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Liquid Sorption in Two-Layer Packets of Structurally Differentiate Knitted Materials

Abstract

The study presents the results of our own experiments which were concerned with liquid sweat sorption through materials designed for garments worn under protective barrier clothing. The analysis was carried out on different two-layer systems, consisting of fabrics made of synthetic and hygroscopic fibres. The study has confirmed the high utility of a two-layer under-barrier package with the diffusive layer directly adjacent to the user's skin and the external sorptive layer eliminating sweat. Both layers, having different physical functions, should be made of fibres characterised by differentiated sweat sorption for effective co-operation in the elimination of sweat from human skin. As follows from the results obtained, the optimal raw material for diffusive layers are non-hygroscopic fibres, especially textured polyester yarns. The experiments have demonstrated viscose fibres to be the most favourable of the traditional materials for sorptive layers. Both the sorption velocity and the effectiveness of liquid sweat absorption are the highest in comparison with other hygroscopic fibres. Instrumental studies of fabrics have confirmed the high utility of superabsorbents in under-barrier packages. In relation to their weight, they absorb several-fold more liquid sweat than the most hygroscopic traditional textiles. The completed studies of different morphological structures of knitted fabrics have demonstrated that those with complex spatial structure, such as pique, have the most favourable sorption parameters. Thus, the hypothesis concerning high utility of porous fabrics, both for sweat diffusion and sorption, is confirmed.

Key words: *protective clothing, barrier clothing, two-layer packets, liquid sorption.*

Introduction

The basic function of protective clothing is to protect humans from factors harmful to their health which are present in the working environment. The protective clothing used can be considerably differentiated according to hazard type and intensity, including in extreme cases tight garments protecting the whole body. Besides their numerous advantages and high protective efficacy, they have several shortcomings related to thermal parameters, which are generally underestimated or neglected in the characteristics of their protective properties.

Advances in the production of textiles, including barrier fabrics, have led to significant progress in the construction of protective clothing. In recent years it has been demonstrated that not only the protective garment, but also all other clothes worn impact on comfort of use [1-3]. It has been emphasised that clothes worn close to the body exert a significant effect on the user's thermal sensations.

Among numerous studies concerning thermal comfort, besides sorption and water vapour penetration, experiments concerning transport and sorption of liquid sweat are of considerable scientific significance. Sweat appears during intensive physical activity when the complete elimination of steam from human skin is impossible. The transport of liquid in textiles depends both on the chemical structure of the fibre surface and on the morphological structure of the fabrics [4-6]. A comprehensive study concerning the theory of capillary transport was presented by You Lo Hsieh [7]. He demonstrated the importance of material porosity in liquid transport mechanism. Some studies which are interesting in this respect [1,4,8,9] demonstrated the positive role of synthetic fibres. They were confirmed by the results of experiments on the use of two-layer fabrics with a synthetic diffusion layer and a hygroscopic sorptive layer designed for everyday clothing [10-12].

The study presents the results of our own experiments concerned with liquid sweat sorption through materials designed for garments worn under protective barrier clothing. The analysis was carried out on different two-layer systems, consisting of fabrics made of synthetic and hygroscopic fibres

Methodology

Materials

The analysis of the mechanisms for producing and eliminating sweat from the body under extreme working conditions was the basis for the selection of the tested fabrics. It indicated the feasibility of adopting two-layer textile packages for use in under-barrier garments [13]. It was presumed that the first layer directly adjacent to the skin would be made of non-swelling nonhygroscopic fibres (textured polyester and polypropylene yarns), enabling the capillary diffusion of water vapour and liquid sweat transfer to the second layer, made of fibres characterised by high sorption of liquids (cotton, wool, viscose). Two knitting weaves were adopted: interlock characterised by a compact structure, and pique-type knit with an open-work structure. The materials tested also included a polyester nonwoven containing 23% of high sorptive fibres. Table 1 presents the morphological structure of the materials qualified for testing.

Methods of measurements

Liquid sweat sorption was determined by assigning the indexes for contact of the fabric surface with liquid. Such a testing method is similar to the actual conditions of garment use. The measurements were carried out in the Textile Research Institute in Łódź using the apparatus whose design is presented in Figure 1 [14].

The fabric sample is placed on a porous plate, whose upper surface corresponds to the constant, automatically controlled, level of the liquid surface. The liquid absorbed by the sample is continuously supplemented by a hydraulic system. The quantity of liquid supplied in the function of time is recorded and plotted as a sorption curve (Figure 2).

The proper sorption time (AB) is characterised by a rapid (rectilinear) increase of the liquid mass in the sample. The tangent of AB section inclination angle to the t-axis corresponds to the sorption velocity V_{AB} [mg/cm^{2}s]. Point

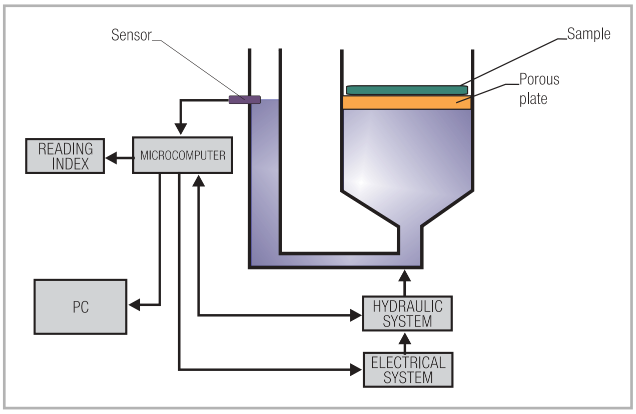

Figure 1. Scheme of the device for liquid sorption measurement [14].

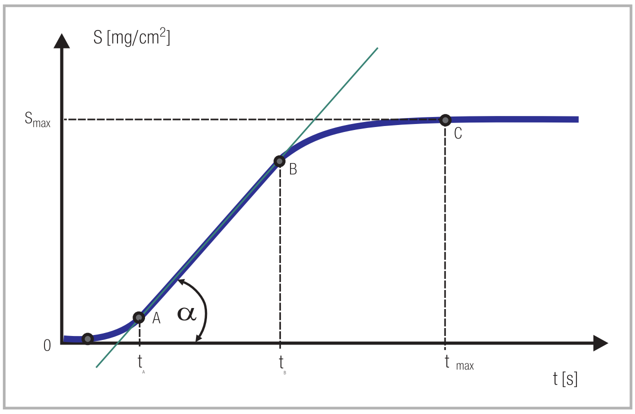

Figure 2. Typical sorption curve.

C indicates maximum sorption S_{max} [mg/cm^2]. For comparative analysis of materials with different surface masses (m_p), sorption effectiveness indexes E [mg of sweat/mg of fabric] were calculated.

$$E = \frac{S_{max}}{m_p},\ mg/mg$$

Sorption studies were carried out using an acid sweat substitute, prepared according to the relevant literature data [14].

Results and Discussion

Single layer knitted fabrics

According to the presumed model of the under-barrier package, single layers of diffusive-conductive synthetic fibre knitted fabrics and sorptive hygroscopic fibre ones were tested. Their characteristics were used to assess and select the optimal solutions with respect to effective elimination of sweat from human skin, applied in construction of a two-layer under-barrier package. Table 2 presents the basic parameters of sorption, and its dynamics is presented in Figure 3.

As follows from Table 1, knitted fabrics with pique-like weave have a surface mass significantly lower than that of interlock fabrics. The relaxation of knitted fabrics in water, as well as the chemical processing of cotton and wool knits (increasing their wettability), cause compacting of the hygroscopic fibre fabric structure, and consequently an increase in their mass per square metre. It is also characteristic that the thickness of pique-type fabrics is much larger than that of interlock ones, despite the fact that the mass of fibres per surface unit is lower. It indicates the high porosity of pique-type knitted fabrics, which is important particularly in synthetic fabrics, which do not swell in liquids and retain their original morphological structure.

Contrary to common expectations, the maximum sorption indexes (S_{max}, Table 2) demonstrate no correlation with the knitted fabric mass per square metre. The favourable effect of porous fabric structure (pique) with complex small capillary system is evident. This is illustrated by maximum sorption indexes related to mass per square metre, which characterise sorption effectiveness (E). For all raw material variants, this is higher for pique-type weave than for interlock. Figure 4 presents the sorption effectiveness of knitted materials with pique weave (Eb_i) related to the sorption effectiveness of knitted materials with interlock weave (Ea_i) for every raw material - **Eb_i/Ea_i** [%] (**E**a was assumed as 100%). Thus, the importance of porous fabric structure in the process of sweat elimination from the human skin is obvious, although not always appreciated in practice.

The nature of these phenomena has been confirmed by studies carried out on knitted fabrics made of hygroscopic fibres. The strikingly higher effectiveness of sweat sorption through both polyester and polypropylene synthetic knitted fabrics was obtained in comparison with fabrics made of

Table 1. List of single layer fabrics used in sweat sorption tests.

Design	Stitch	Raw materials	Mass per square metre, g/m^2	Thickness, mm
a1	interlock	polyester	218	1.01
a2		polypropylene	228	1.09
a3		cotton	300	1.42
a4		viscose	278	1.05
a5		wool	309	1.70
b1	pique	polyester	127	1.48
b2		polypropylene	158	1.66
b3		cotton	202	1.44
b4		viscose	188	1.22
b5		wool	272	2.25
W	nonwoven	77% polyester 23% high sorptive fibres	91	0.36

Table 2. Characteristic of sweat sorption through single layer knitted fabrics.

Design	Parameters of sorption		
	S_{max}, mg/cm^2	V_{AB}, mg/cm^{2}s	E, mg/mg
a1	91	3.24	4.2
a2	102	4.93	4.4
a3	83	10.0	2.8
a4	103	15.5	3.6
a5	143	0.96	4.6
b1	83	0.39	6.5
b2	116	4.76	7.3
b3	81	17.0	4.0
b4	110	18.7	5.9
b5	170	4.19	6.3
w	96	3.60	10.5

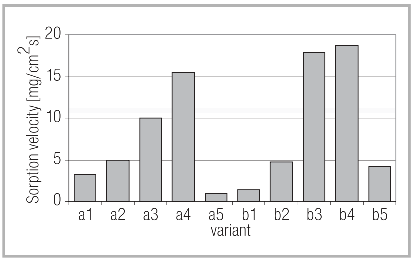

***Figure 3.** Sweat sorption velocity through interlock (a) and pique-type (b) knitted fabrics.*

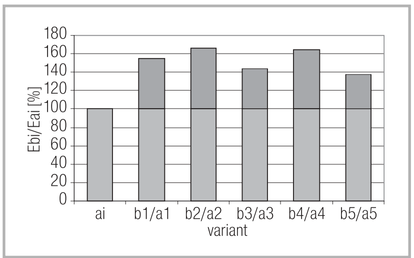

***Figure 4.** Characteristics of sorption effectiveness in pique-type knits compared with that of interlock ones.*

hygroscopic fibres. The above was observed particularly with respect to cotton knits, although viscose ones also had lower sorption effectiveness. High absorption of the liquid by the sorptive fibres causes their swelling, thus reducing porosity of the material. Therefore, sweat sorption inside the fibres is significantly less effective than its diffusion through the capillaries of a synthetic material.

Figure 5 presents the sorption effectiveness of knitted materials with interlock weave made of different raw materials related to the sorption effectiveness of knitted material with interlock weave made of cotton $\mathbf{E}a_i/\mathbf{E}a_3$ [%]. For that purpose it was assumed that $\mathbf{E}a_3$ is 100%. Similarly, Figure 6 presents the sorption effectiveness of knitted materials with pique weave made of different raw materials related to the sorption effectiveness of knitted material with pique weave made of cotton $\mathbf{E}b_i/\mathbf{E}b_3$ [%]. For that purpose, $\mathbf{E}b_3$ was assumed to be 100%.

In comparisons of knitted fabrics made of various hygroscopic fibres, the highest effectiveness of sweat sorption was obtained for chlorinated wool (with increased wettability), slightly lower for viscose, and lowest for cotton. It should be emphasised that both wool and cotton demonstrated very low sorption before chemical processing due to their low wettability. The experimental polyester nonwoven fabric containing 20% highly sorptive fibres (variant w) deserves special attention. Despite its very low surface mass and small thickness, and thus low porosity, its sorption effectiveness markedly exceeds the levels obtained for other materials. The excellent absorption of liquids by highly sorptive fibres confirms the possibility of effective use of such materials.

The practical applications of protective clothing indicate that under-barrier packages, besides high sorptive capacity, should eliminate sweat relatively quickly from the user's skin. Therefore, sorption dynamics is an important factor to be considered in assessing under-barrier package utility. The tests have demonstrated that sweat sorption velocity is several-fold higher for cotton and viscose knits than for those made of synthetic fibres (Table 2). Unlike sorption effectiveness, the factor predominant in this characteristics is liquid sorption into the fibres. The very low sorption velocity through woollen knits (after chemical processing) as well as through highly sorptive nonwoven, similar to the parameters obtained for synthetic knits, should be emphasised here. A considerable improvement in this parameter, by introducing highly sorptive fibres in the respective knitted fabric structures, seems to be possible.

Two-layer systems

The studies of single-layer knitted fabrics have demonstrated their varied capability to eliminate sweat from the skin. Model assumptions concerning the high utility of diffusive synthetic materials designed for under-barrier garments worn next to the skin have been confirmed. Among the sorptive knits tested, viscose fibre fabrics were most highly appreciated. The above observations provided the basis for a two-layer system testing program. Two layer systems of fabrics from Table 3 were tested. The first, diffusive layers (worn next to the skin) were made of interlock and pique-type polyester and polypropylene knits. The second, sorptive layers were made of viscose knits and, for comparison, of highly sorptive fibre nonwoven fabric. Both interlock (a) and pique-type (b) knitted fabric systems were tested according to the program presented in Table 3.

The results of testing these two-layer systems (Table 4) confirm the observations made on the analysis of single-layer fabrics. In the case of the interlock diffusion carrier, the sorption effectiveness (E) for systems containing viscose fibres is significantly lower than the value obtained for systems containing highly sorptive fibres. In Figure 7, we present the sorption effectiveness of packets containing diffusion layer (a_1 or b_1) and sorptive layer with highly sorptive fibres (3w) related to the sorption effectiveness of systems with the same diffusion layer and knitted material of viscose as the sorptive layer (a_4 or b_4).

The expression

$$\mathbf{E}a_{1}/b_{1}+3w/\mathbf{E}a_{1}/b_{1}+a_{4}/b_{4} \ [\%]$$

was calculated.

For this purpose it was assumed that $(\mathbf{E}a_1+a_4)$ or $(\mathbf{E}b_1+b_4)$ is 100%.

Much smaller differences are observed for diffusion carriers in the form of pique-type highly porous knitted fabrics. For systems containing highly sorptive fibres, unfavourable sorption

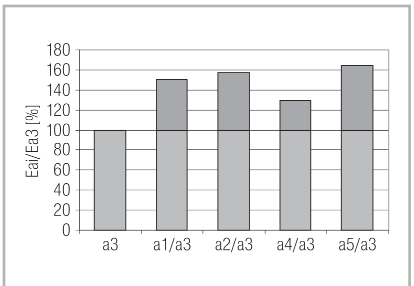

***Figure 5.** Characteristics of sorption effectiveness in interlock knits compared with the cotton variant.*

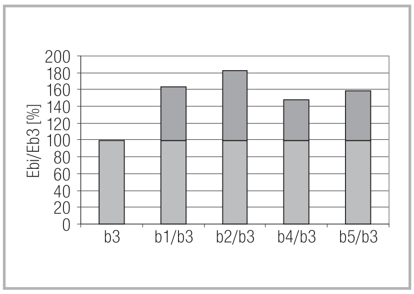

***Figure 6.** Characteristics of sorption effectiveness in pique knits compared with the cotton variant.*

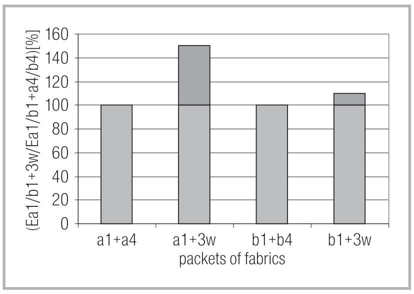

***Figure 7.** Characteristics of sorption effectiveness of two-layer systems consisting of highly sorptive nonwoven and interlock, or pique-type knitted fabric.*

Table 3. Characteristics of two-layer systems used in the tests.

Packets of fabrics	Mass per square metre, g/m²	Thickness, mm	Packets of fabrics	Mass per square metre, g/m²	Thickness, mm
a1 + a4	496	2.06	b1 + a4	405	2.53
a2 + a4	506	2.14	b2 + a4	436	2.71
a1 + 3 x W	491	2.09	b1 + 3 x W	400	2.56
			b1 +b4	315	2.70
			b2 + b4	346	2.88

Table 4. Characteristics of sweat sorption through two-layer knitted fabric (a, b) and nonwoven fabric (w) systems.

Packets of fabrics	Parameters of sorption		
	S_{max}, mg/cm²	V_{AB}, mg/cm²s	E, g/g
a1 + a4	190	17.5	3.8
a2 + a4	179	19.0	3.5
a1 + 3 x W	281	2.23	5.7
b1 + a	196	12.4	4.8
4b2 + a4	202	13.6	4.6
b1 + 3 x W	274	1.44	6.9
b1 + b4	200	11.3	6.3
b2 + b4	207	19.4	6.0

velocity (V_{AB} - Table 4) is confirmed, which requires considerable structural changes to be introduced into that material. For both weave types, similar sorption parameters are obtained for fabric systems which use polyester or polypropylene fibres.

The use of a pique-type diffusion carrier in combinations with interlock knits or highly sorptive nonwoven fabrics enhances the effectiveness of sorption. However, sorption increase is particularly significant if pique-type fabrics are used for both layers. This prompts us to suggest adopting this material for the sorptive layer also, and using highly sorptive fibres in it.

In Figure 8 we present the sorption effectiveness of material systems with a diffusion layer of knitted materials with pique weave (b_1 or b_2) related to the sorption effectiveness of two-layer systems with interlock knitted materials as both layers.

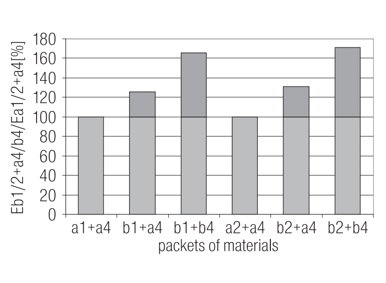

Figure 8. Characteristics of sorption effectiveness of two-layer systems consisting of interlock and pique-type knitted fabric.

The expression

$$\mathbf{E}b_{1/2}+a_4/b_4/\mathbf{E}a_{1/2}+a_4\ [\%]$$

was calculated. For this purpose, it was assumed that ($\mathbf{E}a_1+a_4$) or ($\mathbf{E}a_2+ a_4$) is 100%.

Conclusion

The completed study has confirmed the high utility of a two-layer under-barrier package with the diffusive layer directly adjacent to the user's skin and the external sorptive layer eliminating sweat. Both layers, having different physical functions, should be made of fibres characterised by differentiated sweat sorption for effective co-operation in the elimination of sweat from human skin.

As follows from the results obtained, the optimal raw material for diffusive layers are non-hygroscopic fibres, especially textured polyester yarns. Their hydrophilic surface, and the stability of capillary structure of manufactured fabrics, favours the transport of humidity to the sorptive layers. In this respect, they possess a considerable advantage over all hygroscopic polymers used in fibre production.

The experiments have demonstrated viscose fibres to be the most favourable of the traditional materials for sorptive layers. Both the sorption velocity and the effectiveness of liquid sweat absorption are the highest in comparison with other hygroscopic fibres.

Instrumental studies of fabrics have confirmed the high utility of superabsorbents in under-barrier packages. In relation to their weight, they absorb several-fold more liquid sweat than the most hygroscopic traditional textiles. The disadvantage of superabsorbents is low sorption velocity (at the level of synthetics), which may be due to unfavourable fabric structure (thermoplastic nonwoven). Specialist studies in the field of processing technology and morphologic structure of fabrics should favour the introduction of superabsorbents in protective clothing.

The studies of different morphological structures of knitted fabrics hitherto carried out have demonstrated that those with complex spatial structure, such as pique, have the most favourable sorption parameters. Thus, the hypothesis concerning the high utility of porous fabrics, both for sweat diffusion and sorption, has been confirmed.

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