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Breathability and Dynamic Evaporative Cooling Heat Flow of a Ripstop Defence Fabric

Dihalnost in hladilni dinamični izparilni toplotni tok zaščitne tkanine ripstop

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Abstract

This study investigated the breathability and dynamics of evaporative cooling heat flow through a defence fabric. Two ripstop fabrics were developed by changing the floats in the delimiting plain grid. The influence of fibre kinds was studied using weft threads made of 100% cotton, 65% polyester/35% cotton and 100% polyester. First, the breathability of used materials was evaluated using relative water vapour permeability (RWVP), resistance (Ret) and air permeability. Second, a more in-depth examination was conducted using evaporative cooling heat flow kinetics, and certain distinguishing variables that describe the various evaporative cooling heat flow phases were found. Those parameters consider the evaporative heat flow at 0 seconds, defining the skin's first contact and the time spent to reach equilibrium. The results demonstrated that adding polyester to a fabric makes it more breathable, cooler, faster drying, and provides a more refreshing sensation on initial contact with the skin. Adding floats to the delimiting plain grid reduces the fabric's porosity and breathability.
Keywords: ripstop, breathability, evaporative cooling heat flow, refreshing sensation

Izvleček

V raziskavi sta bila proučevana dihalnost in dinamični izparilni toplotni tok zaščitne tkanine. Z vključitvijo različnih dolžin flotirajočih niti v ojačitveno mrežo osnovne tkanine v vezavi platno sta bili razviti dve tkanini ripstop. Vpliv različne vrste vlaken je bil proučevan z uporabo različnih niti v votku, ki so bile iz 100 % bombaža, 65 % poliestra/35 % bombaža in 100 % poliestra. Najprej je bila ocenjena dihalnost tkanin na podlagi relativne prepustnosti vodne pare, izparilnega toplotnega upora (Riz) in zračne prepustnosti. Sledila je podrobnejša analiza kinetike hladilnega izparilnega toplotnega toka, pri čemer so bile uvedene spremenljivke za opis ugotovljenih različnih faz izparilnega toplotnega toka. Parametri, ki se nanašajo na izparilni toplotni tok v času nič sekund, opredelijo prvi stik s kožo in čas, potreben za doseganje ravnotežja. Rezultati so pokazali, da dodajanje poliestra

tkanini omogoči večjo zračnost in hladnejši otip, ki se hitreje suši in zagotavlja hladen občutek ob prvem stiku s kožo. Dodajanje flotirajočih niti v ojačitveno mrežno strukturo zmanjša poroznost in zračnost tkanine.
Ključne besede: tkanina ripstop, zračnost, izparilni toplotni tok, hladni občutek

1 Introduction

Ripstop is a lightweight and exceptionally durable fabric from polyester, polyamide or natural fibres. It is specifically intended to withstand tearing and wear due to its grid structure, which includes reinforcing threads sewn regularly to form a checkered pattern [1, 2].

Ripstop fabric is often used in military uniforms, which require materials that are both durable and comfortable. The mix of strength, lightweight lightness and breathability make ripstop fabric an excellent choice for these outfits [3]. Its tear-resistant characteristics increase longevity, guaranteeing that uniforms can sustain severe use in extreme environments [4].

Ripstop fabric is also used in daily clothing articles, including casual pants, shorts and jackets. Its durability and comfort make it appropriate for everyday use, and its distinct texture lends a distinctive touch to clothing items.

Ripstop fabric has evolved significantly in terms of materials employed over time. Originally made of polyamide, manufacturers soon began experimenting with various fabrics such as polyester and cotton.

Polyester fibre is an ideal choice for textiles and clothes due to its high durability, wrinkle resistance and colour retention. The global polyester fibre market is anticipated to reach $153.5 billion by 2030, with a 7.5% growth rate throughout the forecast period. The market volume was 70,195.3 kt in 2022, representing a 6.7% increase from 2019 to 2022 [5]. Cotton is a natural fibre. Its cross-section exhibits a shape akin to beans, allowing air to flow easily through it. Thus, air circulation improves evaporation and the resulting cooling freshens the air in contact with the skin. Cotton absorbs moisture fast and dries slowly, so you may remain dry for a certain (limited) time while performing tasks outdoors. The worldwide cotton yarn market was worth $82.81 billion in 2023 and is expected to expand from $86.11 billion in 2024 to $117.79 billion by 2032, with a CAGR of 4.0% during the forecast period [6].

Breathability, as one of the important comfort properties, is expressed in terms of air and water vapour permeability. Thermal evaporative resistance (RET) is used to test textiles' breathability and water vapour transmission [7, 8]. The ability of cloth to allow moisture vapour to pass through it is known as water vapour resistance [9]. The lower this resistance is, the more breathable the fabric is. The ISO 11092 standard [10] defines the associated test procedure.

Water vapour diffusion via textile fabrics, also known as the breathability of materials, is intended to provide water vapour evacuation while preventing water liquid from penetrating [11, 12]. Cooling textiles are made with moisture-wicking characteristics that effectively transport moisture away from the skin [13]. Cooling is primarily the function of water vapour permeability level, and wicking fabrics must be in thermal contact with the skin to cause cooling effects. These materials are designed to provide comfort by efficiently regulating moisture [14], particularly in situations when the body releases sweat during physical activity or in hot environmental conditions [15].

Cooling from fabrics improves moisture transport from the skin to the fabric's outer surface [16], as sweat is released onto the skin surface when the body perspires. The moisture evaporates into the surrounding air, absorbing heat energy from the body. This is known as evaporative cooling, which is an important technique for regulating body temperature and improving comfort [17, 18].

The cooling heat flow mechanism has applications in various industries, including sportswear, outdoor clothes, bedding and protective equipment for hot conditions. The cooling heat flow of textile materials relies on a variety of mechanisms to govern heat transfer and disseminate cooling [15]. Thus, water vapour transfer is a significant factor in textile design [19]. The necessity to examine moisture transfer through textile textiles originates from the human body's continual loss of water, mostly through evaporation from the skin [20, 21]. Water vapour evacuation through clothes is crucial to preserving body temperature balance and comfort. Textile fabric should facilitate fast sweat removal [22] by diffusion and evaporation into the surrounding air [23].

Extensive research work has been performed on water vapour transfer mechanisms across textile fibres [24–26], simple fabrics [27–31], layered fabrics [32, 33], textile systems [34, 35] and clothing assemblies [36–38]. Nevertheless, most investigations were carried out in static conditions where equilibrium conditions were considered, with little work done under dynamic states. Dynamic tests should be considered, as water vapour transfer is strongly related to water vapour diffusion in fibres and condensation in pores, and is time-dependent [39, 40].

Several test methods for measuring the moisture transfer abilities of textile materials have been developed, with different methodologies and testing conditions used. Although every test method applied near real-world conditions, no single test method could fully reconstruct the complicated process [41].

Moisture absorption varies between natural and synthetic fibres. As the solid-water characteristic energy of a polymer increases, the hydrophilic surface attracts water molecules more strongly than the hydrophobic surface [42]. Moisture sorption mechanisms, particularly in hydrophilic fibre materials, are very complicated due to the constant change in fibre structure caused by swelling. This results in a shift in geometric confirmation in the fabric's pores [43, 44]. As a result, it is essential to study the kinetics of water vapour transport. According to the evaluation described in this section, there is little research dealing with dynamic evaporative cooling heat flow through textile textiles.

In this study, two ripstop samples were designed and woven as defence materials utilising 100% cotton, 65% polyester/35% cotton and 100% polyester weft threads. First, the breathability of the utilised samples was studied in terms of water vapour resistance, relative water vapour permeability and air permeability. Second, dynamic evaporative cooling heat flow during evaporation was visualised using the Permetest device. Some characteristic parameters describing the different evaporative cooling heat flow phases were identified. While (Q_0) represents the evaporative cooling heat flow at first contact with the skin, (Q_{min}) represents the minimal evaporative cooling heat flow, (Q_{max}) represents the maximum evaporative cooling heat flow, (Q_{eq}) represents the evaporative cooling heat flow at equilibrium, (t_{Q0}- > Q_{min}) represents the time spent to reach the minimum evaporative cooling heat flow, and (t_{eq}) represents the heat flow equilibrium time. These factors may be useful for comparing and evaluating the competitiveness of comfortable textile textiles.

2 Materials and methods

2.1 Rip-stop fabric pattern design

Two types of rip-stop fabric pattern design are illustrated in Figure 1. Fabric design was based on the delimiting grid variation between the plain-woven structure. Samples were woven using a rigid rapier Dornier HTV/HTVS/PTV weaving machine. The shedding system was controlled by the Bonas ZJ2 jacquard mechanism.

The used fabrics were woven using the same warp yarn with a composition of 100% polyester and a yarn number of 25 Nm. Weft yarns of 25 Nm with different materials (100% cotton, 65%/polyester, 35% cotton and 100% polyester) were used. The chosen warp and weft count were (24 ± 2) threads/cm. The woven fabric thickness was evaluated using the ISO 5084:1996 standard [45]. Mass per unit area, warp and weft densities were measured according to the ISO 7211-6:2020 standard [46]. A yarn's linear

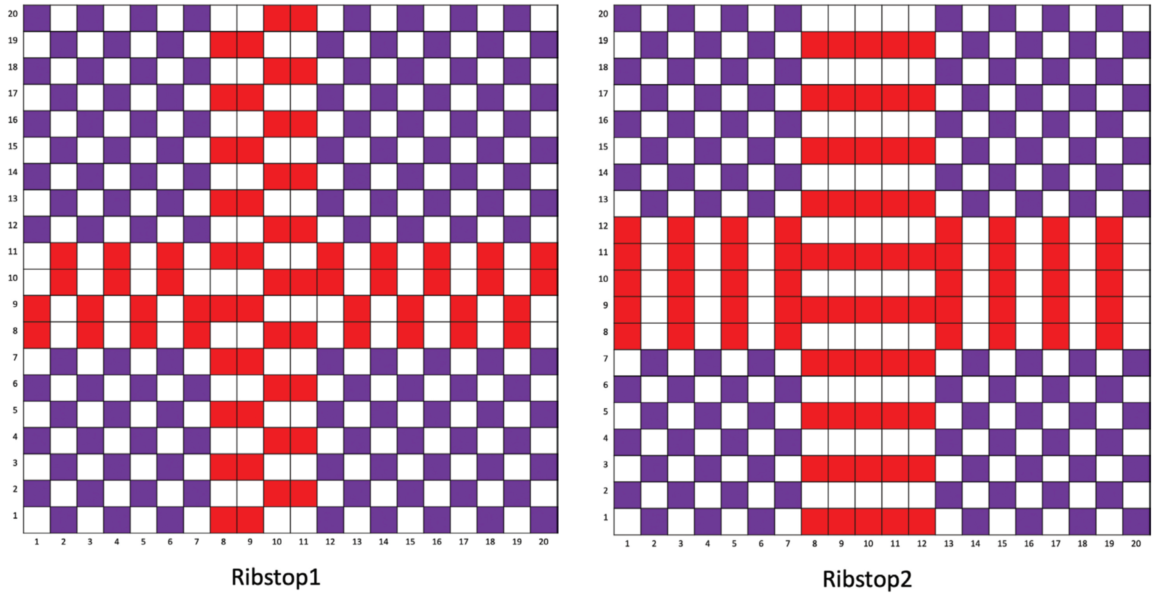

Figure 1: Ripstop fabrics design: ■ plain woven design; ■ floats on the delimiting grid

densities were determined using the ISO 2060:1994 standard [47]. The warp and weft densities were calculated based on the ISO 7211-2:2024 standard [48].

2.2 Total porosity

The total fabric porosity (ε_{total}) was determined using the following equation [49]:

$$\varepsilon_{total} = 1 - \frac{\rho_{fabric}}{\rho_{fibre}} \quad (1)$$

where ρ_{fabric} represents the fabric density (g/m^3) and was determined as follows:

$$\rho_{fabric} = \frac{M}{t} \quad (2)$$

where M represents the fabric mass per unit area (g/m^2) and t represents the fabric thickness (m).

Here, the fibre density average was determined according to the percentage of blend ratio of each fibre in the produced yarns, as mentioned by Kakvan et al. [50]:

$$\rho_{fibre} = \sum_{i=1}^{n} p_i \times \rho_i \quad (3)$$

where p_i represents the percentage of each fibre$_i$ ratio and ρ_i represents its density.

The woven fabric structural parameters are presented in Table 1.

Table 1: Structural parameters of fabrics used

Sample code	Weft yarn composition	Thickness (mm)	Mass per unit area (g/m^2)	Total porosity (%)
Ribstop1-CT	100% cotton	0.56 ± 0.06	215 ± 6	68 ± 4
Ribstop1-PC	65% polyester/35% cotton	0.55 ± 0.02	212 ± 4	73 ± 3
Ribstop1-PO	100% polyester	0.54 ± 0.01	211 ± 3	78 ± 2
Ribstop2-CT	100% cotton	0.59 ± 0.05	217 ± 7	69 ± 2
Ribstop2-PC	65% polyester/35% cotton	0.56 ± 0.01	214 ± 5	71 ± 4
Ribstop2-PO	100% polyester	0.55 ± 0.01	213 ± 2	76 ± 3

2.3 Air permeability

The air permeability measurements were conducted on an FX 3300 Labotester III Textest air permeability tester with a 100 Pa pressure difference according to the ISO 9237:1995 standard [51].

2.4 Relative water vapour permeability and resistance

A Permetest Sensora device, simulating the human skin (Figure 2), was used to measure the relative water vapour resistance and relative permeability according to the ISO 11092 standard [10]. A heated porous semipermeable foil 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 recorded in the steady state. The fabric sample was set on a measuring head over the semi-permeable membrane under a parallel air flow velocity of 1m/s, simulating walking speed.

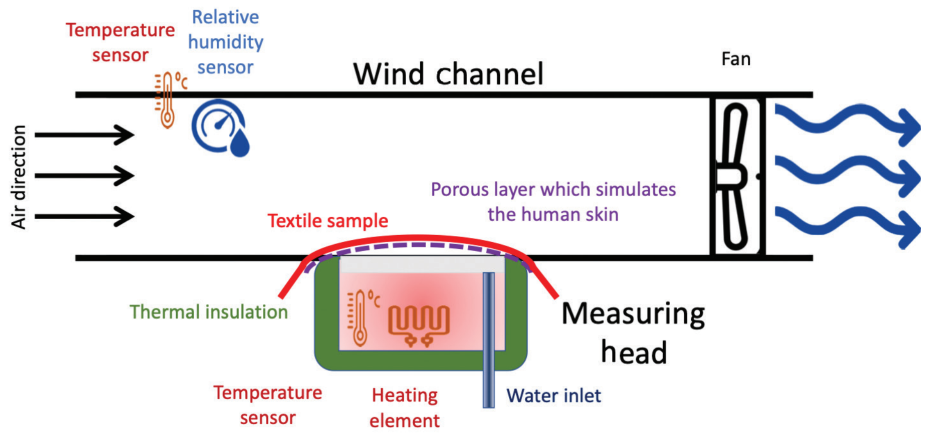

Figure 2: Permetest skin model working principle [52]

The water vapour resistance (R_{et}) of a textile sample according to the ISO 11092 standard [10] was expressed as follows:

$$Ret(m^2Pa/W) = (P_{sat} - P_V)\left(\frac{1}{q_s} - \frac{1}{q_0}\right) \quad (4)$$

where R_{et} represents water vapour resistance (m^2Pa/W), P_{sat} represents saturated water vapour partial pressure at test temperature (Pa) and is equivalent to the skin vapour pressure, P_v represents air partial water vapour pressure (Pa), q_s represents measuring head heating power with sample (W/m^2) and q_0 represents measuring head heating power without sample (W/m^2).

The relative water vapour permeability (R_{wvp}) was determined using the following relation [53]:

$$R_{wvp} = 100 \times \frac{q_s}{q_0} \quad (5)$$

All tests were carried out under standard conditions in an atmosphere of 20 °C ± 2 °C and 65% ± 4% relative humidity relative humidity according to ISO 139:2005 standard [54]. Isothermal conditions inside the instrument during the R_{et} measurements were maintained with a precision of ± 0.1 °C. All fabric samples were conditioned in the same atmosphere 24 hours before testing.

3 Results and discussion

In this part, the breathability properties were initially investigated in terms of water vapour resistance (R_{et}), relative water vapour permeability (RWVP) and air permeability. Second, cooling evaporative heat flow kinetics during evaporation were visualised to identify the various stages of the evaporative cooling heat flow.

3.1 Breathability parameters

Breathability parameters are expressed in terms of water vapour resistance (R_{et}), relative water vapour permeability (RWVP) and air permeability, as presented in Table 2.

It is evident that the relative water vapour permeability and the air permeability look similar and are proportional to total porosity values. On the contrary, water vapour resistance is inversely proportional to total porosity.

Table 2: Breathability parameters of fabrics used

Sample	R_{et} a)			RWVP b)			Air permeability		
	$\bar{x}$ c) (m²Pa/W)	SD d) (m²Pa/W)	CV e) (%)	$\bar{x}$ c) (%)	SD d) (m²Pa/W)	CV e) (%)	$\bar{x}$ c) (l/m²/s)	SD d) (m²Pa/W)	CV e) (%)
Ribstop1-CT	2.51 ± 0.17	0.19 ± 0.09	4.24 ± 0.8	80.2 ± 1.4	3.6 ± 1.3	8.5 ± 0.4	151.8 ± 4.9	7.2 ± 0.7	4.8 ± 0.8
Ribstop1-PC	2.34 ± 0.15	0.17 ± 0.06	3.29 ± 0.5	82.5 ± 1.2	2.4 ± 0.8	6.3 ± 0.3	158.3 ± 2.0	3.9 ± 0.4	3.8 ± 0.6
Ribstop1-PO	2.23 ± 0.14	0.15 ± 0.05	2.34 ± 0.4	86.1 ± 1.3	1.7 ± 0.3	4.1 ± 0.7	165.2 ± 1.6	4.1 ± 0.3	4.6 ± 0.3
Ribstop2-CT	2.98 ± 0.22	0.21 ± 0.08	4.47 ± 0.5	71.6 ± 2.3	3.2 ± 1.1	6.1 ± 0.6	137.5 ± 3.1	6.6 ± 0.6	3.4 ± 0.4
Ribstop2-PC	2.61 ± 0.18	0.19 ± 0.06	3.25 ± 0.3	76.7 ± 2.1	2.1 ± 0.5	4.4 ± 0.4	147.2 ± 1.8	3.8 ± 0.3	3.6 ± 0.5
Ribstop2-PO	2.43 ± 0.116	0.16 ± 0.04	2.23 ± 0.3	82.4 ± 1.5	1.6 ± 0.2	3.9 ± 0.5	157.4 ± 1.2	3.6 ± 0.2	2.4 ± 0.4

a) water vapour resistance; b) relative water vapour permeability; c) average; d) standard deviation; e) coefficient of variation

According to Table 2, the Ribstop1-PO sample was the most breathable fabric, registering a water vapour resistance of about (2.23 ± 0.14) m²Pa/W. Its relative water vapour permeability was 86.1% ± 1.3%, while its air permeability was about (165.2 ± 1.6) l/m²/s.

The least breathable fabric was Ribstop2-CT fabric, with a water vapour resistance of about (2.98 ± 0.22) m²Pa/W. Its relative water vapour permeability was around 71.6% ± 2.3%, while its air permeability was around (137.5 ± 3.1) l/m²/s.

As evident from Table 2, polyester fabrics are more breathable than cotton fabrics. The presented values only consider a steady state. Thus, the dynamics of the evaporative cooling heat flow should be considered for a more in-depth investigation of water vapour transfer through a textile fabric.

3.2 Dynamic evaporative cooling heat flow

Evaporative cooling heat flow kinetics during evaporation are presented in this subsection. It is important to study in detail how water vapour is transferred through textile fabrics. The cooling heat flow kinetics under 1 m/s of air velocity are presented in Figure 3.

Figure 3 suggests that displaying the cooling heat flow dynamics resulted in three phases. Initially, the maximum cooling heat flow was measured as the difference between the sample temperatures at 20 °C ± 2 °C and 65% ± 2% relative humidity and the temperature at the top of the measuring heat, which was around 18 °C ± 2 °C owing to evaporation from the semi-permeable foil. During the second stage, known as the transition phase, cooling heat flow reduces to a minimum value before increasing to an equilibrium value, signalling the beginning of the third stage, i.e. the steady state phase. The initial heat flow drop in most of the heat flow lines is caused by exothermal moisture absorption in the measured fabric.

At zero seconds, the Ribstop1-PO sample had a heating flow of 135.1 W ± 8.2 W, whereas the Ribstop2-PO sample had a heating flow of 121.6 W ± 6.9 W. During evaporation on a Permetest device, samples conditioned at room temperature (20 °C ± 2 °C) had higher temperatures than those in the wind channel (18 °C ± 2 °C), as recorded by an infrared

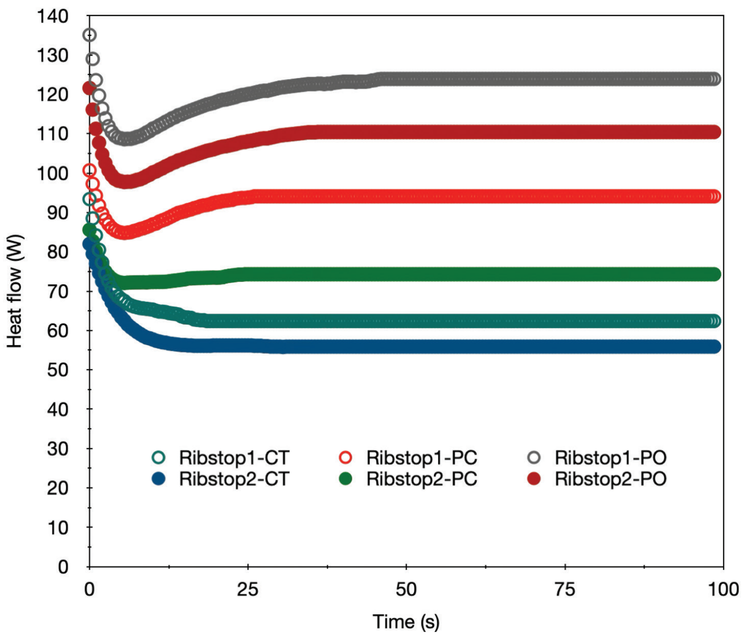

Figure 3: Evaporative cooling heat flow of studied fabrics under an air velocity of 1 m/s

thermometer, due to cooling from the wetted porous grid under the tested fabric.

In the subsequent stage, to equalise the temperature between the fabric and the measuring top head, the heat flow dropped to 108.6 W ± 6.4 W in Ribstop1-PO compared to 97.7 W ± 4.8 W in Ribstop2-PO. In the third step, cooling heat flow was increased until it reached equilibrium. The increase in flow was induced by evaporation through the fabric from the semi-permeable membrane, which cools the fabric's top surface. Equilibrium cooling heat flow is defined as the continual penetration of water vapour through a textile fabric. Figure 3 also shows that the Ribstop1-PO fabric felt cooler than the Ribstop2-PO fabric. This is due to crosshatch lines placed between the plain pattern design, which were observed to have longer drying periods and an increased water vapour concentration.

Concerning the two woven fabrics from 100% of weft threads (Ribstop1-CT and Ribstop2-CT), it is evident that they are less cool than fabrics containing polyester fibres.

Cotton fibre, as a natural cellulosic fibre, has high absorbency due to its many hydrophilic -OH groups. The hydroxyl group is a univalent OH group. OH groups are polar and thus attract water molecules, which are also polar. As a result, the OH groups are responsible for the fibre's ability to absorb moisture [55, 56].

Thus, when textile fabrics made of hydrophilic fibres absorb humidity, the causing swelling of fibres and thus a decrease in the fabric's porosity [57], the phenomena of water vapour diffusion occur.

Regarding polyester-containing textiles, polyester fibre is a hydrophobic fibre that repels water vapour molecules and resists moisture absorption. This fluctuation is generated by a film of water vapour condensing on a sample's pores and blocking evaporation. This process is known as water vapour condensation.

Table 3 shows some of the distinctive factors that define the various evaporative cooling heat flow phases based on Figure 3.

Table 3: Evaporative cooling heat flow characteristics

Sample	Q_0 [a)] (W)	Q_{min} [b)] (W)	Q_{max} [c)] (W)	Q_{eq} [d)] (W)	$t_{Q0->Qmin}$ [e)] (s)	t_{eq} [f)] (s)
Ribstop1-CT	93.4 ± 1.1	62.4 ± 0.5	93.4 ± 1.0	62.4 ± 0.4	18.5 ± 1.5	18.5 ± 0.5
Ribstop1-PC	100.7 ± 1.3	84.8 ± 0.7	100.7 ± 1.1	94.1 ± 0.6	5.5 ± 0.5	26 ± 1.0
Ribstop1-PO	135.1 ± 1.4	108.6 ± 1.1	135.1 ± 1.2	123.9 ± 1.0	5.5 ± 0.5	46 ± 1.5
Ribstop2-CT	82 ± 0.6	55.8 ± 0.4	82 ± 0.6	55.9 ± 0.3	29 ± 1.5	29 ± 0.5
Ribstop2-PC	85.595 ± 0.5	72.08 ± 0.6	85.595 ± 0.5	74.3 ± 0.7	5.5 ± 0.5	24.5 ± 0.5
Ribstop2-PO	121.59 ± 0.8	97.74 ± 0.7	121.59 ± 0.9	110.43 ± 1.0	5.5 ± 0.5	36 ± 1.5

[a)] heat power at 0 s; [b)] minimum registered heat power; [c)] maximum registered heat power; [d)] equilibrium heat power; [e)] elapsed time in seconds from the heat power from Q_0 to the Q_{min} values; [f)] heat flow equilibrium time

Based on the results presented in Table 3, the Ribstop1-PO is the coolest fabric, offering a better fresh feeling for the wearer. Cotton fabrics are less cool than those containing polyester. Moreover, all fabrics containing polyester reach equilibrium at about 5.5 s ± 0.5 s compared to those composed of cotton, which reach equilibrium at about 18.5 s ± 1.5 s in the case of Ribstop1-CT compared to 29 s ± 1.5 s in the case of Ribstop2-CT. Thus, adding polyester to a fabric makes it cooler and fast drying.

4 Conclusion

This study focused on the breathability and the dynamics of evaporative cooling heat flow in a defence fabric. Two ripstop textiles were designed and woven with various weft thread materials: 100% cotton (hydrophilic), 65% polyester/35% cotton and 100% polyester (hydrophobic). A Permetest device was used to determine water vapour resistance (RET) and relative water vapour permeability (RWVP). The same device was used to visualise the dynamics of heat movement during evaporative cooling.

It was discovered that employing various fibre materials (hydrophilic or hydrophobic) had a considerable impact on breathability. Adding floats to the barrier to the delimiting plain woven grid reduces a fabric's breathability.

This is due to overlapping warp and weft floats, resulting in thickness and mass per unit area. This reduces overall porosity and modifies geometrical and pore arrangement.

Three phases were identified when studying the dynamics of evaporative cooling heat flow. Initially, the maximum cooling heat flow was measured as the difference between the sample temperatures at 20 °C ± 2 °C and 65% ± 2% relative humidity and the temperature at the top of the measuring heat, which was approximately 18 °C ± 2 °C due to evaporation cooling from the semi-permeable membrane. During the second stage, known as the transition phase, cooling heat flow dropped to a minimum value before increasing to an equilibrium value, indicating a steady state phase.

The influence of environmental conditions (temperature and relative humidity) on cooling heat flow dynamics will be a key topic of focus for future frameworks.

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