corresponding curves in Figure 3. The values at the other points increase softly, which is caused by the internal membrane between the textile layers. The external membrane yields the maxima of concentrations at the final time point, and these values are comparable within all calculation points.

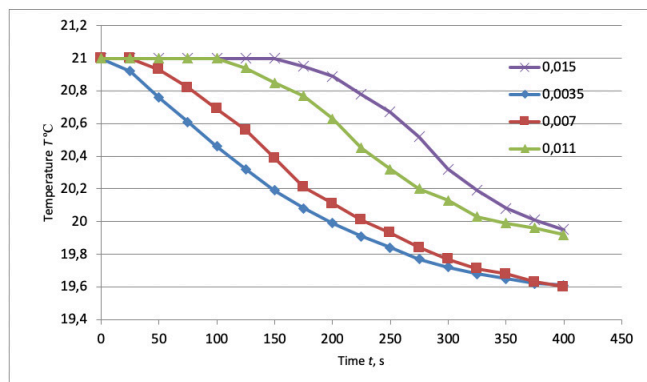


Figure 4. Temperature T versus time for different coordinates x of simple cotton-composite

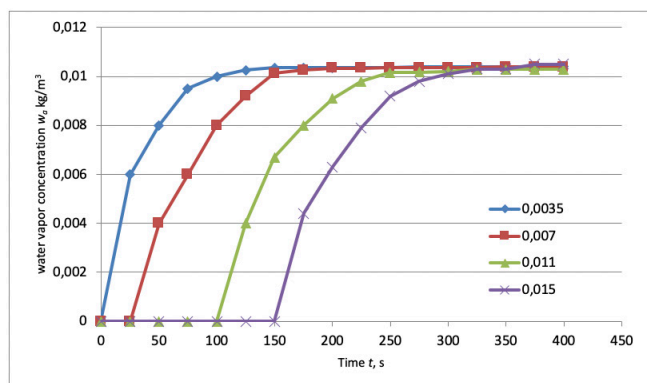


Figure 5. Water vapor concentration in air filling interfiber void space w_a versus time for different coordinates x of cotton-composite with single membrane

Conclusions

The combined transport of water vapor, liquid moisture, and heat in cotton-based composite is a complex phenomenon. The physical model introduces different simplifications, e.g., only the dominant angle of the pore axes, only Fick's diffusion, and so on. However, the model proposed is complicated, although the approximated solution is obtained in a few consecutive steps. The obtained distribution of state variables for a simple structure without membranes is concomitant with that published by other authors [9, 10].

The light protective clothing for firefighters does not contact the flame and withstands a short exposure time to heat flux of prescribed density. The membrane is the additional barrier protecting against complex heat, moisture, and liquid transport, as well as retaining an adequate temperature on the skin. The phenomenon is combined because heat is transported with liquid water, by sorption/desorption of water vapor and liquid moisture in the fibers, and by the phase change (the latent heat of condensation). The textile layers are made of cotton with Kevlar/acryl, which improve both the moisture transport from the skin and the personal comfort of user. The single- and double-membrane structure causes an increase in water vapor concentrations within the void spaces w_a in time. Additionally, the courses of the maximal values for samples with membrane are more convergent than the courses of samples without membrane.

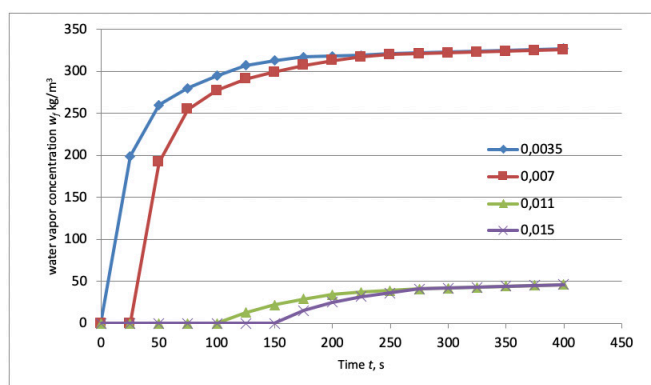


Figure 6. Water vapor concentration within fibers w_i versus time for different coordinates x of cotton-composite with single membrane

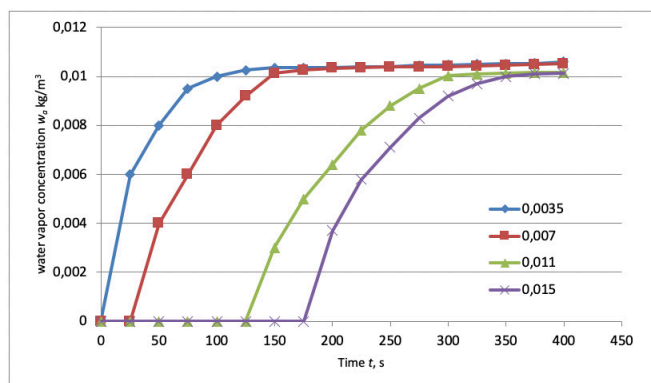


Figure 7. Water vapor concentration in air filling interfiber void space w_a versus time for different coordinates x of cotton-composite with double membrane

The solution of the complex transport process is determinable by significant simplifications of the model. The problem is affected by the optimization balance, i.e., the most accurate results versus the most beneficial computational effort. Thus, the analysis can be developed to find the simplest possible solution, for instance, by some additional simplifications of the model. The problem can be also applied to optimize the shape and material characteristics of textile layers within the composite. The finishing procedure and its influence on the material characteristics can be additionally discussed [22].

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