The dynamic of cooling heat flow of simple jersey polyester fabric

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ABSTRACT – REZUMAT

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The dynamic of cooling heat flow during evaporation of the simple jersey polyester fabrics was investigated in this study. The holding period as a new parameter was introduced to study the dynamic of cooling heat flow during evaporation from the skin through the jersey knitted fabric. The holding period intervals were chosen as follows: 0, 30, 60, 90, 120, 180, 240 and 300 seconds.

The Permetest skin model was used to study and visualize the dynamic of the cooling heat flow at different holding periods. Results demonstrated that adding elastane makes fabrics less cool. Three different stages were noticed concerning the cooling heat flow dynamic: the first with a maximum heat flow (Qmax) indicating the first contact properties of a textile material with the skin. The second is a transition phase where the cooling heat flow decreases to the minimum heat flow (Qmin), and then it reaches the equilibrium (Qeq) mentioning the beginning of the third stage with a constant heat flow. It was found that the holding period does not affect the measured water vapour resistance, in the case of polyester jersey fabrics.

Keywords: *cooling, dynamic heat flow, water vapour resistance, elastane, jersey*

Dinamica fluxului de căldură-răcire a tricotului din poliester

În acest studiu a fost investigată dinamica fluxului de căldură-răcire în timpul evaporării a tricotului din poliester. Perioada de menținere, ca parametru nou, a fost introdusă pentru a studia dinamica fluxului de căldură-răcire în timpul evaporării din piele prin tricot. Intervalele perioadei de menținere au fost alese după cum urmează: 0, 30, 60, 90, 120, 180, 240 și 300 de secunde.

Modelul de piele Permetest a fost folosit pentru a studia și vizualiza dinamica fluxului de căldură-răcire la diferite perioade de menținere. Rezultatele au demonstrat că adăugarea de elastan face tricoturile mai puțin răcoroase. Au fost observate trei etape diferite privind dinamica fluxului de căldură-răcire: prima cu un flux maxim de căldură (Qmax) indicând primele proprietăți de contact ale unui material textil cu pielea. A doua a fost ca fază de tranziție în care fluxul de căldură-răcire scade la fluxul minim de căldură (Qmin), iar apoi ajunge la echilibru (Qeq) menționând începutul celei de-a treia etape cu un flux de căldură constant. S-a constatat că perioada de menţinere nu afectează rezistența măsurată la vapori de apă în cazul tricoturilor din poliester.

Cuvinte-cheie*: răcire, flux dinamic de căldură, rezistența la vapori de apă, elastan, tricot*

INTRODUCTION

Textile comfort plays a fundamental role in our daily activities. It is a multiscale concept including the sensory, psychological, and physical properties [1–3]. The thermo-physiological comfort refers to a well-being and satisfaction overall balance resulting from the interaction between textiles and the human body skin [4–6].

Cooling from fabrics facilitates the moisture transfer from the skin to the fabric's outer surface [7] when the sweat is released onto the skin surface as the body perspires. Then, the moisture evaporates into the surrounding air, taking heat energy from the body. This is called evaporative cooling, a key mechanism for regulating body temperature and enhancing comfort.

Water vapour diffusion through textile fabrics, known as breathable fabrics, are designed to grant water vapour evacuation while restricting the water liquid from penetrating [4, 5]. Cooling fabrics are designed with moisture-wicking properties that efficiently convey moisture away from the skin [8]. These fabrics are conceived to provide comfort by managing moisture effectively [9], mainly in situations where the body produces sweat during physical activity or in warm environments [10].

Fabrics with high breathability let air circulate freely, accelerating the evaporation of moisture and the heat release [11]. The mechanism of water vapour diffusion fabrics typically comprises the use of breathable membranes or coatings [12]. The fabric pores should be small enough to prevent liquid from penetrating the fabric but large enough to allow water vapour molecules to pass through [13]. This is often achieved through the open pores that stimulate airflow and boost cooling. Consequently, perspiration from the body can be evaporated through the fabric [10], improving regulation of the wearer's body temperature and keeping them feeling dry and comfortable.

Generally, cooling fabrics are obtained to reflect or emit infrared (IR) radiation, which supplies heat transfer. By reflecting or emitting IR radiation it minimizes heat absorption and maintains a cooler surface temperature [14]. Certain fabrics combine phase change materials leading to absorption and release of heat through phase transitions. Phase change materials are suitable to regulate temperature by absorbing excess heat from the body (when warm) and releasing it (when the environment cools down) [15, 16].

Special coatings or finishes can be applied to textile fabrics to improve the cooling comfort [17]. These finishing processes can afford a fast-cooling sensation upon contact with moisture or air, giving additional comfort in hot conditions [18, 19].

Cooling heat flow uncovers applications in various industries, involving sportswear, outdoor apparel, bedding, and protective clothing for hot environments. Cooling heat flow textile fabrics is based on diverse mechanisms to manage heat transfer and propagate cooling [10]. These fabrics are engineered to improve comfort by actively dissipating heat from the body or minimizing heat absorption from the environment. By efficiently managing heat balance, textile fabrics improve comfort and performance in warm conditions [20].

Polyester fibre is an excellent choice for textiles and apparel because of its remarkable durability, wrinkle resistance, and colour retention. The Global Polyester Fibre Market size is expected to reach $153.5 billion by 2030, rising at a market growth of 7.5% during the forecast period. In the year 2022, the market attained a volume of 70,195.3 kilotonnes, experiencing a growth of 6.7% (2019–2022) [21]. Elastane is usually used with polyester to enhance comfort. Polyester/Elastane fabrics are recommended for increasing flexibility and freedom of movement and making them perfect for sportswear [22].

Understanding the dynamic cooling heat flow interaction is essential for designing and engineering cooling comfort that regulates temperature and moisture to afford optimal well-being and performance during high activity or in hot and humid environmental conditions.

This paper investigated the dynamic of the cooling heat flow during evaporation from the skin through the simple polyester jersey knitted fabric. A holding period was introduced as a new parameter to study the dynamic of the cooling heat flow. The Permetest was used to visualize the dynamic of the cooling heat flow at different holding periods: 0, 30, 60, 90, 120, 180, 240 and 300 seconds. The statistical analysis was used to explore the effect of the holding period on the water vapour resistance and the dynamic cooling heat flow.

MATERIALS AND METHODS

Fabric properties

Polyester fibre knitted fabrics were used to study the dynamic of the cooling heat flow. The structural parameters properties of used fabrics are presented in table 1.

The knitting thickness was determined following the NF G 07-153 standard. The numbers of wales and courses per centimetre were determined according to the standard ASTM D8007-15(2019). The mass per unit area was determined according to the EN 12127: 1997 standard.

Total Porosity (ε) is defined by the volumetric ratio of accessible pores to total volume. The total porosity was calculated using the following equation:

$$\varepsilon\ (\%) = \left(1 - \frac{M}{\rho \times t_h}\right) \times 100 \qquad (1)$$

This parameter can be expressed as a function of the mass per unit area (M), the thickness of the fabric (t_h), and the density of the fibre (ρ) [23].

The optical microscope views of the used samples zoomed 80 times are illustrated in figure 1. The PET and PET/EL (with 10% elastane), respectively a mass per unit area of 180 ± 1 and 200 ± 2 g/m^2 and almost the same thickness of about 0.571 ± 0.01 and 0.591 ± 0.01 mm. It can be seen that the elastane affects the mass per unit area (180 ± 1 g/m^2 for the PET fabric compared to 200 ± 2 g/m^2 for the PET/EL fabric), stitch's density (20 ± 1 × 12 ± 1 for the PET fabric compared to 22 ± 1 x 20 ± 1 for the PET/EL fabric) and so the porosity of the fabric (77.32 ± 1.5% for the PET fabric compared to 75.30 ± 1.2 % for the PET/EL fabric).

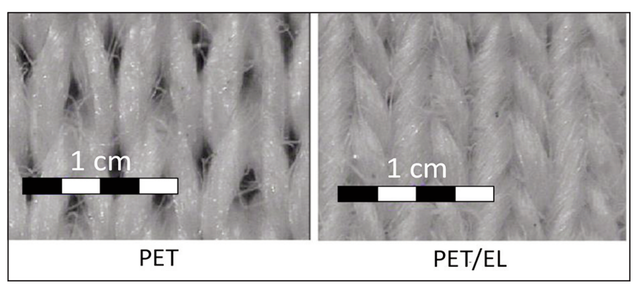

Fig. 1. Optical microscope view of used samples (zoom: ×80)

Table 1

SIMPLE JERSEY KNITTING FABRICS PROPERTIES					
Sample code	**Composition**	**Mass per unit area (g/m²)**	**Thickness (mm)**	**Stitches density (wales/cm × courses/cm)**	**Total porosity (%)**
PET	100% Polyester	180 ± 1	0.571 ± 0.01	20 ± 1 × 12 ± 1	77.32 ± 1.5
PET/EL	90% Polyester / 10% Elastane	200 ± 2	0.591 ± 0.01	22 ± 1 × 20 ± 1	72.30 ± 1.2

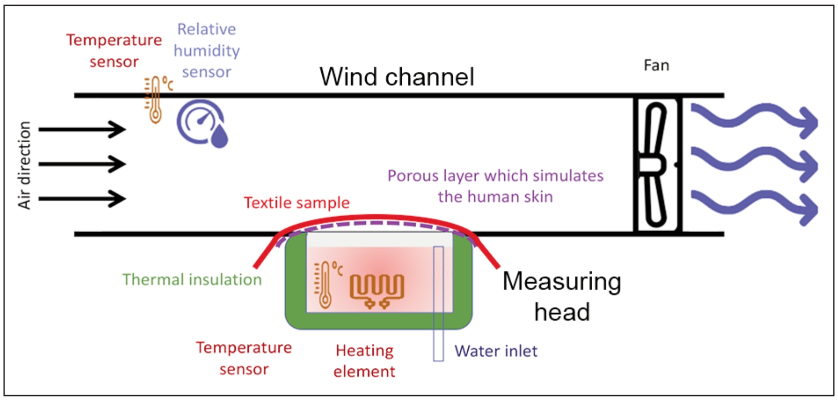

Fig. 2. PERMETEST skin model Working principle

holding period were tested five times.

Statistical tools

Measurement tests were conducted five times for each test. Average values were considered, and standard deviation and CV values were presented for all tests. A one-way ANOVA test analysis was used to study the significance of the holding period on the dynamic of the water vapour resistance based on P values.

Water vapour Kinetics

The cooling heat flow during evaporation through the textile fabrics was determined using the PERMETEST apparatus. Measurements were conducted using the same principle as specified in ISO 11092. A heated semi-permeable porous membrane was used to simulate the sweating skin. The heat required for the water to evaporate from the membrane, with and without a fabric covering, was measured. The fabric sample was placed on a measuring head over a semi-permeable foil and exposed to parallel air flow at a velocity of 1 m/s, as presented in figure 2. The measurements were carried out under isothermal conditions at 20°C. The computer connected to the apparatus determines the evaporative resistance Ret of textile fabrics according to the standard ISO 11092.

The water evaporative resistance (Ret) is determined according to the ISO 11092 Standard: Textiles – Physiological effects – Measurement of the thermal and water-vapour resistance [13] and it is expressed as follows:

$$Ret\ (\mathrm{m^2\ Pa/W}) = (P_{sat} - P_v)\left(\frac{1}{q_s} - \frac{1}{q_0}\right) \qquad (2)$$

where *Ret* is water vapour resistance ($m^2{\cdot}Pa/W$); P_{sat} – saturated water vapour partial pressure at test temperature (Pa) and it is equivalent to the skin vapour pressure; P_v – partial water vapour pressure in the air (Pa); q_s – heating power with sample (W/m^2), presents the heat loss of the wet measuring head (skin model) with a sample; q_0 – heating power without a sample (W/m^2), means the instrument reading without a sample (heat loss of the free wet surface).

Test protocol

The holding period as a new parameter was introduced to investigate the dynamic of the cooling heat flow. It was defined as the time from the sample placement on the measuring head until the measuring was processed. The measurements were carried out under isothermal conditions at 20±2°C and 65±2% of relative humidity. The holding period intervals were chosen as follows: 0, 30, 60, 90, 120, 180, 240 and 300 seconds. All samples for the specific

RESULTS AND DISCUSSION

In this section, firstly, the effect of the holding period on the water vapour resistance (Ret) was studied. Secondly, the cooling heat flow during evaporation was visualized at different holding periods.

Water vapour resistance

As presented in table 2, the water vapour resistance of the PET/EL for different holding periods had an average value of 3.00±0.15 $m^2{\cdot}Pa/W$, it varied from 2.89±0.14 $m^2{\cdot}Pa/W$ to 3.21±0.17 $m^2{\cdot}Pa/W$ with a Standard Deviation of 0.11±0.01 $m^2{\cdot}Pa/W$ and a CV of 3.74±0.2%. It is noticeable that the holding period has no significant effect on effect on the water vapour resistance for the PET/EL fibre under 1 m/s of air velocity.

In the case of the PET sample, the average value of the water vapour resistance was 2.43±0.12 $m^2{\cdot}Pa/W$, the maximum value was 2.72±0.14 $m^2{\cdot}Pa/W$ and the minimum value was 2.04±0.10 $m^2{\cdot}Pa/W$, with a Standard Deviation of 0.27±0.01 $m^2{\cdot}Pa/W$. The CV

Table 2

THE EFFECT OF THE HOLDING PERIOD ON WATER VAPOR RESISTANCE AT 1 M/S AIR VELOCITY

Parameter	Holding period (s)	PET	PET/EL
RET ($m^2{\cdot}Pa/W$)	0	2.12±0.11	3.21±0.17
	30	2.04±0.10	2.89±0.14
	60	2.31±0.12	2.91±0.15
	90	2.33±0.12	2.92±0.16
	120	2.72±0.14	3.00±0.14
	180	2.61±0.13	2.93±0.15
	240	2.62±0.13	3.11±0.16
	300	2.69±0.13	3.01±0.16
	Average	2.43±0.12	3.00±0.15
	Maximum	2.72±0.14	3.21±0.17
	Minimum	2.04±0.10	2.89±0.14
	Standard Deviation	0.27±0.01	0.11±0.01
	CV (%)	10.92±0.55	3.74±0.2

value was equal to 10.92±0.55%. So, the holding period has no noticeable effect on the water vapour resistance under 1 m/s of airspeed.

Adding the elastane to the fabric structure increases the water vapour resistance by about 23% compared to a 100% polyester structure. The results showed that adding elastane leads to stitch overlapping; therefore, the thickness, the mass per unit area, and the stitch density increase. This leads to the decrease of the total porosity and the modification of the geometrical and pores layout.

For deeper discussions, an ANOVA analysis is presented in table 3. Here, one factor was considered: holding period time with 8 levels (0, 30, 60, 90, 120, 180, 240, and 300 seconds).

Table 3

ANOVA: WATER VAPOR RESISTANCE VERSUS TIME (0: 30; 60; 90; 120; 180; 240 AND 300 S) AIR VELOCITY = 1 M/S					
Factor Type Levels Values					
Holding period (s) fixed: 0; 30; 60; 90; 120; 180; 240; 300					
Analysis of Variance for RET_PET					
Source	DF	SS	MS	F	P
Holding period (s)	7	0.27330	0.03904	0.77	**0.632**
Error	7	0.35580	0.05083		
Total	15	2.58910			
S = 0.225452	R-Sq = 86.26%	R-Sq(adj) = 70.55%			
Analysis of Variance for RET_PET/EL					
Source	DF	SS	MS	F	P
Holding period (s)	7	0.03700	0.00529	0.45	**0.844**
Error	7	0.08250	0.01179		
Total	15	1.06040			
S = 0.108562	R-Sq = 92.22%	R-Sq(adj) = 83.33%			

Based on ANOVA analysis, a statistically significant test result ($p \leq 0.05$) means that the studied factor significantly affects the water vapour resistance. As noticed, for the PET and PET/EL samples the holding period time has a non-significant effect on the water vapor resistance as all p-values > 0.05.

Cooling heat flow kinetics at zero holding period

The heat flow kinetics during evaporation are investigated in this subsection. It is important to study in detail how the water vapour is transferred through the textile fabrics. The cooling heat flow kinetics at zero holding period is presented in figure 3.

According to figure 3, it is noticed that the cooling heat flows had the same layout for the studied two fabrics. This means that the pores are narrowed due to the addition of elastane in the structure and without a significant modification in the pore's geometrical layout. At zero seconds the PET sample registered a heating flow of about 135.1±9.4 W while 100.7±7.1 W for the PET/EL sample. At the beginning of the evaporation on the Permetest apparatus measuring head top, the temperatures of the used samples that were conditioned at room temperature

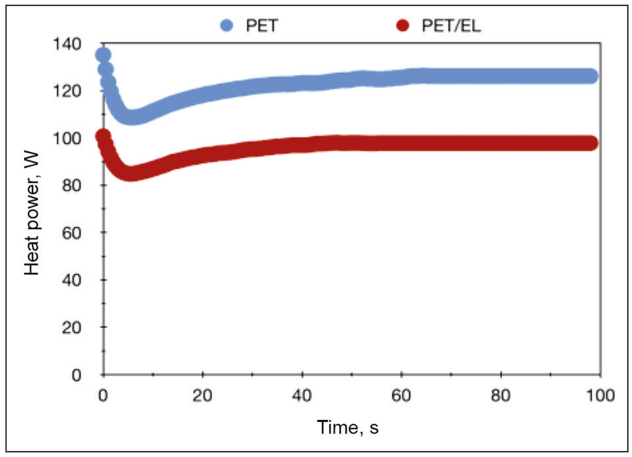

Fig. 3. Cooling heat flow kinetics at zero seconds holding period

(20±2°C) were greater than those in the winding channel (18±2°C) due to the cooling by evaporation from the semi-permeable foil. So, the measuring head was not heated as the fabric was hotter than the semi-permeable foil top side placed on the top of the measuring head. By the time passing and at the second stage, to equalize the temperature between the fabric and the measuring top head, this heat flow decreased to reach a value of about 108.6±7.8 W in the case of PET compared to 84.8±5.9 W for PET/EL sample. In the third stage, the cooling heat flow increased to reach an equilibrium cooling heat flow. The increase in flow is caused by the phenomenon of evaporation through the fabric from the semi-permeable membrane thus causing a cooling at the top surface of the fabric. The equilibrium cooling heat flow is defined as a continuous water vapour penetration through the textile fabric. Figure 3, also suggested that the PET fabric had a more cooling feeling compared to the PET/EL one. This is due to elastane-containing fabrics which have been found to have longer drying times and higher water vapour contents [24].

Based on figure 3, some characteristic parameters defining the different cooling heat flow stages were determined as presented in table 4. It is noticed that adding 10% of the elastane in the fabric structure makes it less cool.

Table 4

COOLING HEAT FLOW CHARACTERISTICS		
Characteristic parameters	**PET**	**PET/EL**
Q_0 (W)	135.1±9.4	100.7±7.1
Q_{min} (W)	108.6±7.8	84.8±5.9
Q_{Max} [W)	135.1±8.2	100.7±6.4
Q_{eq} (W)	126.1±7.9	97.8±6.1
$t_{Q0\text{->}Qmin}$ (s)	5.5±0.3	5.5±0.5
t_{eq} (s)	62±4.5	45.5±3.1

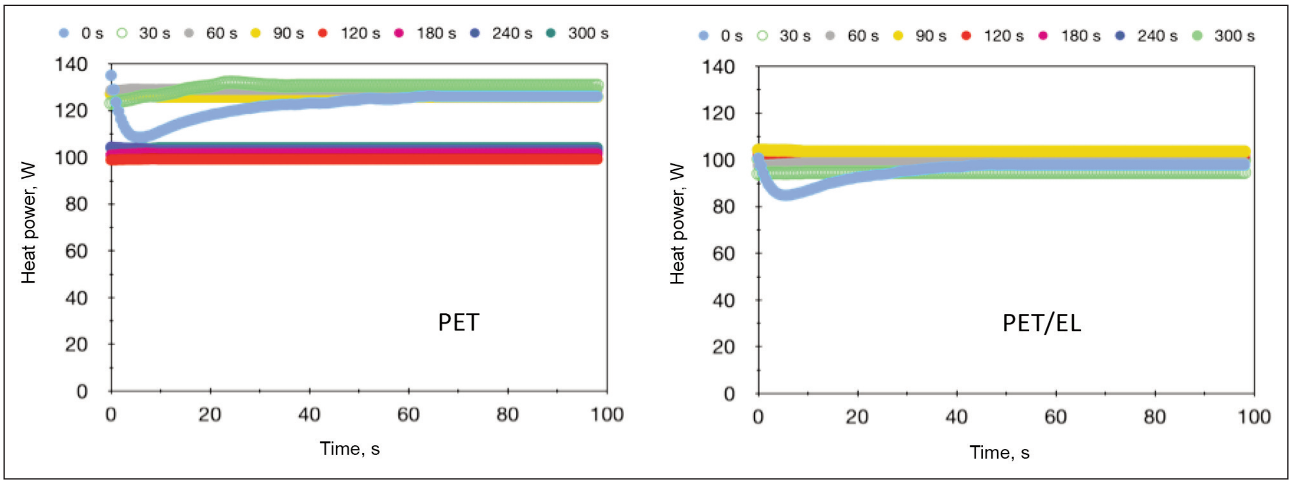

Fig. 4. Effect of holding period on the cooling heat flow kinetics

The effect of the holding period on the cooling heat flow

Figure 4 illustrates the effect of the holding period on the cooling heat flow. In the case of PET/EL, at 0 second holding period, the heat flow started at 100.7 ± 7.1 W and then decreased to reach 84.8 ± 5.9 W at 5.5 ± 0.5 seconds. Then it raised to reach an average value of equilibrium phase of about 97.8 ± 6.1 W at 45.5 ± 3.1 seconds starting from 45.5 ± 3.1 seconds. So, the transition phase before equilibrium took 45.5 ± 3.1 seconds. For the next holding periods starting from 30 seconds to 300 seconds, the cooling heat flow had a linear layout noticing the absence of the transition phase. Comparing the cooling heat flow for the periods from 30 seconds to 300 seconds the average value was about 100.4 W with a standard deviation of about 3.28 W and a CV of about 3.28 %. So, it can be concluded that the holding period does not affect the cooling heat flow after 30 seconds.

Concerning the 100% PET fabric, it was observed that at 0 seconds the cooling heat flow had a nonlinear layout, while for the periods starting from 30 to 300 seconds, it had a linear layout. At 0 seconds holding period the cooling heat flow started at 135.1 ± 9.4 W which was higher than the PET/EL fabric (100.7 ± 7.1 W). This means that the 100% PET fabric absorbed more water compared to the PET/EL fabric from the surrounding air before being put on the top of the measurement to the head of the Permetest apparatus. In the second phase the cooling heat flow, the heat flow decreased to reach a minimum value of about 108.6 ± 7.8 W at 5.5 ± 0.3 seconds. The cooling heat flow's equilibrium value was about 126.1 ± 7.9 W and reached 62 ± 4.5 seconds. When comparing the holding periods starting from 30 seconds to 300 seconds the average value of the cooling heat flow was about 113.3 W with a standard deviation of about 14.3 W and a CV of about 12.61%. So, the holding period affects the cooling heat flow. As illustrated in figure 4, it should be divided into 3 groups and not into 2 groups. The first one was 0 seconds, the second from 30 to 90 seconds, and the third one from 120 to 300 seconds.

Concerning the second interval group (from 30 to 90 seconds), the average value of all the holding periods was approximately 128.4 W with a standard deviation of 0.74 W and a CV of about 0.57%. At this holding period stage, the pores are not completely saturated. In the case of the holding periods of the third interval group (from 120 to 300 seconds), the average value of all the holding periods was approximately 101.9 W with a standard deviation of 0.11 W and a CV of about 0.10 %. During the holding periods of the third group (from 120 to 300 seconds), the interconnections pores (pores between fibres at the yarn scale [12]) are saturated and the evaporation occurs from the macropores (between yarns at the fabric scale [12]) opened to the evaporation from the top side of the fabric exposed to the ventilation in the wind channel [10].

CONCLUSIONS

This study highlights the dynamic of cooling heat flow. A holding period as a new parameter was introduced. It was defined as the time from the sample placement on the measuring head until the measuring was processed. Holding period intervals were chosen as follows: 0, 30, 60, 90, 120, 180, 240 and 300 seconds. The Permetest was used to measure the water vapour resistance by visualizing the cooling heat flow at different holding periods.

Based on the ANOVA analysis, it was found that the holding period has no significant effect on the water vapour resistance. By adding 10% of elastane to the simple jersey structure the water vapor resistance decreases by about 23%. This is due to stitch overlapping; therefore, the thickness, the mass per unit area, and the stitch density increase. This leads to the decrease of the total porosity and the modification of the geometrical and pores layout.

Visualizing the cooling heat flow kinetics, at 0 seconds holding period, denoted three stages. In the beginning, the maximum cooling heat flow was recorded as the difference of the sample's temperatures conditioned at 20 ± 2°C and 65 ± 2% of relative humidity and the temperature at the top of the measuring heat of about 18 ± 2°C due to the cooling by evaporation from the semi-permeable foil. During the second stage, defined as a transition phase, the cooling heat flow decreases to a minimum value, then increases to reach an equilibrium value, mentioning the start of the third stage: a steady state phase.

The effect of the walking speed on the cooling heat flow dynamics will form an important area of interest for future research.

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