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Impact of seam on liquid transmission behaviour of multi-layered ensembles using sweat and water

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Present study is focussed on the effect of seam on the moisture transmission in liquid form. Behaviour of actual sweat is found to be different from pure water used while evaluating the performance of multilayer clothing systems in seamed and unseamed condition in terms of their in-plane (wetting time) & cross-plane moisture transmission and overall moisture management capacity. Uni-directional seam shows higher wetting time at the inner surface as well as better cross-plane transmittance, and hence better overall moisture management capacity as compared to bi-directional stitched and unseamed fabrics. In all the cases, sweat shows less wetting time than water. Multi-layered ensemble with polyester spacer fabric as middle layer exhibits better overall moisture management properties in comparison to layered ensemble with fleece fabric as middle layer both in seamed and unseamed conditions. Seam type plays a most significant role followed by type of layered ensembles then solution type in affecting the overall moisture management behaviour of seamed ensembles.

Keywords: Bi-directional seam, Coated fabric, Fleece fabric, Nylon, Polyester, Protective clothing, Spacer fabric, Sweat, Uni-directional seam

1 Introduction

Comfort properties of textiles are extremely important for functional garments. Among all the comfort properties, good liquid transmission and easy drying are most important for high level of activity[1, 2]. Amount of sweat generation is directly related to the extent of activity in a given situation. Garments should be so designed that they absorb sweat quickly and transport it to the outer surface[3]. The flow of liquid moisture through textiles is caused by fibre-liquid molecular attraction at the surface of the fibre materials, which is mainly determined by the surface tension (wetting), effective capillary pore distribution and pathways (wicking)[4,5]. Transport of water in fabric can take place in two different ways, viz (i) along the plane of the fabric and (ii) perpendicular to the plane of fabric governed by longitudinal and transverse wicking respectively [6,7]. Ideally in-plane wicking of textile material next to the skin should be minimal, while cross-plane wicking and outer-plane moisture spreading out should be maximum for effective moisture management. This will ensure dry feeling and prevent the clinging of textile material with the skin. Usually for better moisture management properties in extreme conditions, multi-layered clothing is used. A standard outdoor jacket contains three layers i.e. inner layer, middle layer and outer layer; where inner layer is generally a underwear which helps in sweat absorption, direct cooling of skin and transmission of sweat to other layers; middle layer provides thermal insulation and outer layer is shell layer to protect the wearer from physical hazards and penetration of water and cold air, while allowing transmission of water vapours from body [7-9]. Heat and moisture transfer properties of layered clothing are of considerable practical significance as they play a major role in determining the thermal comfort.

In an earlier study[8], the influence of sweat and water in vapour form on individual fabric and layered ensemble is investigated. The present study is extension of the above study, wherein the effect of seam on liquid transmission behaviour of sweat has been studied. It is to be noted that till date the effect of seam in multi-layered ensemble on liquid transmission behaviour of sweat and water has not been studied. This will certainly help in developing suitable garment for strenuous activity.

2 Materials and Methods

2.1 Materials

Components of the multi-layered ensemble chosen for above study are polyester knitted (PK), polyester

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spacer (PS), polyester fleece (PF) and polyurethane coated nylon (PUN) as shown in Table 1. The arrangement of multi-layered ensemble is shown in Fig. 1. Polyester knitted fabric represents inner layer (next to skin), since knitted structure can entrap large amount of still air which is prerequisite for thermal insulation and secondly it can transmit the sweat from skin to the next layer through capillary action. Either polyester fleece or spacer fabric represents middle layer because of their thickness and porosity which is important for thermal insulation. Outermost layer consisting of PU coated nylon (coated surface is exposed to outer environment), that minimises the effect of wind and rain which are generally used in outdoor apparel, was selected for the present study. Testing was done on inner side of polyurethane nylon. Three-layered structure was thus made by using either polyester spacer or polyester fleece as middle layer, polyester knit as inner layer and PU coated nylon as outer layer.

The fabric samples were stitched as a layered ensemble using lockstitch machine (JUKI ddl-8100). The stitch density chosen was 3 stitches/inches which is generally used for commercial garments and machine speed was set to 3000 rpm. Polyester spun yarn (3-ply, normal twist 16.7 × 3 tex) was used for stitching the samples. Directions and pattern of stitching as uni-directional and bi-directional are shown in Fig. 2. Testing of all the samples is done using sweat and water.

2.2 Methods

2.2.1 Measurement of Fabric and Solution Particulars

Properties like thickness of fabric ensembles, surface tension of testing solution and their density were measured. Thickness of the seamed (uni-directional and bi-directional seam) and unseamed multi-layered ensembles was also measured using thickness measurement tester following ASTM D 16777 standards (Table 2).

Density of testing solutions was measured using DMA 5000 by selecting density measurement method. Sample was filled using a syringe in a U-shaped capillary and piezoelectric or magnetic oscillations were induced. The mass and thus the density of the sample can be calculated from the resulting resonant frequency of the U-tube oscillator as it is inversely proportional to square root of mass. The density values of water and sweat solution are 0.99 and 1.04 g/cc respectively.

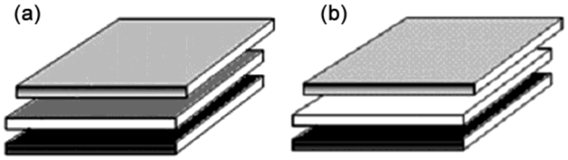

Fig. 1 — Schematic view of layered ensembles (a) three-layered with spacer fabric (PK/PS/PUN) and (b) three-layered with fleece fabric (PK/PF/PUN)

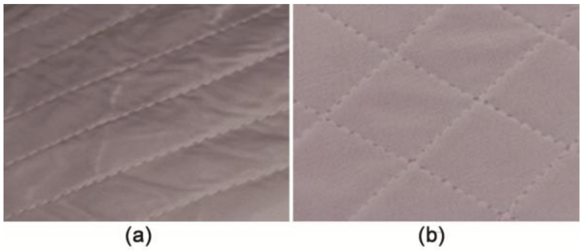

Fig. 2 — Seam patterns (a) uni-directional seams and (b) bi-directional seams

Table 1 — Specifications of fabrics used

Parameter	Polyester knit	Polyester fleece	Polyester spacer	PU coated nylon
Construction	Knitted (double jersey/interlock)	Knitted with fleece on one side (fibres raised on inner side)	Knitted 3D structure (single jersey on both sides with spacer yarn in between)	Woven fabric (nylon filament) with PU coating
Thickness, mm	0.29	0.92	1.92	0.11
Filament /spun type	Multifilament (150D/144F)	Spun polyester	(Outer / Inner) Multifilament /Monofilament	Multifilament (70D/24 F)
Porosity, %	79.4	74	82.5	45.6
GSM, g/m^2	80	320	450	75

Table 2 — Thickness (mm) of multi-layered (unseamed and seamed) ensembles

Fabric type	Unseamed	Thickness, mm			
		Uni-directional		Bi-directional	
		At stitch junction	In between junction points	At stitch junction	In between junction points
Multi-layered spacer	2.91	2.50	3.10	2.24	3.50
Multi-layered fleece	2.25	2.15	2.89	2.08	4.02

Pendant drop method[10] was used for the measurement of surface tension of both the distilled water and sweat solution. The solution was filled in syringe already clamped on the instrument. Solution was then slowly released from the syringe till it forms a complete pendant drop. The surface tension was then calculated from the image of the drop using drop shape analysis (DSA). Surface tensions of water and sweat solution are 72 and 62 dyne/cm respectively.

2.2.2 Testing of Liquid Transmission Behaviour

Liquid transmission behaviour of textile material is assessed using Moisture Management Tester (MMT) according to AATCC Test Method 195–2009. It gives the insight of the various dynamic liquid transport properties of textiles. This one step method is used to quantitatively measure liquid moisture transfer in a fabric in three directions, namely spreading outward on the inner surface of the fabric, transferring through the fabric from the inside to the outer surface and spreading outward on the outer surface and finally evaporating. As the layer near to skin is uncoated, the coated surface is laid upside down while performing the test. A solution (simulating perspiration), is dropped on the center of the upper face (skin side) of the test sample.

During experiment, sample of 8 cm diameter is placed between the top and bottom rings (sensors), bottom layer of the sample facing top. A certain known volume of a pre-defined test solution (water/ sweat) is then put into the nozzle (sweat gland) of the apparatus and introduced onto the top surface of the fabric through a capillary nozzle provided at the centre of the top ring which is integrated with moisture management software which simulate the solution for predetermined 10 s time which is already fed to the software before start of test on to the sample and records the change in resistance between each couple of proximate metal rings individually at the top and lower sensors.

The multi-dimensional moisture transport through the fabric structure is monitored for 180 s. Properties were measured by plotting the graph between time versus moisture content; after the pumping time (10 s) gets finished and results is seen in terms of top and bottom wetting time (time period when top and bottom surface just start to get wet respectively), the spreading speed (accumulative spreading speed from centre to maximum wetted radius), and one way transport capacity (OWTC) were obtained at the end of the test (Fig. 3). Through these results, overall moisture management capacity (OMMC) was calculated for each fabric using the following equation:

OMMC =0.25(MAR)b + 0:5 (OWTC) + 0.25 (SS)

This combines three measured attributes of performance, viz the liquid moisture absorption rate on the bottom surface (MAR)b; the difference between absorption rate of top and bottom surface i.e. liquid transport capability expressed in terms of OWTC or cross-plane transmittance (difference in accumulated moisture content of two surfaces expressed in %/s); and the liquid moisture spreading speed on the bottom surface (SS)b.

Test results obtained from MMT provide insight about the behaviour of material and instrumental response for multi-layer clothing. Here, the technical top and bottom surfaces have been considered as inner surface (next to skin) and outer surface respectively.

Before conducting the test, all the fabric samples were first conditioned at 65% ± 2% R.H. For each test fifteen samples were tested to minimise the error below 2%.

2.2.3 Statistical Method

The ANOVA technique was conducted to see the effect of individual factors on the thermo physiological comfort performance. Fifteen tests were conducted for each sample. All the interpretations are based on 5% level of significance. F-ratio and percentage contribution of different factors were studied. From the ANOVA analysis, % contribution of different factors is evaluated based on the following expression:

$$\% \text{ Contribution}=\frac{(SSf - dff.Ve)}{SST} \times 100$$

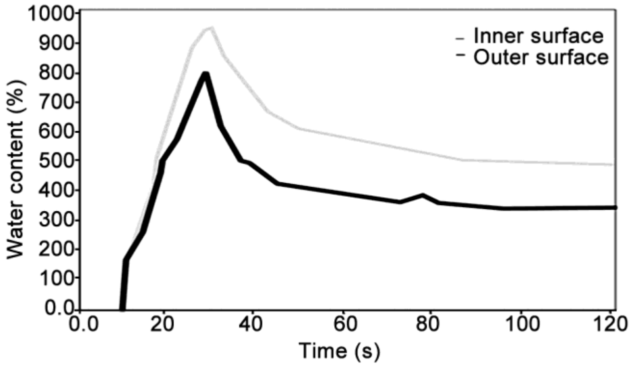

Fig. 3 — Generalised plot between water content and time

where SS_f is the sum of square of the factor; df_f , the degree of freedom of the factor; Ve, the mean square of pooled error; and SS_T, the total sum of squares.

3 Results and Discussion

For the assessment of liquid transmission behaviour, the wetting time, one way transport capacity and overall moisture management index have been analysed. Wetting time indicates in-plane transmission which allows better spreading of liquid moisture. On the other hand, cross-plane moisture transmission capacity to the plane of material away from skin should be maximum for attaining better overall moisture management behaviour and thermal comfort.

3.1 In-plane Liquid Transmission–Wetting Time

Wetting indicates in-plane liquid transmission behaviour of materials at both inner and outer surface in terms of water content (%), shown in Fig. 3. It is desirable as it allows better spreading of liquid moisture in the plane of fabric. Wetting time of different fabric ensembles is shown in Fig. 4. Present study is mainly focussed on inner side of the material. It is observed that there is significant difference in wetting time of seamed and un-seamed fabrics at the inner (top) surface with both sweat and pure water. At the outer (bottom) surface, all fabric ensembles show exceptionally higher wetting time of nearly 180s. Seamed fabric shows higher wetting time at the inner surface as compared to un-seamed fabrics. This can be attributed to the fact that with insertion of seams, junction points increase, which, in turn, increases the chances of cross-plane transmittance as compared to in-plane transmission, resulting in less spreading at the top (inner) surface. Interestingly, wetting time of bi-directional seams at top (inner) surface is found less inspite of having higher stitch density as compared to fabric with uni-directional seams. In case of bi-directional seams, greater bulging of fabric is found which leads to lesser contact in between layers, leading to less transmission of liquid from one layer to another. Therefore, in bi-directional seams, greater number of stitching junction (as compared to uni-directional seams) assist in transmission of liquid through multi-layered ensemble, but the role of fabric-to-fabric contact (except at junction points) is predominating; thus leading to lesser transmission of liquid across the fabric assembly. This also leads to accumulation of liquid moisture inside the ensemble, resulting in less wetting time at the inner surface and higher wetting time at the outer surface whereas in uni-directional seams longitudinal movement of liquid is enhanced leading to delayed wetting at top.

Although surface tension of sweat is lower which accounts for higher spreading as compared to water, but in present case density plays a predominant role. Sweat, being denser, easily seeps down to bottom surface, showing more wetting time at the inner surface[4]. The difference in the wetting time of fabric when wetted with sweat and water has become more pronounced when uni-directional seam is inserted in the layers. Further, it is observed that in case of three-layered ensemble, layered ensemble with spacer fabric as middle layer shows lesser wetting time at the top (inner) surface as compared to multi-layered ensemble containing fleece as middle layer with both sweat and pure water (Fig. 4). This is due to the difference in topography of the middle layer. Smoother and porous surface of spacer fabric assists in faster wetting of

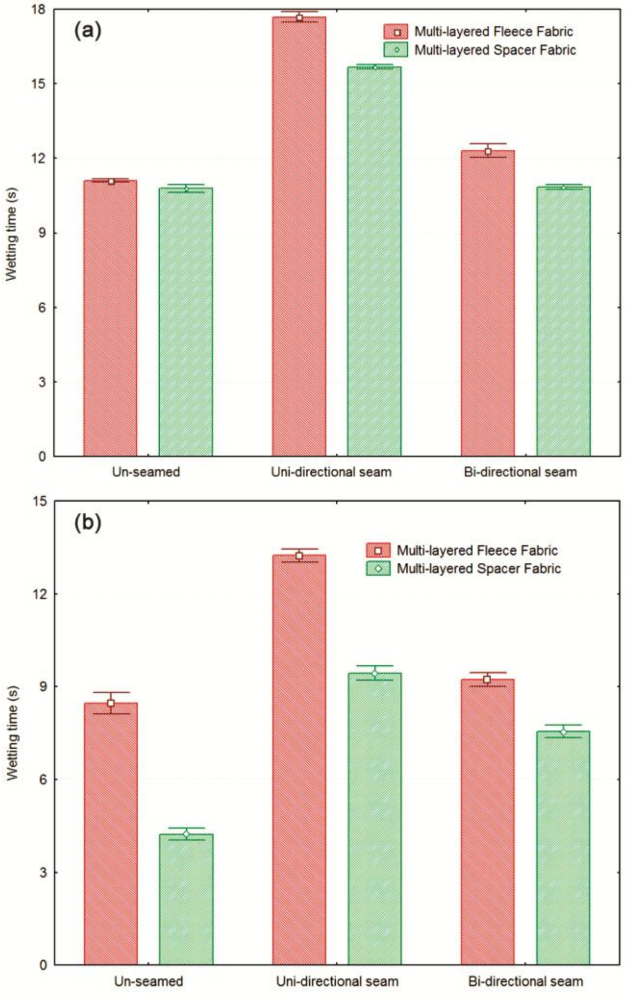

Fig. 4 — Effect of seaming pattern on wetting time of multi-layered ensembles (a) with sweat and (b) with pure water

surface at top (inner), whereas the raised fibrous and coarser surface of fleece fabric resist the movement of water/sweat, resulting in higher wetting time at the inner surface. Greater porosity of spacer fabric leads to better cross-plane transmittance as seepage of fluid is higher for fabric with higher fabric porosity, which is also affected by gravitational force. If liquid can be extracted efficiently by middle layer, then first layer becomes more accessible for liquid transmission.

Further, significant difference in thickness at seam junctions and in between layers both in case of multi-layered spacer and multi-layered fleece ensembles is observed (Table 2). Multi-layered ensembles with spacer fabric possess lower bulging both in case of uni-directional (0.6mm) and bi-directional seams (1.76mm) as compared to multi-layered fleece fabric which shows lesser wetting time. Results also show that the difference in wetting time of the multi-layered ensemble with spacer as middle layer as compared to multi-layered fabric with fleece as middle layer is greater, in case of un-seamed samples.

ANOVA (Table 3) indicates that all factors and their interactions play a significant role on wetting time. Wetting time is mainly affected by the type of seam followed by solution type and type of layered ensemble. It is further seen that the difference between wetting rate of solutions and type of layered ensemble is found highest in case of uni-directional seams. It can be inferred that the transmission of liquid through the fabric is mainly affected by the construction and structure of the fabric. Stitching junction plays a major role, irrespective of presence of differently structured layers. It is conceived that with the insertion of seam, liquid and vapour permeation become easier at the stitch line due to reduced thickness and presence of stitch hole [11, 12]. On the other hand, protection from rain water will also be affected in the presence of stitch holes[13, 14].

3.2 Cross-plane Transmittance

In order to assess the performance of garment in terms of its thermo-physiological comfort, apart from in-plane transmission, it is necessary to evaluate its cross-plane transmission behaviour also. This is indicated by the one way transport index, which is the accumulative difference in moisture content (expressed in %) of two fabric surface, viz top (inner) and bottom (outer) surface per unit testing time (s). It is observed from Fig. 5 that sweat shows better cross-plane transmittance as compared to water. Higher density of sweat accounts for better cross-plane transmittance. Further, significant difference is found in cross-plane liquid moisture transmission rate

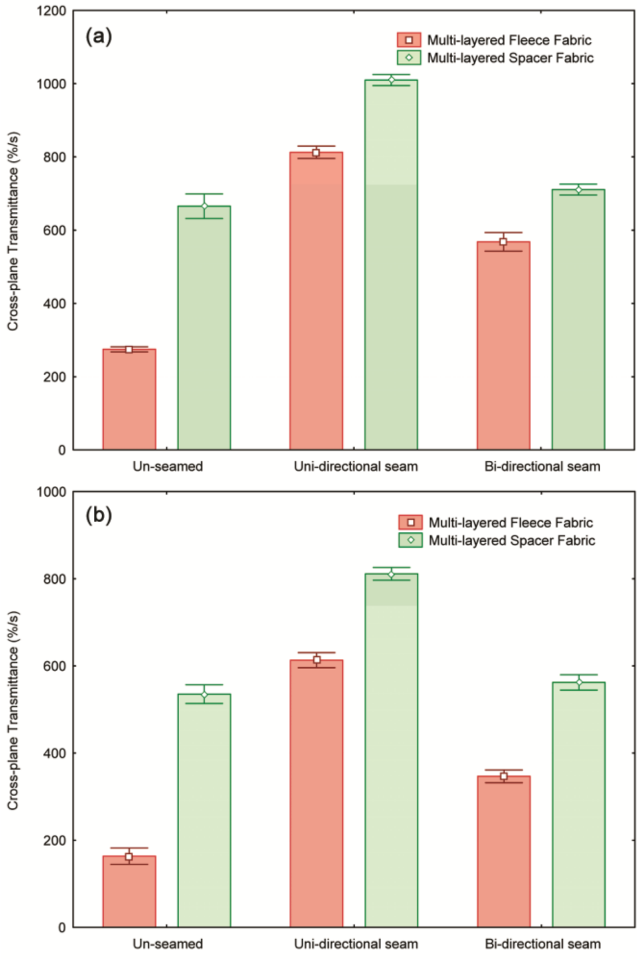

Fig. 5 — Effect of seaming pattern on cross-plane transmittance of multi-layered ensembles (a) with sweat and (b) water

Table 3 — ANOVA results and % contribution of different factors.

Factor	F- Calculated			% Contribution		
	Wetting time, s	OWTC, %/s	OMMC	Wetting time, s	OWTC, %/s	OMMC
Type of layered ensemble	332.05	278.44	278.07	14	24	24
Seams	477.35	307.49	306.98	42	54	54
Solution type	737.87	146.93	146.64	33	13	14
Type of layered ensemble × seams	5.74	34.420	34.349	3	6	5
Type of layered ensemble × solution type	90.62	-	-	4.6	-	-
Seams × solution type	40.28	-	-	3.6	-	-

(OWTC) of seamed and un-seamed fabric. Seamed fabric exhibits better cross-plane transmission as compared to un-seamed fabric ensemble. It may be added that uni-directional seam shows higher OWTC followed by bi-directional and then un-seamed fabric in both the cases of multi-layered ensemble. As evident from the data of wetting time (in-plane transmission of liquid) in case of fabric with uni-directional seams, both the liquids (sweat and water) shows greater wetting time at the top layer, which implicates lower in-plane transmittance but better cross-plane transmittance. Behaviour of bi-directional and un-seamed fabric can be explained based on the concept as discussed in Section **3.1** (with respect to uni-directional seamed fabric). Results also show that cross-plane transmittance of multi-layered ensemble with spacer as middle layer is found higher as compared to three-layered structure with fleece as middle layer. This can be explained on the basis of greater porosity of spacer fabric (Table 1) which enabled better cross-plane transmittance. Further, lesser bulging among the layered component in case of multilayered ensemble with spacer fabric assists in better cross-plane transmittance of testing solutions (Table 2). Results also reveal that multi-layered spacer with uni-directional seams shows higher cross-plane transmittance as compared to bi-directional seamed multi-layered spacer fabric. This is attributed to lesser bulging in between fabric layers in case of uni-directional stitched fabric ensemble (Table 2).

Significant difference in the cross-plane transmittance of multi-layered ensembles with water as compared to sweat is also observed. Multi-layered ensemble with spacer as middle layer shows higher cross-plane transmittance as compared to multi-layered ensemble with fleece fabric in case of both sweat and water (Fig. 5).

From ANOVA table (Table 3), it can be inferred that all the three parameters (type of layered ensemble, type of seams and type of solution) were found to be significant. Seams play a prominent role by contributing around 54% followed by type of layered ensemble with 24% contribution level and then solution type with nearly 13% significance. This implies that role of stitching is very important while forming multi-layered garments.

3.3 Overall Moisture Management Capacity

Higher values of overall moisture management capacity (OMMC) indicate that fabric can handle moisture in better way as it depends on bottom absorption rate, bottom spreading speed and cross-plane transmittance (OWTC) of fabric. OMMC values of all the fabric with both the solution (sweat and water) are shown in Fig. 6. Uni-directional seamed fabric ensemble exhibits better overall moisture management capacity as compared to bi-directional stitched and un-seamed fabric ensemble. This is attributed to the fact that uni-directional stitched fabric ensemble exhibits better cross-plane transmittance (OWTC) and higher wetting time on the top (inner)surface which implies that liquid moisture quickly seeps down to the bottom (outer) surface.

Further it may be added that there is significant difference in OMMC rate of sweat and water. Densities appear to play a predominant role as compared to surface tension. Sweat being denser shows better OMMC rate as compared to water. On comparing the two multi-layered ensemble, it is found that multi-layered ensemble with spacer as middle layer shows better overall moisture management capacity

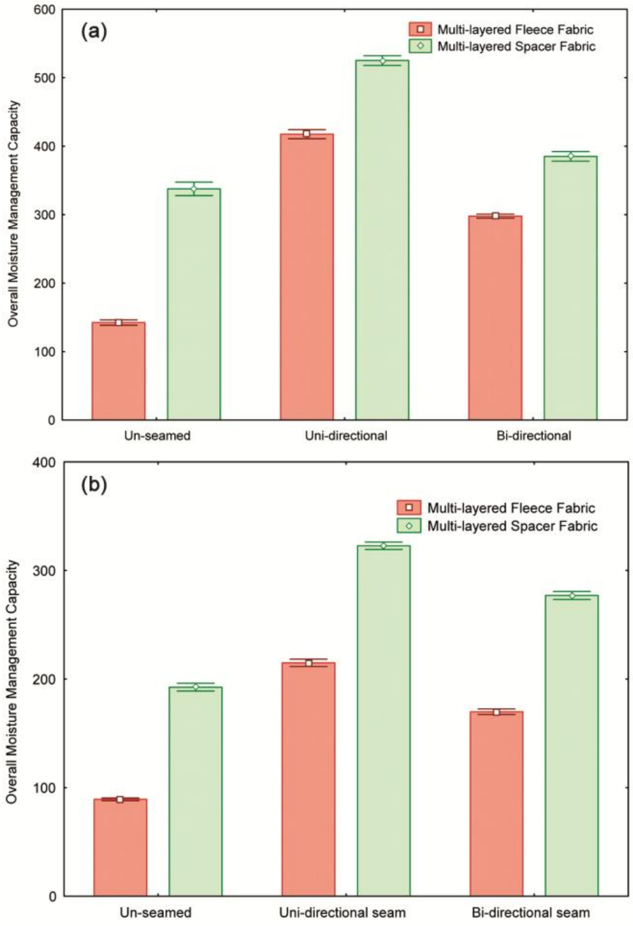

Fig. 6 — Effect of seaming pattern on overall moisture management capacity of multi-layered ensembles (a) with sweat and, (b) with water.

Overall moisture management capacity is highly dependent on one way transport capacity, which is also indicated by ANOVA results. All the individual parameter affects the OMMC rate significantly. The role of seams is the most significant followed by type of layered ensemble and then type of solution (Fig. 6).

4 Conclusion

Based on the present study of liquid moisture transmission through seamed and unseamed fabric ensemble, it has been found that the presence of seams greatly influence the transmission behaviour of liquid moisture through the fabric followed by type of multi-layered ensemble (spacer /fleece) and solution (sweat/water). The influences are mentioned below.

4.1 It is observed that the seamed and un-seamed fabrics exhibit significant difference in terms of in-plane transmittance and cross-plane transmission of liquid moisture. Seamed fabric shows higher wetting time at the inner surface, i.e. lower in-plane transmittance and better cross-plane transmittance as compared to un-seamed fabrics. This can be attributed to the fact that with insertion of seams, junction points increase, which, in turn, increases the chances of cross-plane transmittance as compared to in-plane transmission, resulting in less spreading at the top (inner) surface.

4.2 Although junction points are increased in case of bi-directional seams but interestingly wetting time of bi-directional seams at the top (inner) surface is found lower as compared to uni-directional seams, inspite of having higher stitch density. In case of bi-directional seams, greater bulging of fabric is found which leads to lesser contact in between layers, leading to less transmission of liquid from one layer to another.

4.3 Due to better cross-plane transmittance, uni-directional seamed fabric shows higher overall moisture management capacity as compared to bi-directional stitched and un-seamed fabric ensemble.

4.4 Solution type (water/sweat) influence more in-plane transmission rather than cross- plane transmission. Although surface tension of sweat is lower as compared to water, but the role of density is predominant. Sweat shows better cross-plane transmittance as compared to water. Higher density of sweat accounts for better cross-plane transmittance.

4.5 Multi-layered structure with spacer as middle layer is found better as compared to multi- layered fleece ensemble as it possess higher one way transport capacity and overall moisture management capacity. Middle layer plays a influential role in overall performance of stitched layered ensemble

4.6 Results indicate that stitching pattern plays an important role in affecting the overall behavior of moisture transmission and hence comfort of the garment. Though this will also affect protection against rain water to a certain extent but in terms of dissipating sweat away from the skin, uni-directional seam were found better in terms of technical performance of garments as compared to bi-directional stitched apparels. It may be added that nowadays most of the commercial jackets are stitched with uni-directional seam patterns.

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