Indian Journal of Fibre & Textile Research
Vol. 49, March 2024, pp. 100-104
DOI: 10.56042/ijftr.v49i1.9547

Influence of waterproof and breathable membrane on thermal comfort properties of multi-layer clothing system

Elena Codau[1,a] & Teodor Cezar Codau[2]

[1]Textile Leather and Industrial Management Faculty, Technical University "Gheorghe Asachi" Iasi, 700050-Iasi, Romania

[2]Fibrenamics, University of Minho, 4800-058 Guimarães, Portugal

Received 16 December 2022; revised received and accepted 31 March 2023

In this study, two multi-layer fabric systems intended for firefighters have been tested in order to determine the basic parameters of thermal comfort. The thermal comfort is evaluated effectively by measuring the thermal properties of clothing on the sweating-guarded hotplate (skin model). The first assembly is composed of an external layer, a middle layer (thermal insulation), and an inner layer [moisture barrier - hydrophilic polyurethane (PU) membrane coated on knitted fabric]. The second one contains an external layer, a middle layer (thermal insulation), and an inner layer (liner). Both assemblies contain the same external layer and middle layer. These layers are tested as monolayers and in multi-layer clothing systems. The influence of the membrane on the thermal and water-vapour resistance of the multi-layer fabric system has been studied. When the combinations of different materials are used for a multi-layer fabric system, the thermal comfort is dependent not only on the properties of each monolayer but also on the manner in which they act together. The results show that the monolayer acting as a moisture barrier has a considerable influence on the overall water-vapour transport abilities. The position of the moisture barrier in the assembly is also important in the overall value of water-vapour resistance of the multi-layer system.

Keywords: Hydrophilic polyurethane membrane, Moisture barrier, Multi-layer fabric, Protective clothing, Sweating guarded hotplate (skin model), Water vapour resistance

Various protective clothing (firefighters, military, industrial workers, etc.) and many outdoor sports clothing (cycling, running, skiing, climbing, etc.) should exhibit excellent barrier properties (against rain and snow) and, at the same time, good hygiene features and high comfort of use. For these applications, waterproof and water vapour-permeable (breathable) textiles are state-of-the-art[1]. Breathability is defined as the ability of a fabric to allow perspiration, evaporated by the body, to escape (diffuse) to the outside (termed moisture vapour transmission), thereby allowing complete comfort[2].

The current waterproof and breathable (W&B) fabrics include high-density fabrics, coated fabrics, and laminated fabrics. High-density fabrics provide good moisture permeability, due to the thin and smooth yarns that are usually made of microfiber, but the property of waterproofing is relatively poor for these types of fabrics. Regarding the coated fabrics, their waterproofing is good, due to the non-porous structure, but the moisture permeability is not very good. The third type of W&B fabrics (laminated fabrics) have excellent comprehensive waterproofing and breathability compared to the previous two types of fabrics, which is due to the W&B membranes[3]. Thus, the membranes with highly effective protection against water, air-non-permeable, and with high permeability for water vapour can be used in monolayer or multi-layer clothing systems to protect the wearer from external rain, snow and harmful liquids, and to provide a good level of comfort in various applications, including sportswear, raincoats, and protective work wear[4].

Depending on the application and required characteristics of the clothing system, the membrane (its component) must also show a suitable set of properties. Additional requirements include a low surface weight and thickness, low rigidity, and resistance of the membrane to the conditions of use and washing. In some cases (e.g. protective clothing for firefighters), resistance to heat at elevated temperatures, non-flammability, and resistance to specific organic solvents are also required[2].

Today, a wide range of membranes is available in the market, but there are two basic types, viz micro-porous membranes (mostly with hydrophobic character), and hydrophilic membranes with a compact structure. The most frequently used polymeric membranes in textile systems include[5]:

- Hydrophobic microporous–polytetrafluoroethylene (PTFE) membranes (Gore-Tex) from the American Company W.L. from Gore & Assoc.s Inc.; polyurethane-based

---

[a]Corresponding author.
E-mail: eonofrei@yahoo.com,
elena.codau@academic.tuiasi.ro

membranes (Porelle membranes) from the British company Porvair.

- Hydrophilic membranes (mainly based on polyester and polyurethane) – this group includes the well-known polyester materials manufactured by Sympatex Composites Co. under the trade name Sympatex, as well as Toyo Cloth Co.'s BION II polyurethane products.

Both principles (microporous and hydrophilic) can be combined, resulting in bi-component micro-porous and hydrophilic laminates. In this case, a hydrophilic covering layer is applied to the microporous membrane as realized in Gore-Tex second generation[1].

The microporous membranes´ pores (0.02 – 1 µm) are larger than that of water-vapour molecules (usually < 0.0003 µm) which can diffuse through the membrane. The capillary mechanism of water-vapour transmission through pores takes place in the case of a microporous membrane. On the other hand, the diameter of water drops (200–5000 µm) is higher as compared to that of the pores of the membrane. Strong interaction keeps water molecules in a drop, preventing their spreading. Hence, they are too large to penetrate through the membrane pores[1,6] [Fig. 1 (a)].

Hydrophilic membranes are nonporous and transmit water vapour by a molecular mechanism. The driving force for the water-vapour transmission process is a difference in water-vapour pressure between two sides of the membrane, which gives rise to a concentration gradient within the membrane[1,6]. The water vapour is first adsorbed on the surface of the membrane on the side of the highest water-vapour concentration. Water molecules occupy free volume among the molecular chains of polymer and move across the membrane without destroying polymer when penetrating through the membrane with a nonporous structure. In the case of polymers with active hydrophilic groups, water molecules not only fill in the free volume among the polymer molecular chains but also interact with their active hydrophilic groups [Fig. 1 (b)]. Due to the moisture gradient, they move across the membrane gradually joining the active groups. Then they diffuse across by dissolving in the polymer membrane, which is usually called activated diffusion. Upon arriving at the opposite surface of the polymer membrane, which has a lower vapour pressure, it is desorbed and enters the surrounding air space as vapour[6].

Although PTFE membranes have better performance, the high price and the difficulties in recycling are disadvantages that limit their wide application[4]. Therefore, in this study, a hydrophilic PU membrane is tested as a monolayer and in a multi-layer clothing system intended for firefighter personal protective equipment (PPE).

Thermal comfort is strongly affected by two intrinsic properties of protective clothing, thermal resistance and water-vapour resistance. The focus of this study is the investigation of these properties of each individual layer and corresponding clothing assemblies using sweating guarded hotplate, regarded as the best-standardized test method to simulate the heat and mass transfer conditions on a clothed body[8]. The influence of the membrane on the thermal and water-vapour resistance of the multi-layer fabric system is also analysed.

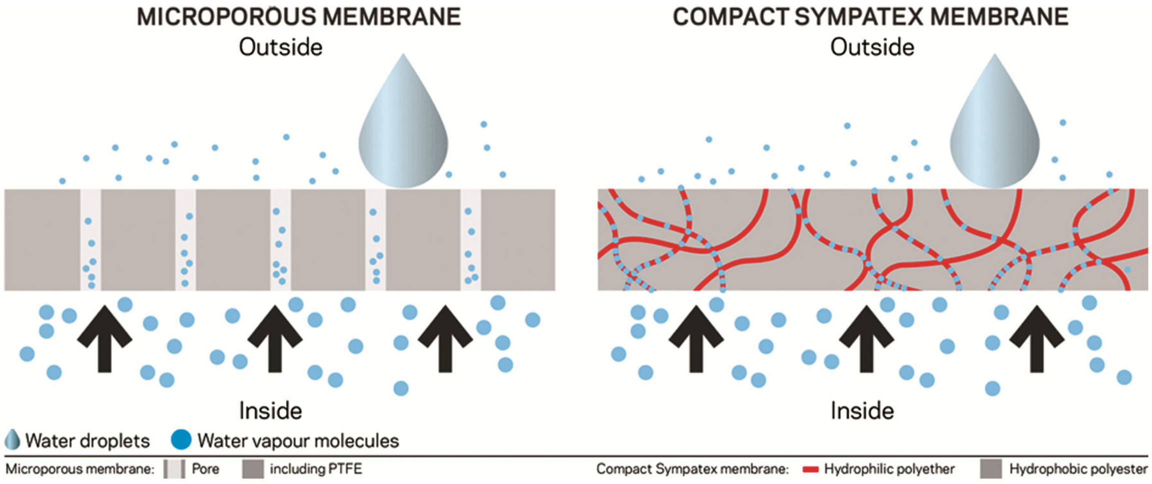

Fig. 1— Principle of water-vapour transfer through (a) microporous and (b) hydrophilic membranes[7]

Experimental

Material

Two multi-layer protective clothing structures as the combinations of three monolayers were used for the study. The first assembly (As1) is composed of the external layer (E), the middle layer (M) which is a thermal insulator, and the inner layer (I_M), which is a moisture barrier. The second one (As2) contains an external layer (E), a middle layer (M) which is thermal insulator, and an inner layer (I_L) which is a liner. Both assemblies contain the same external layer and middle layer. The inner layer for the first assembly is a hydrophilic polyurethane membrane coated on knitted fabric and for the second assembly a woven fabric. In addition, another assembly was tested for comparison (As1_1), which was conducted from As1, but the position of the middle and inner layers was changed between them.

The tested multi-layer assemblies are used as protective clothing for firefightersand are state-of-the-art firefighter PPE. Thus, they fit the requirements of EN 469:2014 and guarantee a high protection level against fire.

Physical and Thermal Comfort Properties

The thickness of the monolayers and the multi-layer systems was measured according to the standard ISO 5084:2013 with the use of a digital thickness gauge (SDL Int. Ltd., England). Values of materials' surface weight were determined by the gravimetric method according to standard ISO 3801:2011. Density was calculated from the values of fabric thickness and surface weight.

Measurements of thermal and water-vapour resistance of mono- and multi-layer fabrics were conducted on the sweating-guarded hotplate, in compliance with the standard ISO 11092:2014. Specific environment testing conditions prescribed by this standard were met using a climatic chamber.

The measuring unit of the sweating-guarded hotplate possesses both temperature and water supply control. According to the standard, the procedure for determination of the thermal resistance of material implies the placement of the specimen on an electrically heated porous stainless-steel plate with conditioned air conducted to flow across and parallel to its upper surface. For the measurement of water-vapour resistance, an electrically heated porous plate is covered by a water-vapour permeable but liquid-water impermeable membrane. Water is supplied by the channels beneath the hotplate (measuring unit) and can evaporate through the numerous pores of the plate, just like sweat from the pores of the skin. The hotplate is kept at 35°C. Thus, heat and moisture transport are comparable to those of the human skin. Tests for determination of thermal resistance were performed at the ambient conditions of 20±0.1°C and 65±3%RH, while the standard conditions for measurement of water-vapour resistance were maintained as 35±0.1°C and 40±3%RH.

According to the ISO 11092:2014, the values of thermal resistance (R_{ct}, $m^2 \cdot K \cdot W^{-1}$) and water-vapour resistance (R_{et}, $m^2 \cdot Pa \cdot W^{-1}$) were calculated using the followings equations:

$$R_{ct} = \frac{(T_m - T_a) \cdot A}{H - \Delta H_c} - R_{ct0} \quad \dots (1)$$

$$R_{et} = \frac{(p_m - p_a) \cdot A}{H - \Delta H_e} - R_{et0} \quad \dots (2)$$

where T_m is the temperature of the measuring unit (°C); T_a, the air temperature in the test enclosure (°C); and A, the area of the measuring unit (m^2). By analogy, p_m is the saturation water-vapour partial pressure (Pa) at the surface of the measuring unit at temperature T_m; and p_a is the saturation water-vapour pressure (Pa) of the air in the test enclosure at temperature T_a. Further, H is the heating power supplied to the measuring unit (W), while ΔH_c and ΔH_e are the correction terms for heating power (W) for the measurement of thermal resistance (R_{ct}) and water-vapour resistance (R_{et}). R_{ct0} ($m^2 \cdot K \cdot W^{-1}$) and R_{et0} ($m^2 \cdot Pa \cdot W^{-1}$) are corresponding apparatus constants, determined as the "bare plate" values.

In addition to the values of R_{ct} and R_{et}, the monolayers and fabrics assemblies are compared regarding the water-vapour permeability index (i_{mt}), as a measure of the material's ability to transmit water-vapour from the body. It was calculated according to the following equation:

$$i_{mt} = S \frac{R_{ct}}{R_{et}} \quad \dots (3)$$

where S is the ratio of R_{et} and R_{ct} for air, a constant equal to 60 $Pa \cdot K^{-1}$. The values of the index i_{mt} can vary from 0 for an impermeable fabric up to 1 when all the moisture, that the ambient environment can take up, can pass through the fabric.

Results and Discussion

The composition and the average values of the general physical properties of each monolayer and the assemblies along with the corresponding standard deviations are displayed in Table 1.

The average values of thermal and water-vapour resistance, the corresponding standard deviations, and the calculated water-vapour permeability indices are shown in Table 2. The average values are obtained from 10 individual determinations and therefore the range of variation is also given. These differences between the individual values for the same materials arise, on the one hand, due to the tolerance of the device, which is perfectly normal and, on the other hand, due to the way of making contact between the plate and the material and between the different textile layers (for multi-layer structures) in the case of different tests.

It can be noted that the sum of the R_{ct} values of individual layers is close to the measured R_{ct} of the assemblies composed of the corresponding layers (Table 2). In contrast with the thermal resistance, the total water-vapour resistance of a combination of textiles is not always equal to the sum of the single resistances. In particular, the inclusion of hydrophilic components imparts the complexity of the phenomenon, as the water-vapour resistance of these materials depends on the relative humidity of the membrane.

Among the monolayers, I_M has the highest water-vapour resistance (R_{et}= 22.33 $Pa \cdot m^2 \cdot W^{-1}$). It is known that the moisture barrier has a powerful impact on the total heat loss of the clothing assembly[9]. Considerably higher R_{et} values of the I_M reflects the high water-vapour resistance of the As1. It confirms the fact that moisture loss by evaporation is impeded in poorly permeable systems. The assembly As2 has no moisture barrier and consequently exhibits the lowest R_{et}.

The tested multi-layer assemblies As1 and As2 are used as protective clothing for firefighters and are state-of-the-art firefighter PPE. These materials were provided by Sioen Industries Division Fabrics-Coating, Belgium, and they fit the requirements of EN 469:2014 and guarantee a high protection level against fire. Within this European Standard, two performance levels are given below for water-vapour resistance:

Level 1 — R_{ef} > 30 $Pa \cdot m^2 \cdot W^{-1}$, but not exceeding 45 $Pa \cdot m^2 \cdot W^{-1}$.
Level 2 — R_{ef} < 30 $Pa \cdot m^2 \cdot W^{-1}$.

Level 1 is not water-vapour permeable. Both As1 and As2 assemblies correspond the Level 2 and provide a good degree of vapour transport. As1 has an acceptable degree of vapour transport, but due to the higher water-vapour resistance the comfort properties are reduced, and it can lead to a higher risk of steam burns. As2 provides the best comfort, but its major disadvantage is that it does not provide protection against environmental water.

Tests were performed for the moister barrier (monolayer) with the membrane placed near the plate (skin) - current position - and with the membrane placed to the exterior. The water-vapour resistance is 14.5 % lower with the membrane placed near the plate.

Moreover, the moisture barrier is placed at different positions in combination, such as a third layer, after the thermal liner (As1), and as a second layer, between the outer shell and thermal liner (As1_1).

Table 1— General physical properties of tested monolayers and assemblies

Sample code	Sample	Composition and structure	Surface weight, $g \cdot m^{-2}$	Density, $kg \cdot m^{-3}$	Thickness, mm
E	External	Aramid woven fabric	242±2	489±5	0.50±0.01
M	Middle	Aramid nonwoven	98±2	67±2	1.46±0.03
I_M	Inner	PU-coated 100% aramid knitted fabric	195±2	418±6	0.47±0.00
I_L		Aramid woven fabric	150±1	403±6	0.37±0.00
As1	Assembly	E+M+I_M	540±4	224±5	2.40±0.04
As1_1	Assembly	E+I_M+M	540±4	224±5	2.40±0.04
As2	Assembly	E+M+I_L	494±4	218±3	2.26±0.03

Table 2 — Thermal properties of tested monolayers and assemblies

Sample code	Thermal resistance (R_{ct}) $K \cdot m^2 \cdot W^{-1}$	Σ R_{ct} of monolayers $K \cdot m^2 \cdot W^{-1}$	Water-vapour resistance (R_{et}), $Pa \cdot m^2 \cdot W^{-1}$	Σ R_{et} of monolayers $K \cdot m^2 \cdot W^{-1}$	Water-vapour permeability index (i_{mt})
E	0.013±0.009	-	4.26±0.27	-	0.183
M	0.069±0.003	-	4.91±0.21	-	0.843
I_M	0.013±0.003	-	22.33±0.02	-	0.035
I_L	0.013±0.008	-	2.54±0.14	-	0.307
As1	0.094±0.005	0.095	25.88±0.04	31.5	0.217
As1_1	0.096±0.006	0.095	35.45±0.05	31.5	0.162
As2	0.098±0.003	0.095	10.63±0.06	11.71	0.558

Table 2 shows that the water-vapour resistance of the hydrophilic membrane is lower in the case of a combination than in the case of an individual. This result is consistent with other studies[1]. If the membrane is quite near to the measuring unit, there is a comparatively high value of relative humidity, and the water-vapour resistance of the hydrophilic component is lower. If an additional textile layer is placed between the laminate and the measuring unit, some of the water-vapour concentration gradient drops off over that layer, and consequently, the relative humidity of the membrane is lower than in the first case.

The water-vapour resistance of the whole assembly is 27 % lower in the combination (As1) that places the membrane close to the measuring unit than in the (As1_1) with the membrane placed between the other two layers.

The tests were done only for water-vapour transfer and not liquid water. At the beginning of human activity, the temperature increases, and the wearer starts to sweat sensitively, but the sweat evaporates within channels of skin pores and no liquid sweat is produced. In this stage, the water-vapour resistance of the garments is the most important for comfort. During an intense activity, a further increased temperature leads to liquid sweat. In this stage, the buffering capacity of liquid sweat plays a crucial role, and the hydrophilic membrane can become more efficient and gain importance in providing comfort.

Water-vapour permeability indices given in Table 2 vary from 0.035 for highly impermeable moisture barrier I_M up to 0.843 for the thermal insulation M. High value of i_{mt} for the thermal insulation M is explained by the monolayer low density due to its air capsules. The thermal barrier M is a light, flexible and breathable produc tISO'AIR®. It is a fire and heat-resistant nonwoven fabric manufactured with virgin Nomex® fibres[10].

Among the clothing assemblies, the As2 exhibits the highest efficiency of evaporative heat transport, having more than two times higher water-vapour permeability index (0.558) than the other assembly As1 (0.217). According to the literature, a typical i_{mt} value for most permeable clothing ensembles in "still air" is a bit less than 0.5[11].

Hence, the assembly As2 has very good comfort properties, but the great disadvantage of this assembly is its low protection against environmental water. As opposed to As2, the low i_{mt} value of the As1 which contains a moisture barrier indicates that the release of sweat from the surface of the skin to the atmosphere is reduced and can easily induce discomfort in the conditions of intensive perspiration.

From the study, it is observed that when combinations of different materials are used for a multi-layer fabric system, the thermal comfort is dependent not only on the properties of each monolayer but also on the manner in which they act together.

The results show that the monolayer acting as a moisture barrier has a considerable influence on the overall water-vapour transport abilities. The position of the moisture barrier in the assembly is also important in the overall value of water-vapour resistance of the multi-layer system.

The measured thermal resistance of the multi-layer assemblies is close to the sum of the values of the thermal resistances of the individual layers, and the thermal resistance of the assemblies does not depend on the position of the individual layers in the multi-layer assembly.

References

1 Bartels V T, Physiological comfort of sportswear, in *Textiles in Sports* (Woodhead Publishing Limited, Cambridge, UK), 2005.

2 Hunter L & Fan J, Waterproofing and breathability of fabrics and garments, in *Engineering Apparel Fabrics and Garments* (Woodhead Publishing), 2009, 283-308.

3 Mukhopadhyay A & Midha V K, *J Ind Text*, 37 (3) (2008) 225-262.

4 Junlu Sheng, Jing Zhao, Xi Yu, Lifang Liu, Jianyong Yu & Bin Ding, Electrospun Nanofibers for Waterproof and Breathable Clothing, in *Electrospinning: Nanofabrication and Applications, Micro and Nano Technologies* (Elsevier), 2018, 543-570.

5 Brzeziński S, Malinowska G, Nowak T, Schmidt H, Marcinkowska D & Kaleta A, *Fibres Text East Eur*, 13(6) (2005) 53.

6 Gulbinienė A, Jankauskaitė V, Sacevičienė V & Mickus K V, *Mater Sci - Medžg*, 13(3) (2007) 255.

7 http://www.sympatex.com/en/membrane/213/performance, (accessed 04.06.2022).

8 Rossi R, Interactions between protection and thermal comfort, in *Textiles for Protection* (Woodhead Publishing Limited, Cambridge, UK), 2005.

9 Song G, Paskaluk S, Sati R, Crown E M, Dale J D & Ackerman M, *Text Res J*, 81 (2011) 311.

10 http://vidal-protection.com/, (accessed on 11.11.2022).

11 Goldman R F, Biomedical Effects of Clothing on Thermal Comfort and Strain in *Handbook on Clothing: Biomedical Effects on Military Clothing and Equipment Systems*, (Defense Technical Information Center, USA), 2007.