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The Interaction of Water with Fabrics

RITA M. CROW

Brantford, Ontario N3T 5L7, Canada

RANDALL J. OSCZEVSKI

Defence and Civil Institute of Environmental Medicine, North York, Ontario M3M 3B9, Canada

ABSTRACT

This study examines the interaction between water and a range of fabrics because of claims that synthetic fibers such as polypropylene do not pick up moisture and so when made into active wear, leave the wearer warm and dry. We have found that all fiber types, when made into fabrics, pick up water, with a strong correlation between a fabric's thickness and the amount of water it picks up freely expressed in absolute terms rather than percent of its mass. We have also found that properties relevant to clothing on an exercising person, such as drying time and energy required to evaporate water from under and through a dry fabric or dry a wet fabric, depend on the amount of water the fabric picks up, not fiber type. The amount of water wicked from one layer to another depends on pore sizes and their corresponding volumes. These results are supported by manikin and human subject experiments.

Trying to stay warm and dry while active outdoors in winter has always been a challenge. In the worst case, an individual exercises strenuously, sweats profusely, then rests. During exercise, liquid water accumulates on the skin and starts to wet the clothing layer(s) above the skin. Some of the sweat evaporates from both the skin and the clothing and moves out through the clothing. Depending on the temperature

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and humidity gradient across the clothing, the water vapor either leaves the clothing or condenses and freezes somewhere in its outer layers.

When one stops exercising and begins to rest, active sweating soon ceases, allowing the skin and clothing layers to eventually dry. During this time, however, the heat loss from the body can be considerable. Heat is taken from the body to evaporate the sweat, both that on the skin and that in the clothing. The heat flow from the skin through the clothing can be considerably greater when the clothing is very wet, since water decreases clothing's thermal insulation. This post-exercise chill can be exceedingly uncomfortable and can lead to dangerous hypothermia.

A dry layer next to the skin is more comfortable than a wet one. If one can wear clothing next to the skin that does not pick up any moisture, but rather passes it through to a layer away from the skin, heat loss at rest will be reduced. For such reasons, synthetic fibers have gained popularity with winter enthusiasts such as hikers and skiers.

Advertising and the popular press would have us believe that synthetic materials pick up very little moisture, dry quickly, and so leave the wearer warm and dry. In contrast, warnings are given against wearing cotton or wool next to the skin, since these fibers absorb sweat and so "lower the body temperature." A further property credited to synthetics, in particular polypropylene, is that they wick water away from the skin, leaving one dry and comfortable.

In the early fifties, when synthetic fibers such as nylon and the acrylics were first coming onto the consumer market, Fourt *et al.* [12] and Coplan [5] compared the water absorption and drying properties of these "miracle" fibers with those of conventional wool and cotton. Forty-five years later, we again compared the water absorption and drying properties of synthetics with natural fibers, this time to test the claims for synthetic fibers mentioned above [6, 9]. As in the earlier studies of Fourt and Coplan, we found that regardless of fiber content, all fabrics pick up water, and the time they take to dry is proportional to the amount of water they initially pick up.

We also found that properties relevant to clothing on an exercising person, that is, the energy required to evaporate water from under and through a dry fabric or to dry a wet fabric and layer-to-layer wicking [8], do not depend on fiber type. In this paper, we summarize this work and compare it with the results of others, including physiological studies.

Method

MATERIALS AND EXPERIMENTAL PROCEDURES

Most of the fabrics we used came from Testfabrics Incorporated, New Jersey, and supplemented as required by commercially available underwear and coated fabrics. In all experiments, the fabric samples were wetted out with distilled water to which a small amount of liquid detergent had been added to make about an 0.01% solution. Where not indicated otherwise, the amount of water held by the conditioned samples is expressed in grams of water per unit sample area. All experiments occurred in a textile conditioning room set at 20°C and 65% relative humidity.

TABLE I. Pertinent properties of and results for fabrics used in water absorption and drying experiments.

Fabric	Mass, g/m^2	Thickness, mm	Mass of water in fabric, g	Time to dry, hours
Cotton duck	362	0.66	1.25	5
Cotton sheeting	155	0.41	0.96	5
Cotton lawn	100	0.28	0.58	2
Polyester plain weave A	159	0.41	0.73	3
Polyester plain weave B	121	0.30	0.58	2
Polyester batiste	71	0.20	0.32	1
Wool plain weave	124	0.46	0.58	3
Wool single knit	213	0.81	1.64	7
Acrylic plain weave	144	0.38	0.50	2
Acrylic knit	124	0.69	1.45	5
Nylon doubleknit	215	1.02	2.52	10.5
Nylon tricot knit	84	0.25	0.25	1.1
Cotton/polyester knit	162	0.64	1.97	8.75
Polypropylene plain weave	160	0.64	0.80	3
Polypropylene knit	221	1.24	2.26	8.75
Nylon/tricot Goretex	175	0.43	0.63	2
Dermoflex[a]	201	0.23	0.16	1

[a] Water-vapor permeable waterproof polyurethane coated nylon.

TABLE II. Pertinent properties of the fabrics used in the energy required to dry experiments.

Fabric	Mass, g/m^2	Thickness, mm	Count, yarns/cm or courses and wales/cm	Regain, %
Cotton sheeting	155	0.41	22 × 17	7.0
Cotton lawn	100	0.28	32 × 32	7.0
Polyester plain weave A	159	0.41	20 × 16	0.4
Polyester plain weave B	121	0.30	25 × 21	0.4
Polyester knit	155	0.58	10 × 14	0.4
Polypropylene knit	212	1.45	24 × 36	0
CF underwear	313	2.57	waffle knit	7.0

Water Absorption

To measure the absorption of liquid water in fabrics, circular samples of sixteen fabrics varying in fiber content and construction (Table I) were diecut to identical areas (38.5 cm^2) uniformly wetted out in water, and left overnight sandwiched between two wet sponges. The next day, the mass of water freely absorbed by each sample was recorded [7].

Water Absorption Versus Drying Time

To determine the drying time of the fabrics, we continued this experiment, automatically recording the mass of each sample at regular intervals. The time to dry was when the mass of the sample had reached 105% of its conditioned dry mass; the 5% reflects the accuracy of the balance used.

Energy Required to Dry

Four Testfabrics woven fabrics were supplemented with well-used and laundered cotton waffle-weave Canadian Forces (CF) underwear and two commercially-available knitted underwear, an as-received polyester, and a five-times laundered polypropylene (Table II).

A guarded hot plate was used for the experiments. The test area had a surface of 0.01 m^2 (approximately 11 cm in diameter), surrounded by a 2.5 cm wide guard ring of identical area. Surface temperatures of both were set at 30°C. Fabric samples of identical area were cut to cover the entire plate.

In the first set of experiments, the fabrics were wetted out by soaking in water, squeezed by hand, and blotted on paper towels to remove the excess water. This technique was acceptable, since the amount of water left in the sample was not critical to the experiment. The sample was weighed to determine the amount of water in it, then placed on the dry guarded hot plate and allowed to dry. The amount of water reported is what would have been held in the sample over the test area only.

In the second set of experiments, drops of distilled water from a full 2.5 ml hypodermic syringe were placed in decreasing circles onto the test surface (not on the guard ring) until the syringe was empty. The drops of water wicked into the surface of the fabric covering the hot plate, spreading to cover it. A dry fabric was placed on top of the plate, and the water was allowed to evaporate from the hot plate surface through the fabric.

In both experiments, the heat flux was recorded and the energy to evaporate the water was calculated (*i.e.,* the total area under the curve of heat flux versus time). For the first experiment, this was corrected for the heat loss from the plate when the fabric was dry.

Layer-to-Layer Wicking

Samples 70 mm diameter were cut from six fabrics found to wick from layer to layer (Table III). Two samples from each fabric were weighed and one wetted out in water. The wet sample with the dry sample on top was placed on an inverted plastic petri dish and covered with a second petri dish weighing about 7 g. This allowed some light and constant pressure on the layers and limited evaporation of water from the sys-

TABLE III. Properties of fabrics used in the layer to layer wicking experiments.

Fabric	Mass, g/m^2	Thickness, mm	Count, yarns/cm or courses and wales/cm	Regain, %
Acetate tricot knit	69	0.28	11 × 16	5.5
Acetate plain weave	168	0.46	16 × 12	5.8
Polyester plain weave	184	0.50	34 × 24	0.6
Cotton doubleknit	244	1.65	9 × 13	7.2
Cotton plain weave	328	0.58	21 × 17	8.5
Silk noil plain weave	139	0.56	21 × 20	9.7

tem. Both samples were weighed at intervals until there was no further change in mass of the initially dry sample. The initially wet sample was recharged with water and the experiment reassembled and allowed to continue. This was repeated until the initially dry upper sample picked up no further water from the wet lower fabric.

To wet out the sample, it was held by tweezers, immersed in water, and then each side of the specimen was briefly patted on paper toweling. This removed sufficient water from the fabric surface so that none was transferred to the balance pan or the petri dish surface. To explain the results of this experiment, it was necessary to determine the amount of water held in the variously sized pores of the fabrics using the method described by Miller and Tyomkin [19]. Here, the dry sample is brought into contact with a capillary-supported column of water. The amount of water taken up by the sample is measured at a range of pressures created by varying the height of the column. At small negative pressure heads, almost all capillaries in the sample are filled with water. Because the capillary pressure in a pore of the sample is inversely related to its radius, as the negative pressure head increases, water is withdrawn only from the larger pores. From consideration of the volume taken up at different negative pressures, one can deduce the volumes of pores of various sizes.

Results

WATER ABSORPTION

The results are given in Table I. We found no relationship between regain and the amount of water picked up by the fabric ($r = 0.074$). Initially, we had plotted the percent water in the sample, based on its mass, against thickness and found a poor correlation ($r = 0.48$). However, after plotting actual water content against various physical properties, we found the best correlation ($r = 0.92$) to be between the actual amount of water in the samples and their thicknesses (Figure 1).

When we converted the results of others (Maejima [17], Dolhan [10], Fourt *et al.* [12], Bertioniere [3]) from percent liquid content to actual liquid content and plotted these values against thickness, we again found a very good correlation. The results of Fourt *et al.*, whose experiment included a very wide range of materials, are given in Figure 2. We did find some exceptions. The outlier in Fourt *et al.*'s results was a papermaker's felt. The outlier of Dolhan's eight underwear materials had a fishnet structure. Fabrics finished with crosslinking agents or water repellents had decreased total water pickup and thus did not support this water retention/thickness relationship (Knight [15], Mecheels [18]).

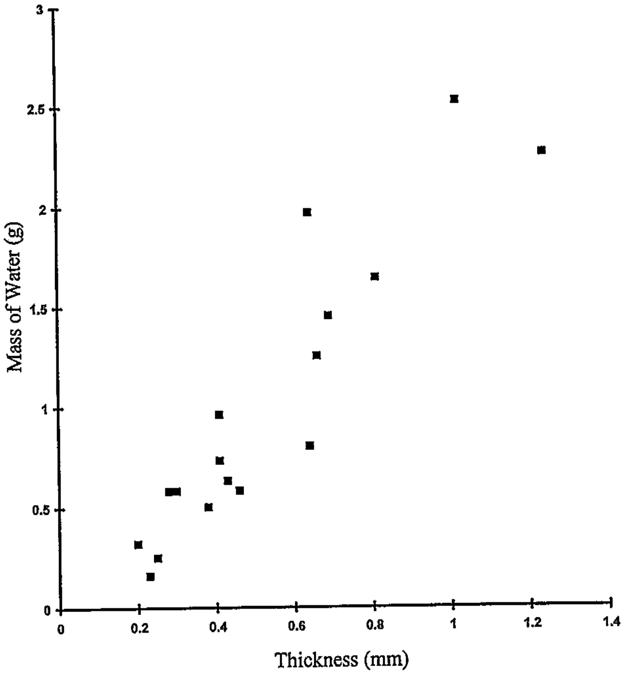

FIGURE 1. There is a good correlation between the mass of water held by the fabric and its thickness.

We concluded that expressing the amount of water in a fabric as a percent of its mass is simply an exten-

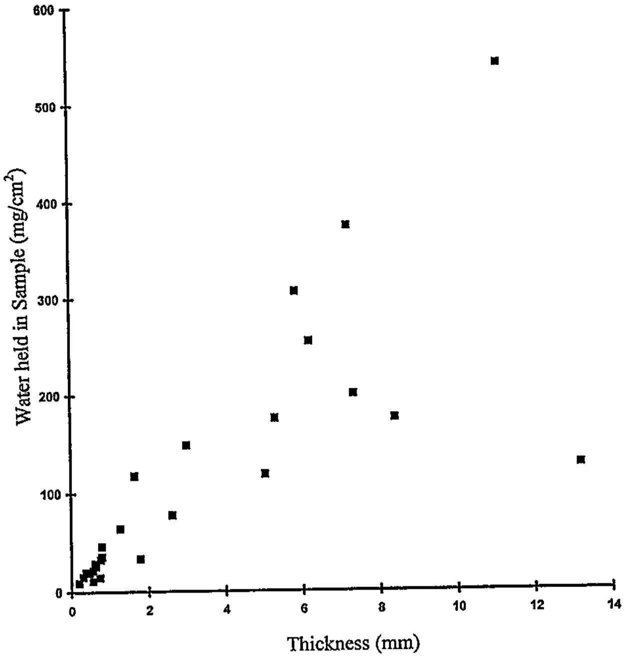

FIGURE 2. A plot of Fourt *et al.*'s results for thickness versus the amount of water held by his wide range of fabrics.

sion of the percent regain calculation for water vapor to that for liquid water. The amount of water vapor a fiber picks up, expressed as a percent of its mass, is valid because it is directly related to the number of hydrophilic sites the fiber has to which water vapor can bond; this is proportional to fiber mass. However, the amount of liquid water a fabric picks up depends on the total capillary volume, which is usually related to the fabric's thickness. As Coplan [5] rightly pointed out, we would never express the mass of a liquid in a beaker as a percent of the mass of the beaker. It is uninformative at best, to express the mass of water as a percent of the mass of fiber holding it, and it may be misleading, especially when comparing fabrics with different densities.

In our literature review, we found several papers in which alternative conclusions might have been drawn if the results had been expressed as the actual amount of water in the fabric rather than as a percent of fabric mass (Bertoniere [3], Knight [15], Cary [4], Skeleton [23], Harper [13], Schneider [22]). A good example is Bertoniere [3], who studied a series of cotton fabrics woven with an increasing number of weft yarns. She found that the percent water in the fabrics, based on their mass, remained the same and concluded that increasing the number of weft yarns had no influence on the water absorption properties of her fabrics. When we calculated the actual amount of water in her series of fabrics, we found the actual amount of water held by the fabrics increased with the number of weft yarns. The increase in water uptake with increasing number of weft yarns was masked by increasing fabric mass.

Although the thicknesses of Bertoniere's fabrics weren't given in her paper, we have assumed that they were similar. Thus, in this case, the amount of water picked up by her series of fabrics was not thickness dependent. We confirmed this in reverse by systematically removing weft yarns from a fabric and determining the water pickup in each case. As we would expect, there was a decrease in water pickup as the number of weft yarns in the fabric decreased. This shows that it is the water held in the intrayarn spaces (*i.e.,* between the fibers) that is more important that the water held in the interyarn spaces. This would be particularly noticeable for fabrics with large voids, such as the fishnet underwear that produced the anomalous results mentioned above. This might also account for the scatter of results in Table I.

WATER ABSORPTION VERSUS DRYING TIME

Our results are shown in Table I and Figure 3. Like Coplan [5] and Fourt *et al.* [12], we found a very good correlation ($r = 0.98$) between the amount of water initially in these fabrics and the time for them to dry; this correlation was independent of fiber type. Note that Fourt *et al.* found this relationship did not hold for some of their napped fabrics, explaining that the napped surface retarded heat flow to the water in the fabric and thus limited the evaporation rate.

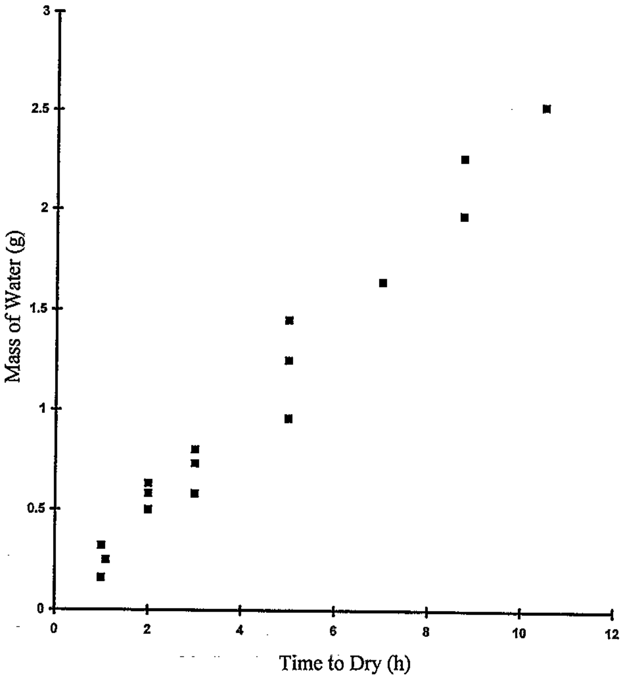

FIGURE 3. Linear relationship between the initial mass of water in the fabric and the time to dry for a range of fabrics made from various fiber types.

We weighed a water drop in a petri dish at half-hour intervals until it evaporated. Equivalent amounts of water in the fabric samples evaporated more quickly than the free-standing water drop. We concluded that in a fabric, the water is spread out through the yarns and so has a much larger surface area from which it can evaporate.

ENERGY REQUIRED TO DRY

The results for both experiments are given in Table IV. Like Farnworth and Dolhan [11], we found that the curve of heat flux versus time for the cotton fabrics tailed off; those for the synthetic fabrics did not, and there was a sharp drop in heat flux when the water had evaporated from the fabric (Figure 4). Further information on drying behavior can be found in reference 25.

Again, we found the time to dry was linearly related to the amount of water initially in the fabric ($r = 0.994$). Not surprisingly, the energy drawn from the "skin" of the hot plate to dry the sample was also linearly related to the amount of water initially in the fabric ($r = 0.985$) (Figure 5). Farnworth and Dolhan's study of heat and water transport through cotton and polypropylene underwear fabrics, using slightly different conditions, also found no discernible differences in the heat loss through the two materials at the higher, heavy sweat rate. It would appear from their graphs that the energy extracted from the "skin" of the sweating hot plate to evaporate water is much the same for these two fabrics, at a high or low sweat rate.

We were unable to keep 2.5 g of water at all times in the fabric covering the hot plate. Occasionally a small amount wicked into the fabric over the guard ring. We also saw a small amount that had wicked from the wet hot plate fabric onto the cotton sheeting fabric. Despite advertisements of special wicking abilities, no water wicked from the plate into the polyester or polypropylene underwear. In fact, in the first experiment, the laundered polypropylene underwear was extremely difficult to wet, the hydrophilic finish obviously having been removed in the laundering.

Table IV shows that the amount of energy required to evaporate 2.5 g of water from the bare wet surface is 558 KJ/m^2. This is 2.20 mJ/kg, which is within 10% of the theoretical amount of energy, 2.43 mJ/kg, required to evaporate water under these conditions. The amount of energy transferred from the wet plate through all the dry woven fabrics and the polyester knit was the same within experimental limits and was therefore independent of fiber type, the average being 474 KJ/m^2.

The polypropylene sample would not lie flat on the plate: pockets of air randomly occurred across it, effectively increasing its thickness. This would account for the low energy transferred from the plate (387 KJ/m^2).

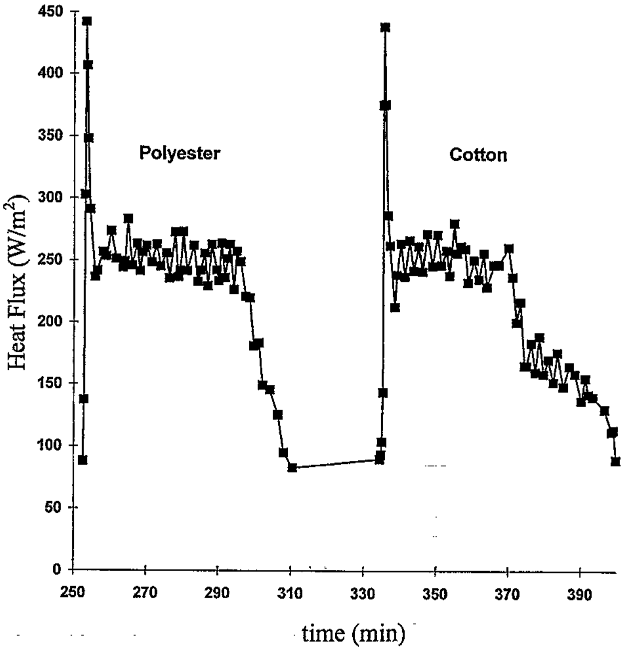

FIGURE 4. The curve on the left shows the sudden drop in heat flux for a polyester fabric; in contrast, the curve on the right for cotton shows a tailing off of heat flux with time.

These results agree with Nielsen's [20] manikin studies, which found that more energy was required to evaporate the same amount of water from the inner layer of a two-layer clothing ensemble than from the outer layer. This is to be expected, as a dry inner layer would allow the wet outer layer to be cooled to a lower

TABLE IV. Columns 2 to 4 give the results of the experiment in which the fabric was wetted and placed on the dry plate. Column 5 gives the amount of energy required to evaporate 2.5 g of water from the plate.

Fabric	Initial amount of water in fabric, g	Time to dry, minutes	Heat flux × time to dry, KJ/m^2	Heat flux × time for 2.5 g water to evaporate, KJ/m^2, $n = 3$
Cotton A (sheeting)	3.2	53	249	471
	2.9	57	246	
Cotton B (lawn)	1.7	28	90	490
	1.3	25	105	
Polyester plain weave A	1.3	24	142	445
	0.6	11	41	
	2.6	50	255	
Polyester plain weave B	1.1	22	111	491
	2.6	50	190	
Polyester knit	3.0	46	278	475
	1.9	27	172	
				mean = 474 $CV = 4\%$
Polypropylene knit	5.6	107	410	387
CF underwear	13.7	217	145	–
Plate alone	2.5	47	372	558

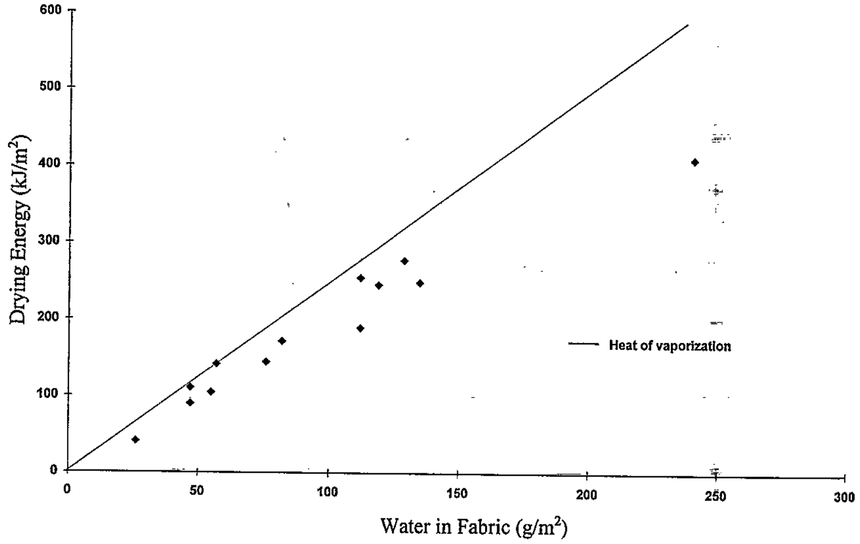

FIGURE 5. The energy required to evaporate water from wet fabrics is linearly related to the amount of water initially in the fabric and agrees well with the heat of vaporization for water.

temperature by evaporation, so that heat could come from the ambient air. Our layer-to-layer wicking studies also suggest that some of the water may not have been in the fabric where it was presumed to be. Some water from the underwear layer might have transferred to the manikin itself where it would extract more energy from the manikin when it evaporated, or to the outer layer, where it would extract more energy from the environment and less from the manikin.

LAYER-TO-LAYER WICKING

We found that there had to be a threshold amount of water in the wet fabric layer before it would wick water to the second, initially dry, layer. However, this amount varied considerably from fabric to fabric, expressed as a percent (80 to 277%) or as the actual amount of water in the fabric. When Spencer-Smith [24] and Adler [1] conducted similar experiments, Spencer-Smith found that his fabrics generally had to hold more than 80% (by fabric mass) of liquid water before the water would be absorbed by an upper dry layer. He concluded that this critical moisture content for liquid water transfer between layers only occurred when there was free water on the upper surface of the wet, lower fabric. Adler also found that layer-to-layer wicking did not take place until there was a critical amount of moisture in the fabric, concluding that this was 110% above the fabric's regain (as measured at 20°C and 65% RH) for the cotton woven fabrics. The polyester and knitted fabrics in her experiment did not wick layer-to-layer at all. We chose fabrics that would wick layer-to-layer, including two knitted fabrics and a woven polyester.

The reproducibility of our results was excellent and pointed to a constant and consistent filling-emptying-filling process. The wet fabric always picked up the same amount of water when immersed and patted dry. If it contained less than that amount of water, the mechanism of water donation to the dry layer would not start. When it did donate water, it always gave up the same amount of water to the upper, initially dry fabric. The upper "dry" fabric always stopped picking up water when a certain limit was reached following the rechargings of the lower, wet fabric. As mentioned above, these amounts of water varied from fabric to fabric. We found the reason to lie in the pore size of the fabrics. By plotting the amount of water in the fabric versus its accumulative pore sizes, we found that when the fabrics were wetted out in water, their pores of 5.8μ and less had been filled (Table V). At this level of wetness and in the first charging, they would start to donate water

TABLE V. Amount of water in various fabric layers expressed as a percent of the conditioned mass of the fabric with the corresponding pore size (μ) for that amount of water in the brackets.

% Water (pore size, μ)	Acetate knit	Acetate plain	Polyester plain	Cotton knit	Cotton duck	Silk plain
Max held by wet layer	110 (5.8)	114 (6.7)	164 (7.6)	277 (5.8)	80 (4.4)	188 (4.3)
Max picked up by dry layer	99 (4.5)	82 (4.1)	85 (3.9)	200 (3.2)	62 (2.7)	126 (2.7)
Left in wet layer after wicking into dry layer	51 (3.4)	65 (3.2)	54 (2.5)	128 (2.2)	43 (2.9)	99 (2.1)

to the upper dry fabric and would stop doing so when the pore size of 2.6μ was reached. After repeated recharging of the bottom wet layer and repeated wicking into the upper dry layer, the dry fabric stopped accepting water when its pores of 3.6μ or less were full. The difference (5.8 versus 3.6μ), we surmised, was due to the fact that the wet fabric had been immersed in water, allowing water into pores that were inaccessible in the wicking process.

Quantitatively, we calculated the space between tightly packed and touching 15μ diameter fibers to be 5.6μ. As well as being the right magnitude, it is also in good agreement with our experimental results. A detailed explanation of the interaction of water in porous materials is given by Luikov [16].

Application of Results

Finally, the question arises—Can our results be applied to the person exercising strenuously and sweating? Several researchers have examined the effect of clothing made from various fibers or constructions on the physiological responses of subjects during work followed by rest.

Holmér [14] compared the heat exchange and thermal insulation of two ensembles, one made from wool, the other from nylon, worn by subjects who exercised either lightly (dry condition) or strenuously (wet condition) for 60 minutes, then rested 60 minutes. He found that there was a significant difference in the physiological and subjective responses between dry and wet conditions, but not between the two fiber types. Further, there was no significant difference between the ratings of temperature and humidity sensations for the wool and nylon garments. The wool garment picked up more water than the nylon garment (245 g versus 198 g) for the wet condition. However, the wool fabric may have been slightly thicker than the nylon fabric, since it was reported to have a slightly greater thermal resistance and would therefore hold more water.

Nielsen and Endrusick [21] evaluated the effect of five kinds of knit structures, all made from 100% polypropylene, on subjects exercising for 40 minutes at 5°C followed by 20 minutes of rest, and then repeated. The thickest knit, a fleece, caused the greatest total sweat production, retained the most moisture, and wetted skin the most. They stated that the hydrophobic polypropylene prevented extensive sweat accumulation in the underwear (10 to 22%), causing the sweat to accumulate in the outer garments. However, based on our research, it may well be that the underwear had reached its water holding capacity, which was only 10 to 22% that of the outer garments. Alternatively, the sweat production might have been localized, funneling through the underwear into the outer garment, where it could wick laterally.

Bakkevig and Nielsen [2] repeated the protocol above, but used low and high work rates with three kinds of underwear (a polypropylene 1 × 1 knit, a wool 1 × 1 knit, and a fishnet polypropylene) worn under wool fleece covered by polyester/cotton outer garments. Total sweat production and evaporated sweat were the same for all three underwear fabrics, but where the sweat accumulated differed significantly. More sweat accumulated in the wool underwear than either polypropylene at both work rates. At the higher work rate, more sweat moved into the fleece layer from both kinds of polypropylene underwear than for the wool. Most likely for the 1 × 1 knits, the thicker wool underwear (1.95 mm) simply holds more water than the polypropylene underwear (1.41 mm) and based on outer layer-to-layer wicking results, needs a greater volume of sweat to fill its pores before it starts to donate the excess to the layer above it. Dolhan [10] found that the fishnet underwear held less water per unit thickness than the conventional underwear materials, Thus, although it was much thicker than the other two knits, its water holding ability was much less, and so would presumably fill and "overflow" readily to the layer above it. Finally, there were no significant differences in the evaporation rate between the wool and the polypropylene 1 × 1 knits at either activity level. This is in keeping with our results that fiber content does not determine evaporation rates.

Conclusions

Our overall conclusion is that for the range of fabrics studied, we found no correlation whatsoever between fiber regain and the amount of liquid water a fabric absorbed or freely picked up. Water absorption, expressed in absolute terms rather than a percent of fabric mass, is best related, of all common fabric properties, to the thickness of a fabric. However, fabric structure, particularly the fiber-enclosed or intrafiber volume, influences the amount of water a fabric picks up (*e.g.*, a fabric with an increasing or decreasing number of weft yarns or a fishnet structure). We also found that properties that are relevant to clothing on an exercising person, such as drying time and energy required to evaporate water from under a dry fabric or to dry the wet fabric, depend on the amount of water a fabric picks up, not fiber type. Layer-to-layer wicking depends on pore sizes and their corresponding volumes. These results appear to be supported by the manikin and human subject experiments.

ACKNOWLEDGMENT

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