Effect of walking speed on the evaporation coefficient of defence workwear

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ABSTRACT – REZUMAT

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The ripstop fabrics are highly appreciated in the military and defence workwear. One of the qualities requirements in defence clothing is quick evaporation. The effect of the wearer's walking speed on textile fabric evaporation during capillary rise was investigated in this study. To achieve this, two steps were taken: modelling the capillary considering evaporation and estimating the coefficient of evaporation using a program designed for image analysis. The walking speed was simulated by varying the air velocity from 0 m/s (non-walking) to 1 m/s (walking) and 2 m/s (running). Results conclusively demonstrated that the evaporation coefficient is directly relational to the water vapour in the surrounding air layer and is highly dependent on the aeration rate. Furthermore, liquid equilibrium front level and capillary diffusion were found to be inversely proportional to the walking speed. The walking speeds affected the indirect water amount on the fabrics and it was more difficult to evaporate liquid from the 100% cotton compared to 65% polyester/35% cotton.

Keywords: *walking speed, evaporation coefficient, ripstop fabric, comfort*

Efectul vitezei de mers asupra coeficientului de evaporare al îmbrăcămintei de protecție

Țesăturile ripstop sunt foarte apreciate în îmbrăcămintea militară și de protecție. Una dintre cerințele caracteristicilor în îmbrăcămintea de protecție este evaporarea rapidă. În acest studiu a fost investigat efectul vitezei de mers a purtătorului asupra evaporării țesăturii textile în timpul procesului de capilaritate. Pentru a realiza acest lucru, au fost parcurși doi pași: modelarea capilarității luând în considerare evaporarea și estimarea coeficientului de evaporare, folosind un program conceput pentru analiza imaginilor. Viteza de mers a fost simulată prin varierea vitezei aerului de la 0 m/s (staționare) la 1 m/s (mers) și 2 m/s (alergare). Rezultatele au demonstrat în mod concludent că, coeficientul de evaporare este direct relațional cu vaporii de apă din stratul de aer din jur și este foarte dependent de rata de aerare. În plus, nivelul frontal al echilibrului lichid și difuziunea capilară s-au dovedit a fi invers proporționale cu viteza de mers. Vitezele de mers au avut un efect asupra cantității indirecte de apă pe țesături și a fost mai dificil să se evapore lichidul din țesătura din 100% bumbac, comparativ cu cea din 65% poliester/35% bumbac.

Cuvinte-cheie*: viteza de mers, coeficient de evaporare, țesătură ripstop, confort*

INTRODUCTION

Thermal discomfort can have a substantial impact on a worker's productivity. Continued exposure might cause fatigue, decreased productivity, and concentration. Employee dissatisfaction and absenteeism may also increase. Sweating increases proportionally to the thermal challenge degree to maintain thermo-physiological heat balance [1, 2]. The accumulated sweat on the skin's surface must be rapidly soaked up by the fabrics and drained to the external environmental air via wicking kinetics to avoid wetness and the uncomfortable fabric sticking to the body feeling. The dispersion of water vapour via textile textiles is critical to sustaining physical comfort. Creating and manufacturing comfortable textiles is a significant task for fibre, yarn, and fabric design [3].

The army and police train and exercise in extreme environmental conditions and may come into touch with water, which gets wet and makes the clothes bulkier and less comfortable. This reduces their effectiveness and endangers their lives. Therefore, one of the qualities needed in defence clothing is quick evaporation. Consequently, when designing workers' clothing, wicking and evaporation should be considered. Compared to civilians, soldiers are exposed to more environmental factors. The military protective fabric was primarily designed to safeguard soldiers from weather-related factors including wind, rain, and snow while also allowing them to move freely [4].

The following list of essentials can be used to summarize the main requirements of an advanced integrated combat clothing system: Physical requirements include weather resistance [5]; environmental requirements [6] include water repellency and windproofness; physiological requirements include comfort, minimum heat stress, low weight, and vapour permeability; and battlefield requirements include flame resistance, ballistic protection, good camouflage properties [7], and low noise generation [8].

Some of these needs could be in conflict. Enhancing environmental protection, in particular, may result in bodily issues such as heat stress and exhaustion. The military uniform restrictions imposed by battlefield situations may inhibit the soldier's operational efficiency. Low weight and bulk are typically sought for operating efficiency, but the level of protection provided by ballistic vests is lowered.

Depending on the necessities of the outfit, military uniforms are often fashioned from a range of textiles. Cotton, wool, nylon, and polyester are common textiles used in military uniforms. These textiles were chosen for their durability, comfort, and resistance to a variety of climatic situations [9]. Furthermore, to suit the requirements, military uniforms frequently integrate specialized qualities such as moisture-wicking properties, flame resistance, and camouflage designs [10, 11]. Because of their capacity to survive harsh environments, ripstop textiles are highly appreciated in military fabrics [12]. They contribute to ensuring the longevity of clothes and equipment, even during intense exercise.

The term "ripstop" refers to a weaving process that requires strengthening the fabric at regular intervals with strong reinforcing threads [12–14]. This keeps minor tears and rips from spreading and becoming larger.

Ripstop materials are frequently used in military uniforms for severe stress or abrasion, such as knees, elbows, and pockets. The use of ripstop materials extends the life of garments by reducing the risk of tears and holes.

The type of ripstop fabric used in defence applications varies based on the needs of the uniform. Polyester ripstop materials have suitable properties, such as strength and durability [15]. They are frequently used in military uniforms, outerwear, and equipment that require tearing and abrasion resistance. Cotton ripstop materials are less frequent in military uniforms, but they can be employed in particular situations. They have the comfort and breathability of cotton with the added durability of a ripstop weave [16].

The common wicking action via textile materials is caused by the constituted fibres [17–19].

Consequently, plenty of investigation has been carried out to figure out how capillary functions in textile materials. Based on major studies in this area, yarns have also been managed as a porous media [20–22], where the liquid movement in the textile fabric may be predicted using the Lucas-Washburn law, or as capillary pipes. But in the first case, common measurements like permeability are hard to calculate and need to be analytically estimated [23]. Like the preceding situation, fitting the experimental results provides data on the effective contact angle and average effective capillary radius. The average radius of a dynamic pore might change during wicking due to fibre swelling [24]. Some studies focused on fabric geometrical modelling to predict physical properties [25].

When studying capillary rise, surrounding airspeed is typically neglected, in contrast to water vapour transfer tests where the airspeed is almost equivalent to walking speed conditions [26, 27]. Textile fabric evaporation [28] was mostly studied when exploring drying or cooling [29–33]. Relative air humidity was shown to be a significant factor in the climate conditions that had the biggest impact on evaporation intensity [34]. Among the presented literature review, modelling the evaporation during capillary actions considering the walking speed is still lacking.

This paper explored the evaporation rate during capillary kinetics over plain ripstop fabric as a defence clothing considering walking speeds. A theoretic mathematical model of the capillary wicking considering evaporation based on the fabric geometrical layout. Investigations were done into how walking speed affected capillary kinetics. At various walking speeds, the evaporation coefficient was determined using experimental results.

EVAPORATION COEFFICIENT DETERMINATION

The capillary kinetics concept of water over the woven fabric was used as an extension mathematical model [35]. As illustrated in figure 1, the capillary rises from the infinite reservoir through a porous media, the evaporation will take place from the external porous media perimeter open to the evaporation.

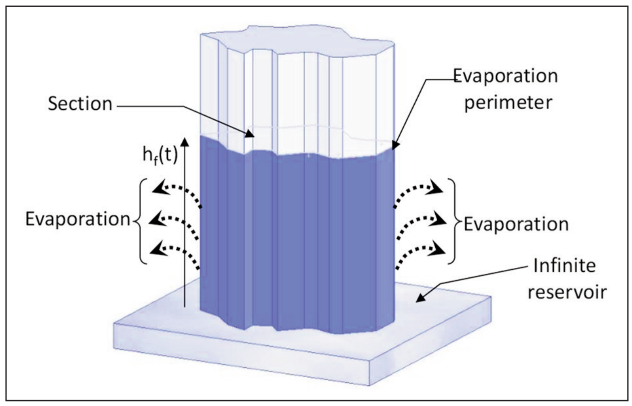

Fig. 1. Volatile liquid evaporation during capillary rise through porous media from infinite reservoir

An introduced physical parameter is presented in this model: the volume of the liquid evaporated from the textile fabric (Ω [m^3/s]) and the function of capillary front height ($h_f(t)$):

$$\frac{d\Omega}{dt} = -2\alpha W h_f(t) \tag{1}$$

where W is the textile fabric width in m and α is the intrinsic evaporation parameter of the liquid in m/s.

During the capillary rise, the liquid evaporates from the external walls. The evaporation surface will depend on the liquid front height and the width of the cross-section (S) of the porous media.

The liquid flow conservation on the wetting region Δh at a height h_f and section S gives:

$$\varepsilon S V_{h_f+\Delta h} = \varepsilon S V_{h_f} - 2\alpha W \Delta h \tag{2}$$

where V_{h_f} is the liquid front speed at the liquid front position h_f. By making Δh tend towards zero, the following expression is obtained:

$$\left(\frac{dV}{dt}\right)_t = -2\frac{\alpha W}{\varepsilon S} \tag{3}$$

In our case, the section S exposed to the evaporation is expressed as follows:

$$S = V \times t_h \tag{4}$$

Here t_h is the fabric thickness. So, the equation (3) could be written as follows:

$$\left(\frac{dV}{dt}\right)_t = -2\frac{\alpha}{\varepsilon t_h} \tag{5}$$

By integration between $h = 0$ and $h = h_f$ we have:

$$V_h = V_0 - 2\frac{\alpha h}{\varepsilon t_h} \tag{6}$$

Furthermore, the liquid front speed during capillary rise is:

$$V_h = \frac{dh_f}{dt} \tag{7}$$

And

$$V_0 = \frac{\left(\frac{R_D}{\tau}\right)^2}{8\mu h_f}\left(\frac{2\gamma_L \cos\theta}{R_D} - \rho g h_f\right) \tag{8}$$

The equation 8 corresponds to the liquid capillary rise without evaporation. So, combining equation 6 with the expressions of V_h and V_0 we obtain the capillary rise considering the evaporation equation:

$$\frac{dh_f}{dt} = \frac{\left(\frac{R_D}{\tau}\right)^2}{8\mu h_f}\left(\frac{2\gamma_L \cos\theta}{R_D} - \rho g h_f\right) - \frac{h_f}{\psi} \tag{9}$$

where $\psi = \frac{\varepsilon t_h}{2\alpha}$ is a function of liquid volatility and fabric construction parameters. It defines the liquid critical time to be evaporated from the fabric.

Considering the evaporation at equilibrium $\frac{dh_f}{dt} = 0$ and $h_f = h_{eq}^{ev}$. Solving the equation 9 gives the following form of the equilibrium front height:

$$h_{eq}^{ev} = \frac{-1 + \sqrt{1 + 4\frac{4\tau^2\mu}{\gamma_L \psi \cos\theta\, R_D} \times \left(\frac{2\gamma_L \cos\theta}{\rho g R_D}\right)^2}}{2\frac{4\tau^2\mu}{\gamma_L \psi \cos\theta\, R_D} \times \frac{2\gamma_L \psi \cos\theta}{\rho g R_D}} \tag{10}$$

Here $\frac{2\gamma_L \cos\theta}{\rho g R_D}$ is the liquid height equilibrium without evaporation defined by the Jurin law.

Considering equations 10 and 1, the evaporation coefficient α is determined as follows:

$$\alpha = \frac{\varepsilon t_h (2R_D \gamma_L \cos\theta - \rho g R_D^2 h_{eq}^{ev})}{16\mu\tau^2 (h_{eq}^{ev})^2} \tag{11}$$

where R_D is the dynamic equivalent capillary radius (m), τ – the capillary channel tortuosity, μ – the liquid viscosity (N·s/m^2), h_{eq}^{ev} – the liquid front equilibrium height with evaporation consideration, ρ – the water density (Kg/m^3), g – the acceleration of gravity (m/s^2), μ – the water viscosity (N·s/m^2), θ – the equilibrium contact angle, γ_L – the water surface energy (N/m).

Equation 11 contains the contact angle as a liquid/fibre interaction, the physical properties of the liquid (μ, γ_L) and the fabric structural parameters (t_h, ε, τ and R_D). All of these parameters should be evaluated to determine the coefficient of liquid evaporation from textile fabrics.

Thus, it exists a maximum liquid front position which does not correspond to a balance between gravity and capillary forces but to a kinetic balance due to the evaporation of the liquid. The greater the evaporation, the smaller the equilibrium height will be.

The effective dynamic average pore radius R_D is expressed as follows [24]:

$$R_D = \frac{2\gamma_L \cos\theta}{\rho g h_{eq}^{ev}} \tag{12}$$

MATERIALS AND METHODS

Experimental device

In the experimental device (figure 2), a steel ruler and lab jack were, respectively, employed in the device to measure the wicking front level and elevate the liquid reservoir containing the wicking liquid. An installed gap plate was introduced on the reservoir's top side to allow fabric penetration and capillary ascent while minimizing liquid evaporation from the reservoir.

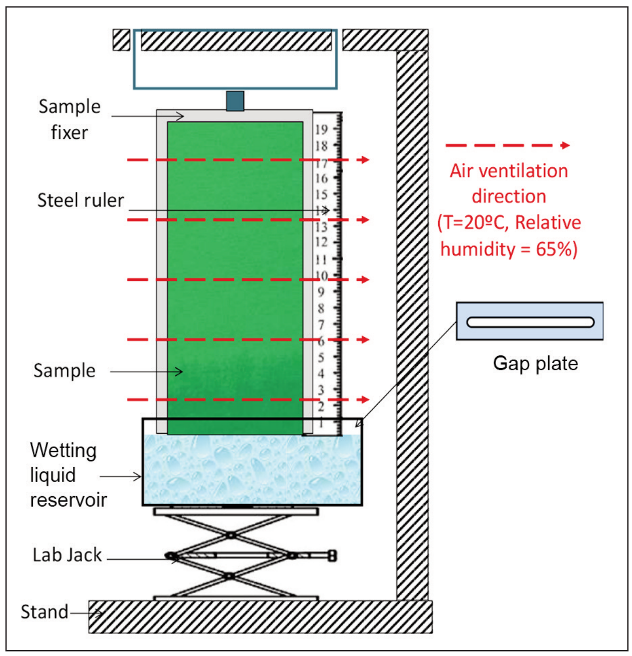

Fig. 2. Capillary rise experimental setup considering evaporation

The capillary liquid front was observed and measured at various periods by capturing images with a CCD camera on frequently. The capillary rise and time were captured until equilibrium was established. The photos were adjusted in Photoshop for brightness, size, cropping and calibration. MATLAB software was used to monitor the liquid front position using grayscale images. The contrast of each grayscale photo was attuned using histogram equalization, subsequent in lower grey levels visible in the contrast-adjusted photo. Wetted regions were represented by the image's dark sections, while non-wetted areas of the fabric were transparent. The photo threshold level was determined for binarization.

Used weaving fabric

The Rip-stop fabric pattern design as illustrated in figure 3, was woven using the rapier Dornier weaving machine HTV/HTVS/PTV with the Bonas ZJ2 jacquard mechanism.

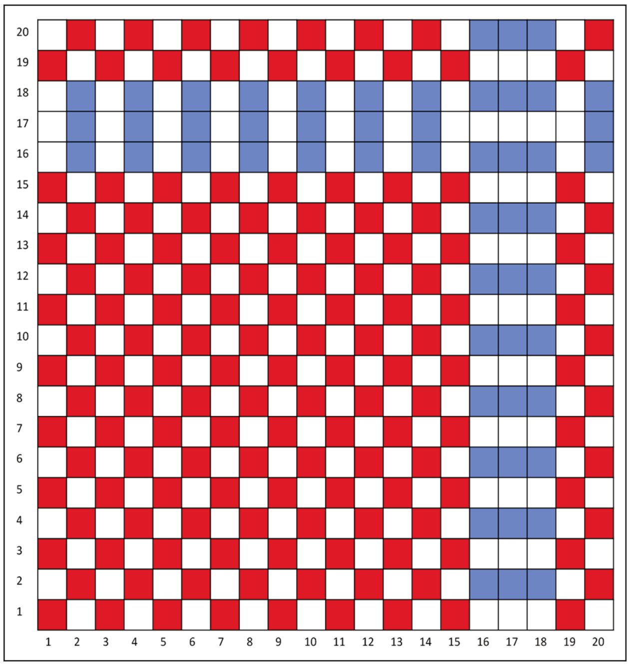

Fig. 3. Rip-stop fabric pattern design

The woven fabric thickness was evaluated using the ISO 5084:1996 standard [36]. The mass per unit area, warp and weft densities were measured according to the ISO 7211-6:2020 standard [37].
The woven fabric structural parameters are presented in table 1.

Experimental test conditions

The used wetting liquid was distilled water; with a density of 998.29 kg/m^3, a dynamic viscosity of 0.001003 N·s/m^2, a surface energy of 0.0725 N/m, a contact angle $\cos\theta = 0.97$ in the case of cotton fibre 100% cotton fibre and $\cos\theta = 0.94$ in the case of polyester fibre. The polyester fibre is a hydrophobic polymer with a low contact angle. Generally, synthetic fibres are smooth, resulting in a low contact angle [18].

Different air speeds were used to assess the effect of a wearer's walking speed on capillary rise evaporation. The air speeds tested were 0 m/s, 1 m/s, and 2 m/s referring respectively to non-walking, walking and running speeds.
All experimental tests were conducted under a standard atmosphere of 65±2% relative humidity and 20±2ºC. Tested fabrics were conditioned for 24 hours before testing and each capillary rise test was repeated three times.

RESULTS AND DISCUSSIONS

Based on figure 4, it can be observed that the walking speed of workers has an impact on capillary rise. The equilibrium liquid front decreases as the walking speed increases and is caused by the evaporation that occurs from the open-pores sample. The walking speed is closely related to the water vapour diffusion layer, which is proportional to the evaporation rate. When the capillary front level is small, the impact of walking speed and air ventilation on liquid evaporation remains insignificant for short periods. For cotton, the height of the capillary front stands fewer than 20 centimetres with a standard deviation of 0.58 and a CV of 2.95%, however, for polyester, a front level of fewer than 6 cm with a standard deviation of 0.24 and a CV of 1.62% does not disturb evaporation. With time passing the liquid speed becomes lower caused by the gravitational forces decelerating the capillary rise rate. At equilibrium, in the case of the polyester fabric the liquid reaches the maximum height of 44.8±1.2 cm with a CV of 1.84% for the non-walking speed (0 m/s). During the walking speed of 1m/s, the equilibrium front height was 40.4 ±1.5 cm with a CV of 3.63% compared to 31.5±2.7 cm with a CV of 4.71% for the running speed (2 m/s). According to the statistical results of the presented standard deviation and CV values, it is clear that the air mobility caused by the increase in walking speeds affects the stability of the equilibrium height. The statistical values during the running speed are higher than walking and non-walking speeds.
The same phenomenon was found in the case of the cotton fabric. However, the effect of the walking speeds on the equilibrium height was less noticed as for the cotton fibre it is more difficult to evaporate liquid where the amount of the direct water (more difficult to be evaporated) compared to polyester. As illustrated in figure 4, the equilibrium heights were found to be 35.1±0.3 cm with a CV of 0.92%, 32.7±0.7 cm with a CV of 1.12% and 28.4±1.1 cm

Table 1

USED SAMPLES STRUCTURAL PARAMETERS

Sample code	Fibber	Yarn number (Nm)	Mass per unit area (g/m^2)	Warp count (threads/cm)	Weft count (threads/cm)	Thickness (mm)
Ribstop-PC	65% Polyester, 35% Cotton	25	215±4	24±2	24±3	0.56±0.03
Ribstop-CT	100% Cotton		210±3	24±1	24±2	0.55±0.02

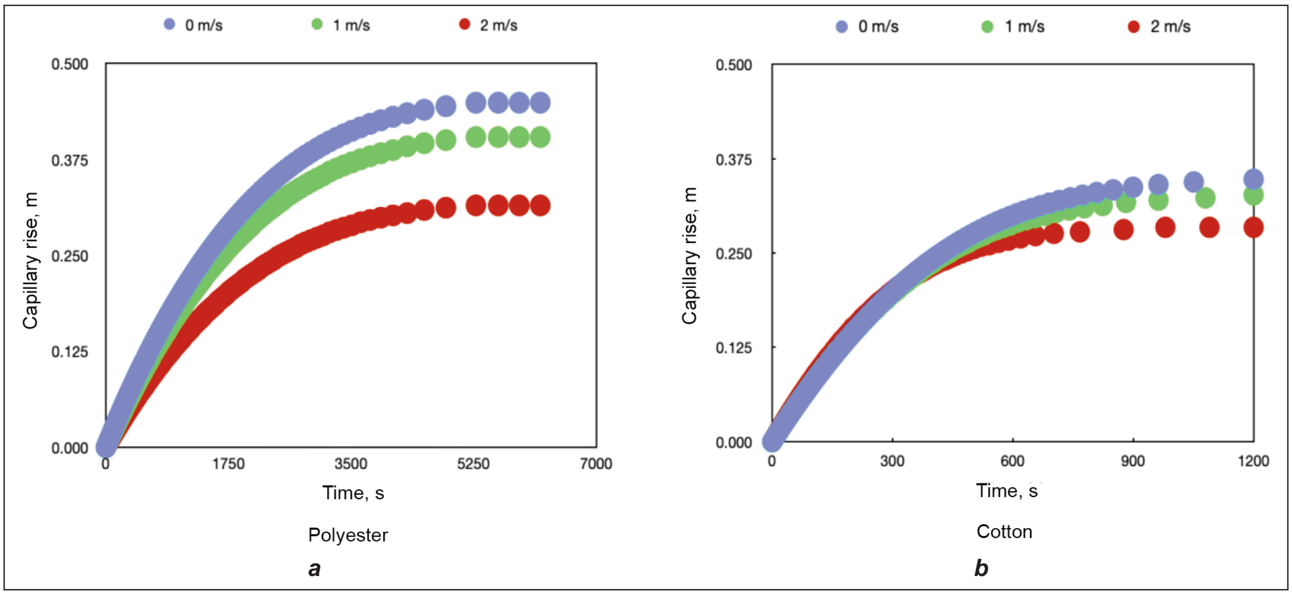

Fig. 4. Effect of walking speed on the capillary rise (20°C and 65% of relative humidity: standard environmental conditions): *a* – Ribstop-PC; *b* – Ribstop-CT

Table 4

THE WICKING PROPERTIES OF THE USED FABRICS					
Sample	R_D (μm)	**Total porosity (%)**	**Walking speed (m/s)**	h_{eq}^{ev} (m)	α (m/s)
Ribstop-PC	3.11	83.2±2.3	0	0.448±0.001	$1.762 \pm 0.007 \cdot 10^{-08}$
			1	0.404±0.002	$2.783 \pm 0.028 \cdot 10^{-08}$
			2	0.315±0.003	$3.497 \pm 0.093 \cdot 10^{-08}$
Ribstop-CT	2.45	76.5±1.8	0	0.351±0.002	$2.974 \pm 0.011 \cdot 10^{-08}$
			1	0.327±0.005	$4.682 \pm 0.084 \cdot 10^{-08}$
			2	0.284±0.007	$5.813 \pm 0.067 \cdot 10^{-08}$

with a CV of 1.41%, respectively during walking speeds of 0 m/s, 1 m/s and 2 m/s. Comparing the presented statistical values, the equilibrium heights in the case of the cotton fabric are more stable compared to the polyester ones. It could be said that the walking speed does not affect the direct water amount evaporation during the capillary rise.

The difference between polyester and cotton fabrics' capillary kinetics is due to the amount of direct and indirect water in the fibre. Cellulosic fibre has a greater proportion of direct water, which is difficult to evaporate, compared to polyester fibre [38].

When designing comfortable fabrics, it is important to consider the phenomenon of evaporation. The surface of the textile that is opened to evaporation and in contact with the surrounding air must be carefully sized to effectively evacuate sweat through the fabric and allow evaporation into the surrounding air. If the surface is too small, evaporation may not occur as efficiently. The evaporation coefficients can be determined based on the water equilibrium front level and considering evaporation based on equation 11. All the wicking parameters are shown in table 2. The results for different walking speeds are also presented in table 2.

Based on figure 4, it is noticeable that the evaporation coefficient is directly proportional to walking speed. This means that when walking at high speed, the air around us is not fully saturated, allowing for greater vapour mobility and more water to evaporate. It is noticed that the evaporation coefficient for 100% cotton was $2.974 \pm 0.011 \cdot 10^{-08}$ m/s, which is greater than the $1.762 \pm 0.007 \cdot 10^{-08}$ m/s for 65% polyester/35% cotton at non-walking speed (0 m/s).

Additionally, when running at 2 m/s, the difference in evaporation coefficient values between 100% cotton and 65% polyester/35% cotton was even more significant, with 100% cotton having a coefficient of $5.813 \pm 0.067 \cdot 10^{-08}$ m/s and 65% polyester/35% cotton having a coefficient of $3.497 \pm 0.093 \cdot 10^{-08}$ m/s.

The moisture equilibrium isotherms exhibit hysteresis during sorption and desorption cycles, signifying structural modifications of the fibre due to water interaction. It's worth noting that while cotton absorbs quickly, it dries slower than other materials due to hysteresis during wetting [38].

CONCLUSIONS

This study explored the water evaporation during the capillary rise of two ripstop woven fabrics made of 65% polyester/35% cotton and 100% cotton. The coefficient of evaporation rate was determined from the equilibrium liquid front level through an image analysis developed program. Based on the developed mathematical model of the capillary kinetics it was established that the evaporation coefficient is a function of various fabric construction parameters (tortuosity, dynamic equivalent pore's radius, thickness and porosity), the water's physical properties (water viscosity and surface energy) and the contact angle resulting from liquid/fibre interaction. The effect of walking speeds (0 m/s as non-walking, 1 m/s as walking and 2 m/s as running speed) was considered, and it was figured out that the evaporation coefficient is directly related to the water vapour diffusion layer and is directly related to the walking velocity. It was found that the walking speeds have an effect on the indirect water amount on the fabrics and it is more difficult to evaporate liquid from the 100% cotton compared to 65% polyester/35% cotton.

Nevertheless, the purpose of this study is to gain insight into the subject and to lay the groundwork for future research. The influence of different air directions on evaporation during wicking will be investigated in future studies.

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