The effect of fabric parameters on the evaporative cooling heat flow kinetics

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ABSTRACT – REZUMAT

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This study explored how fabric parameters and walking speed affect the dynamics of evaporative cooling. Walking speed is equivalent to 1 m/s, while running speed is 2 m/s. Knitting fabrics made from natural and synthetic fibres were used to examine how hydrophilic and hydrophobic properties influence evaporation. Visualising the evaporative cooling heat flow kinetics allowed us to identify different evaporation stages. We defined new parameters: Q_{max}, Q_{min}, Q_{eq}, Flow drop (Q_{max} – Q_{min}), and equilibrium time. Q_{max} represents the thermal absorptivity of water vapour at the very first moment of contact between the fabric and the skin. Q_{min} signifies the decrease in the cooling flow. T_{eq} denotes the equilibrium time. These parameters describe the dynamics of water vapour transfer.

The results showed that incorporating synthetic fibres into a fabric enhances its breathability, lowers the temperature, accelerates drying, and provides a refreshing sensation when first touched by the skin. It was found that Coolmax is twice as cool as wool.

Keywords: *walking speed, evaporation, cooling, dynamic heat flow*

Efectul parametrilor materialului textil asupra cineticii fluxului de căldură în răcirea prin evaporare

Acest studiu descrie modul în care parametrii materialului textil și viteza de mers afectează dinamica răcirii prin evaporare. Viteza de mers este echivalentă cu 1 m/s, în timp ce viteza de alergare este de 2 m/s. Au fost utilizate tricoturi din fibre naturale și sintetice pentru a examina modul în care proprietățile hidrofile și hidrofobe influențează evaporarea. Vizualizarea cineticii fluxului de căldură al răcirii prin evaporare a permis identificarea diferitelor etape de evaporare. Au fost definiți noi parametri: Q_{max}, Q_{min}, Q_{eq}, scăderea fluxului (Q_{max} – Q_{min}) și timpul de echilibru. Q_{max} reprezintă absorbția termică a vaporilor de apă în primul moment de contact între materialul textil și piele. Q_{min} semnifică scăderea fluxului de răcire. T_{eq} denotă timpul de echilibru. Acești parametri descriu dinamica transferului vaporilor de apă.

Rezultatele au arătat că incorporarea fibrelor sintetice într-un material îmbunătățește respirabilitatea acestuia, scade temperatura, accelerează uscarea și oferă o senzație de răcorire la primul contact cu pielea. S-a constatat că Coolmax este de două ori mai răcoros decât lâna.

Cuvinte-cheie: *viteza de mers, evaporare, răcire, flux de căldură dinamic*

INTRODUCTION

The evaporation cooling mechanism is utilised in various applications, such as sportswear, outdoor clothing and protective garments designed for hot environments. The cooling of textile materials through heat flow relies on multiple mechanisms to regulate heat transfer and diffuse cooling [1]. Consequently, water vapour transfer is crucial in textile design [2]. The necessity to consider moisture transfer through textiles stems from the continuous loss of water from the human body [3], primarily through evaporation from the skin [4, 5]. The evacuation of water vapour through clothing is essential for maintaining body temperature balance and comfort. The textile fabric must facilitate the rapid removal of sweat through diffusion and evaporation into the ambient air [6–8]. Extensive research has been conducted on the mechanisms of water vapour transfer through textile fibres [9–11], single fabrics [12–16], double-faced fabrics [17, 18], multilayers [19, 20], and garment assemblies [21–23]. However, the majority of this research has been conducted under static conditions, where equilibrium conditions have been assumed, with limited work being done under dynamic conditions. Dynamic testing is necessary because water vapour transfer is strongly correlated with water vapour diffusion in fibres and condensation in pores, and is time-dependent [24, 25]. Several methodologies and test conditions have been developed to assess the moisture transfer capabilities of textile materials. Although each test method closely approximates real-world conditions, none can fully replicate the intricate process [26]. The measurements of water vapour transfer phenomena through textile fabrics, following ISO 11092, solely consider the steady state. Consequently, all values presented are static modes. This limitation prevents the simulation of actual functional textile usage conditions.

Therefore, comprehending the dynamic interaction of cooling heat flow is paramount to designing and developing a cooling comfort system that balances temperature and humidity. This ensures optimal well-being and performance during intense physical activity or in hot and humid environmental conditions. The kinetics of the cooling evaporative heat flow during evaporation were the subject of investigation in this study. Consequently, the Permetest was employed to elucidate and visualise the dynamics of the cooling evaporative heat flow. The findings revealed that the incorporation of elastane resulted in a reduction in the cooling effect of the fabrics. Three distinct phases were observed in the kinetics of the cooling evaporative heat flow: the initial phase, characterised by a peak heat flow (Q_{max}), which corresponds to the initial contact properties of the textile material with the skin. The subsequent phase represents a transition phase during which the cooling heat flow decreases to its minimum value (Q_{min}) and subsequently reaches equilibrium (Q_{eq}), marking the commencement of the third phase, characterised by a constant heat flow.

MATERIALS AND METHODS

Five simple Jersey samples with different material compositions (Natural and synthetic) were used in this study.

The mass per unit area of the fabric was determined using the standard ISO 3801:1977. The ISO 5084 standard was used to measure the thickness of fabric samples. According to ISO 9237, air permeability in the transverse direction was measured using the FX3300 (Textest, Switzerland) under a pressure of 100 Pa [27].

Total porosity (ε) is defined as the volumetric ratio of accessible pores to the total volume. The porosity values were calculated using the following equation:

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

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) [28].

Before testing, all samples were scoured with non-ionic synthetic detergents (1.5–2 g/l) and alkali (0.5–1.5 g/l sodium carbonate) using a RELAXLAB according to the standard NF G 07 102. Knitted structures, material weights, thicknesses, and porosity are listed in table 1.

The evaporative cooling heat flow was visualised using the Permetest instrument. The water vapour resistance, Ret, and the relative water vapour permeability of the tested fabrics were also expressed in the units defined in ISO 11092 [31] using the same instrument.

All tests were conducted under standard atmospheric conditions of 20±2 °C and 65±4 % of relative humidity, as per ISO 139:2005 [32].

RESULTS AND DISCUSSION

Based on table 1, the two samples, PET and PET/EL (with 10% elastane), have respectively a mass per unit area of 180 and 200 g/m^2, and an almost identical thickness of approximately 0.571 and 0.591 mm. Elastane influences the bulk density, thereby affecting the porosity of the sample. The total porosity of the 100% polyester knit is 75.30±1.2%, while the 90% polyester/10% elastane sample has a porosity of 77.32±1.5%. Cotton and wool knits with discontinuous yarns and short fibres can potentially inhibit the flow of air and water vapour [29, 30].

The water vapour resistance values of different tested samples are presented in table 2.

In the case of wool fabric, the water vapour resistance was about 8.088 m^2·Pa/W, with a standard deviation of 0.528 m^2 Pa/W and a CV of 6.52%, and 7.004 m^2·Pa/W, with a standard deviation of

Table 1

KNITTING FABRICS PROPERTIES

Sample	PET	PET/EL	CoolMax	Cotton	Wool
Composition	100% PET*	90% PET/ 10% EL*	100% CoolMax	100% Cotton	100% Wool
Wales/cm	20±1	22±1	14±1	25 ±1	18 ±1
Courses/cm	12±1	20±1	30±1	22±1	18±1
Mass per unit area (g/m²)	180±1	200±2	180.58	175±1	220±2
Thickness (mm)	0.571±0.01	0.591±0.01	0.412±0.01	0.766±0.01	1.037±0.02
Total porosity (%)	75.30±1.2	77.32±1.5	86.46±1.2	85.26±2.3	80.71±3.2
Air permeability (mm/s)	1442±12	367±06	693.4±11	1168±23	280.3±10

Note: *PET (Polyester); EL (Elastane).

Table 2

WATER VAPOUR RESISTANCE AT DIFFERENT WALKING SPEEDS

Sample	PET		PET/ EL		CoolMax		Cotton		Wool	
Walking Speed (m/s)	1	2	1	2	1	2	1	2	1	2
RET (m^2·Pa/W)	2.9±0.1	2.5±0.2	2.4±0.1	1.7±0.2	2.3±0.1	1.4±0.1	3.2±0.2	3.0±0.4	8.0±0.8	7.0±1

0.481 $m^2 \cdot Pa/W$ and a CV of 6.87%, for walking speeds of 1 m/s and 2 m/s, respectively.

For cotton, the average RET value is 3.240 $m^2 \cdot Pa/W$ with a standard deviation of 0.093 $m^2 \cdot Pa/W$ and a CV of 2.87%, under a walking speed of 1 m/s and 3.041 $m^2 \cdot Pa/W$ with a standard deviation of 0.197 $m^2 \cdot Pa/W$ and a CV of 6.49%, under a running speed of 2 m/s.

In the case of walking (1 m/s), the water vapour resistance of PET had an average value of 2.990 $m^2 \cdot Pa/W$ with a standard deviation of 0.113 $m^2 \cdot Pa/W$ and a CV of 3.77%. In the case of running (2 m/s), the average value of 2.502 $m^2 \cdot Pa/W$ with a standard deviation of 0.066 $m^2 \cdot Pa/W$ and a CV of 2.65% was noticed.

It was noticed that the CoolMax fabric was the most comfortable as it has the lowest water vapour resistance values under different walking speeds. In fact, in the case of walking, the RET was about 2.33 $m^2 \cdot Pa/W$ with a standard deviation of 0.272 $m^2 \cdot Pa/W$ and a CV of 2.33% and 1.42 $m^2 \cdot Pa/W$ with a standard deviation of 0.103 $m^2 \cdot Pa/W$ and a CV of 1.42% for walking speeds of 1 m/s and 2 m/s, respectively.

Evaporative cooling heat flow kinetics

In this section, the evaporative cooling heat flow kinetics of Wool, CoolMax, PET, PET/EL, and Cotton samples were visualised under a walking speed of 1 m/s.

From figure 1, at t = 0 s, the heat flow recorded a maximum value and then decreased until reaching an equilibrium state for all studied samples. This result is explained by the fact that at t = 0 s, the temperature of the tested sample is equal to the laboratory temperature (20°C – 22°C), which is higher than the temperature of the semi-permeable membrane of the Permetest instrument measuring unit. This temperature difference explains the decrease in heat flow in the measuring unit. Indeed, this transferred heat accompanied by water vapour passes through the semi-permeable membrane until reaching a thermal balance of the microclimate existing between the membrane and textile fabric.

The mass and heat diffusion through the knit depend on the material type used. It is noted that CoolMax is the most comfortable by recording an evaporative cooling flow of the order of 142 W at t = 0 s, and throughout the evaporation, this flow always remains higher than that of the other samples. The cooling heat flow in the case of the natural fibre of 100% wool is the most remarkable. Indeed, the cooling heat transferred ($Q_{max} - Q_{min}$) through this knit is equal to 37.8 W, which is the most important value transferred during a longer period of 30.6 s. Furthermore, in the case of 100% cotton fabric, a cooling-heating flow of 22.5 W was transferred in 7.5 s. This transferred heat is less significant compared to that diffused through the 100% polyester knit (25.0 W for 5.5 s). However, the heat transferred through the knit composed of

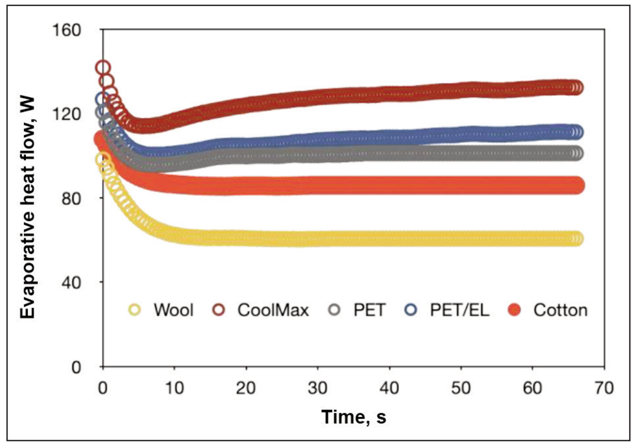

Fig. 1. Evaporative cooling heat flow kinetics under a walking speed of 1 m/s

90% polyester and 10% elastane (26.3 W for 6.5 s) is greater than that transferred through the 100% polyester sample.

Regarding the equilibrium time, the cotton sample reached equilibrium for 10 seconds more rapidly than other samples, but recorded an equilibrium cooling heat flow of about 86 W, which is less important compared to samples composed of synthetic fibres. The cotton fibre absorbs water vapour rapidly but dries slowly, which slows down the water vapour diffusion. The same phenomenon was noticed in the case of the wool fabric, where equilibrium was reached at 60.7 W for 32 s. Contrarily, in the case of fabrics made with synthetic fibres, the equilibrium values of cooling and heating flow were greater than 100 W. These results are explained by the fact that in CoolMax, PET, and PET/EL samples, water molecules are not absorbed by polyester and elastane fibres due to their hydrophobic behaviour.

When the relative humidity of the microclimate, existing between the membrane and the fabric, increases and the diameter of the pores is small, the diffused water will be adsorbed on the solid surface of the pores under the influence of the physical forces of Van der Waals. Subsequently, multimolecular water layers will be formed until condensation by a liquid bridge connection separates the gas phase by a meniscus (figure 2). The smaller the diameter of the pores, the greater the capillary condensation, which explains the high flow of PET/EL knitting compared to that of PET. This is because the incorporation of elastane yarn into the knitting leads to a reduction in its porosity.

In contrast, fabrics composed of hydrophilic fibres, such as wool and cotton, rapidly absorb water due to their polar groups. As the relative humidity in the microclimate between the membrane and the sample increases, water vapour molecules are adsorbed and subsequently diffused through the fibre substrates (figure 2). This process leads to sample swelling, resulting from the breaking of hydrogen bonds in the amorphous zones and the formation of hydrogen bonds with the diffused water molecules constrained by temperature and pressure. The higher the humidity, the greater the likelihood of saturation of the sample with water vapour. The diffusion step is followed by the evaporation of water vapour from the upper surface of the sample held on the semipermeable membrane and exposed to an air speed of 1 m/s. Surface evaporation is dependent on the thermal resistance of the sample. For instance, the evaporation rate on the surface of a 100% wool knit is negligible or even low. This is attributed to the high thermal resistance of the wool fibre (thermal insulator), which prevents the diffusion of water molecules within the structure, hindering liquid transport. Consequently, the slow cooling of wool from the outer surface to the inner surface observed in front of the semipermeable membrane, as indicated by the Permetest measuring unit, can be attributed to this factor. However, as depicted in figure 1, the thermal equilibrium in the cases of CoolMax, PET, and PET/EL knits is followed by a significant increase in the heat flow measured in the unit compared to that observed in the cases of the 100% wool and 100% cotton samples.

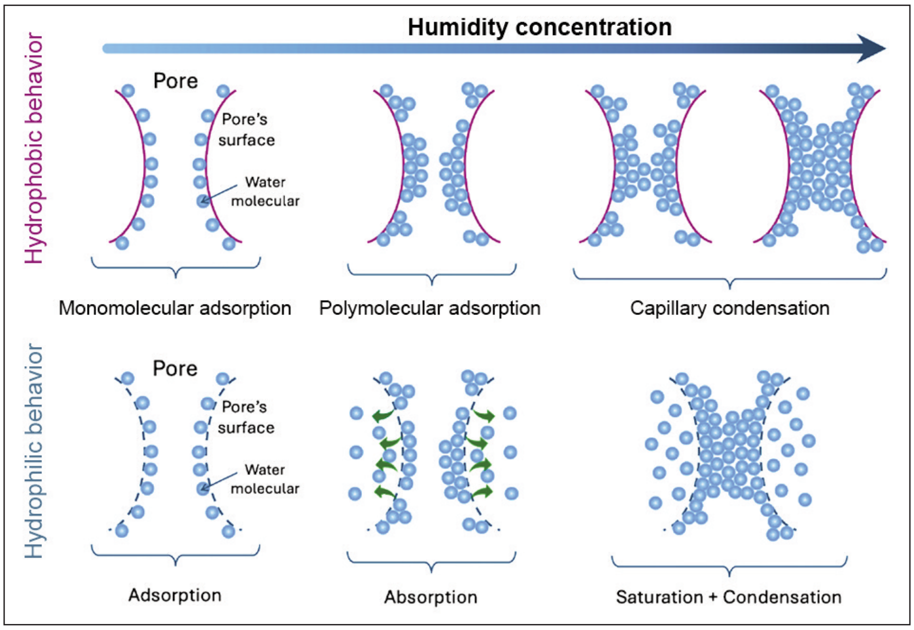

Fig. 2. Water vapour diffusion through pores in hydrophilic and hydrophobic materials

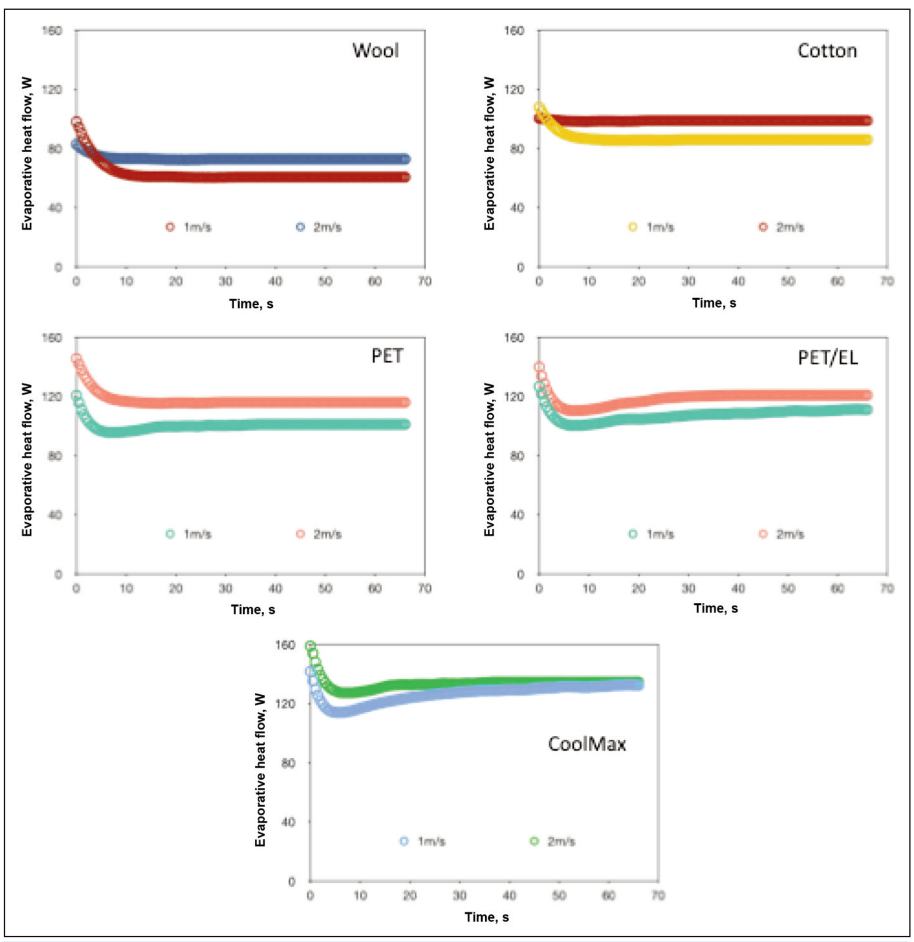

Fig. 3. The effect of walking speed (1 m/s et 2 m/s) on the evaporative cooling heat flow

This is because CoolMax, PET, and PET/EL knits have low thermal resistance, facilitating the rapid transport of liquid. This ensures the cooling effect on both the upper and lower sides of the sample.

Effect of walking speed on the evaporative cooling heat flow

In this section, the evaporative cooling heat flow of various used samples under different air speeds (1 m/s and 2 m/s) was represented to investigate the impact of walking speed on the heat flow traversing textile fabrics (figure 3).

Figure 3 depicts evaporative cooling heat flow kinetics during the water vapour resistance test of the tested knitted fabrics at two distinct air speeds (1 m/s and 2 m/s). The two curves representing the heat flow of the wool knitted fabric during the two different speeds exhibit a decreasing trend. Notably, at an air speed of 1 m/s, the curve started at 98.2 W at 0 s and subsequently reached a constant flow of 60.7 W after 32.0 s. Conversely, at an air

Table 3

EVAPORATIVE COOLING HEAT FLOW CHARACTERISTIC PARAMETERS							
Sample			**Q_{max} (W)**	**Q_{min} (W)**	**$Q_{max} - Q_{min}$ (W)**	**Q_{eq} (W)**	**T_{eq} (s)**
Wool	Walking speed(m/s)	1	98.2±8.2	60.4±5.7	37.8±4.3	60.7±5.4	32±3.2
		2	82.9±9.1	72.5±8.2	10.4±2.9	72.8±7.8	26.5±2.5
Cotton		1	108±7.2	85.4±5.6	22.5±1.6	86±5.7	10±1.1
		2	100.6±8.3	98.3±6.7	2.3±1.2	98.9±6.6	11.5±1.7
PET		1	120.8±9.4	95.7±7.6	25±2.1	101.2±8.3	36.5±2.4
		2	145.7±10.3	115.3±8.1	30.4±2.3	116.1±8.4	29±2.8
PET/EL		1	126.8±8.5	100.5±6.6	26.3±1.8	111.2±7.3	58±3.2
		2	140±9.6	110.6±7.8	29.4±2.1	120.9±8.6	40±3.6
CoolMax		1	141.9±11.3	114±8.9	27.8±2.2	132.4±10.3	62.5±4.5
		2	159±12.7	127.3±10.3	31.7±2.6	134.6±10.8	36.5±4.1

speed of 2 m/s, the curve commences at 82.9 W at 0 s and attains a constant flow of 72.8 W after 26.5 s. These observations can be attributed to increased airspeed leading to a concomitant rise in surface evaporation through the wool knitted fabric. This phenomenon results in a faster cooling rate, consequently facilitating an enhanced evaporation rate within the measurement unit. However, heat transfer through the wool sample remains predominant due to the inherent thermal resistance of wool.

The same phenomenon was noticed in the case of the cotton sample. Under 1 m/s of airspeed, the maximum evaporative cooling heat flow was 108.2 W at 0 s and subsequently reached an equilibrium heat flow of 86 W after 10 s. While at an airspeed of 2 m/s, a maximum heat flow of 100.6 W at 0 s was registered and reached a constant flow of 98.9 W after 11.5 seconds. So, it could be stated that the cotton has a lower permeation of water vapour. In fact, as the cotton absorbs the water vapour particles, leading to condensation and saturation in the pores and swelling, it will inhibit the water vapour diffusion. So, the cooling by evaporative flow will be altered.

When comparing the evaporative cooling heat flow at different walking speeds, in the case of running (air speed = 2 m/s), all fabrics were more permeable to water vapour, indicating greater evaporative cooling heat flow caused by the increase in the water vapour particles' mobility compared to walking speed (air speed = 1 m/s).

As illustrated in figure 3, the cooling heat flow curves for synthetic fibres such as CoolMax, PET, and PET/EL exhibit a higher value at an air speed of 2 m/s compared to 1 m/s. These findings demonstrate that the air flow speed within the ventilation channel serves as a variable that influences the shape of the heat flow. Consequently, an increase in the air speed leads to a heightened mobility of water vapour particles. This, in turn, results in an increase in the transferred water vapour amount through the polyester sample, thereby facilitating a faster cooling rate of the textile fabric. However, the low thermal resistance of these synthetic fibres facilitates an enhanced heat transfer, which ultimately dominates the evaporation process, leading to a state of thermal equilibrium.

Based on figure 3, the characteristic parameters of the evaporative cooling heat flow were determined as presented in table 3.

The new comfort parameters characterising the dynamics of water vapour transfer are presented in table 3. Here, Q_{max} characterises the thermal absorptivity of water vapour at the first instant of contact of the fabric with the skin. Q_{min} reflects the drop in the cooling flow. In addition, this drop is significant and rapid; the less thermally resistant the sample is, the greater the drop. The Q_{eq} presents the cooling flow at equilibrium; for more comfort, we seek that this value is the most important. In terms of equilibrium time (T_{eq}), a more comfortable sample must have a faster cooling flow stabilisation time, which allows a faster regulation of the microclimate and maintains a state of equilibrium of the thermal balance.

CONCLUSION

The impact of walking speed on the dynamics of evaporative cooling heat flow was investigated in this study. Visualisation of the cooling evaporative heat flow enabled the study of its kinetics during natural evaporation. This study demonstrated that synthetic fibres provide greater comfort from the perspective of water vapour transfer, offering a more refreshing sensation for the wearer. Increased walking speed leads to an enhancement in the mobility of water vapour particles, resulting in improved cooling generation through evaporation.

New comfort parameters based on heat flow kinetics: Q_{max}, Q_{min}, Q_{eq}, Flow drop ($Q_{max} - Q_{min}$), and equilibrium time were introduced. These parameters compare water vapour transfer dynamics. Where Q_{max} represents the thermal absorptivity at initial contact. Q_{min} represents a rapid cooling flow drop, lower thermal resistance, greater drop. Q_{eq} defines the cooling flow at equilibrium, higher for enhanced comfort.

represents the thermal absorptivity at initial contact. Q_{min} represents a rapid cooling flow drop, lower thermal resistance, greater drop. Q_{eq} defines the cooling flow at equilibrium, higher for enhanced comfort. T_{eq} states the faster cooling flow stabilisation time for quicker microclimate regulation and thermal equilibrium.

Future frameworks will be constructed on how external factors, such as temperature and relative humidity, affect the dynamics of the cooling heat flow.

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