Moisture and Heat Transfer in Hybrid Weft Knitted Fabric with Artificial Intelligence

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ABSTRACT: One of the most important properties of clothes is their ability to help the body's thermal system to keep the body temperature in its natural range, even if the environmental conditions or physical activities are outside the body's ideal range. Perspiring is one of the most important effects of physical activities in warm weather for shedding the body's excessive heat. Therefore, the basic requirement of a fabric worn next to the skin is to transfer this moisture to the atmosphere to reach comfort through the avoidance of a feeling of wetness and clamminess and also through the generation of a situation for the best surface evaporation of moisture. The main goal of this study was to achieve a kind of fabric that guarantees comfort for the body by good heat and moisture transport. To achieve this goal, a group of double-surface fabrics containing hydrophilic and hydrophobe fibers were knitted, and their simultaneous heat and moisture transport was evaluated with the help of a perspiration-simulation machine; the results were analyzed as transfer process plots. Also, the transmission of heat and moisture was evaluated for all of the samples by differential modeling as an artificial neural network. Effective parameters on heat and moisture transfer were taken into consideration with modeling and statistical methods. The results were analyzed to find a suitable fabric with optimum comfort. The final results showed that a fabric made of micropolyester filaments and cotton yarns on the bottom and top surfaces, respectively, had the best heat and moisture transfer. © 2009 Wiley Periodicals, Inc. J Appl Polym Sci 114: 1731–1737, 2009

Key words: fibers; modeling; thermal properties

INTRODUCTION

Clothing works as a person's second skin and like an animal's biological system protects the body from harsh environmental conditions. Clothing is an integral part of human life, and an understanding of the role of clothing in the thermal balance of the human body and thermal comfort under steady-state conditions has developed over the past few decades.[1,2]

For years, the operation and duties of clothing have been improved continuously. In this way, one of the most important duties of clothing as an agent between the body and environment is heat and moisture transport. This property of the fabric is known as an effective parameter in human comfort and demands under critical conditions. Therefore, a lot of research has been performed in this area.

During hard activity or in a warm environment, not only the thermal characteristics of clothing but also its moisture properties should be considered as effective parameters of clothing comfort. At a higher ambient temperature or during strenuous bodily activity, the wearer perspires profusely, so clothing worn next to the skin becomes saturated with perspiration. Ideally, the liquid on the body's surface or in the inner layer of clothing should be transferred to the outer layer to keep the skin dry, and the liquid should evaporate from the outer layer to the environment.[3] The heat needed for evaporating moisture is taken up by the fibers so that the body gets a little cooler and feels better and more comfortable. As a result, the layer of fabric worn next to the skin should have several properties. First, it should always keep the skin dry through the wicking transfer of moisture to avoid the uneasy feeling of clamminess and wetness.[4] Second, it should have the ability to evaporate the transferred moisture at the outer layer of the fabric and provide the desired feeling of coolness for the body through heat exchange between the human body and environment.[5] Third, it should prevent the retention of the moisture in layers of fabric to avoid decreasing insulation of the fabric and the resulting phenomenon of afterchill.[6]

Diffusion and wicking are the two ways in which moisture is transferred to the atmosphere. These two are mostly governed by the fiber type (hygroscopicity) of the layers of fabric and its structure, and they can widely affect the thermal and moisture comfort of clothing. The effects of conditioning and fiber type on the wicking rate and total absorption capacity of fabrics have been investigated in past

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research, but the used systems did not have the ability to evaluate the moisture transport rate from one side of the fabric to the other side, and the rate of drying in the inner layer of clothing, which is so important in comfort, has been ignored in transfer studies.[6,7] In the case of moisture transfer, only the transfer between two separate layers of wet and dry fabrics and the effect of their position on each other have been investigated.[8,9]

Lots of mathematical simulations have been performed for fabric heat and moisture transfer,[10–12] but the reality of transfer phenomena cannot be captured by dynamic modeling because of the unreal assumptions and impossibility of correctly evaluating the influencing factors.

With due attention to the fact that a garment's comfort depends on the properties of each of the layers of the fabric and the combination of all the layers, we decided to produce double-surface fabrics with different fibers on the two sides and thus generate different moisture properties for the inner and outer layers. For example, the inner layer of fabric next to the skin should not absorb moisture so that it remains dry, and layers made from synthetic fibers are better than cotton or wool fibers for this situation because their moisture pickup is very low but their capacity for wicking transfer is high. On the other hand, in hot and dry weather, the outer layer of a garment should be made of fibers with a high capacity for moisture retention (e.g., cotton) to keep and evaporate the water for a long time and make the body cooler.

Thus, the goal of this research was to determine some effective parameters for fabric moisture and thermal comfort and then evaluate their effects. To achieve this goal, some two-surface fabrics were knitted from different compounds of fibers, and the capacity for thermal and moisture transfer of selected samples was evaluated with a perspiration-simulation machine; finally, the results were analyzed to find a suitable fabric with optimum thermal and moisture comfort. The transmission of heat and moisture was also evaluated for all of the samples by differential modeling as an artificial neural network.

EXPERIMENTAL

The samples used in this study were knitted by a double-cylinder weft knitting machine. Samples with a double surface have the ability to have two different fibers on each side, so each side can have completely different properties from the other side. To knit the samples, we used different yarns formed with different fibers, different structures, and different fiber finenesses so that we could evaluate the effects of parameters such as the hygroscopicity of each side, fiber fineness, and texturing operation of the yarn on the heat and moisture transport of the fabric. To knit two-surface fabrics with different fibers, four different kinds of yarns were used in different combinations. The used yarns were

1. Cotton spun yarn.
2. Polypropylene (PP) textured yarn.
3. PP flat filament yarn.
4. Polyester (PET) microfilament yarn.

TABLE I
List of Knitted Samples

Sample number	Type of top side	Type of bottom side
1	Cotton	PP
2	Cotton	Micro-PET
3	PP	PP
4	Micro-PET	Micro-PET
5	PP	Cotton
6	Micro-PET	Cotton
7	Cotton	Cotton
8	Cotton	Flat PP

With the use of different yarns, sample fabrics with different compounds were knitted, as shown in Table I. The system used to simulate the perspiration phenomena in the samples and then evaluate their moisture and heat transfer was different from the systems used in other investigations up to now.[3,4,6,7,13,14] In methods used in other approaches, only the fabric's total ability to absorb water was evaluated, but in this study, the quality and rate of moisture transfer from the lower layer to the upper layer of fabrics and also the rate of moisture fall in the lower layer were observed simultaneously. In this way, the rate of drying of the bottom layer of the fabric as an effective parameter of comfort was also observed.

All the experiments were done at 33°C and at a relative humidity of 20%, and each measurement lasted 15–25 min until the sample's temperature and humidity became the same as the environmental conditions.

In the first step of the experiments, samples were cut into 10 × 10 squares, and the lower layer of each fabric was wetted with a spray of 2 mL of pure water. Then, the samples were fitted to a support 1 cm above the ground. An air flow with a rate of 2 m/s was generated on the samples with the help of a fan held onto the samples at an angle of 30° from the horizon. The aim of generating air flow on the samples and the space of 1 cm underneath them was to simulate the usual space between body and clothing and body movement or clothing movement on the skin.

In the next step, digital temperature and moisture sensors were fitted at the top and bottom of the samples and used to record their temperature and humidity at defined intervals. In this way, with the experiment finished for each sample, there were two temperature curves and two moisture curves: a pair of temperature and moisture curves for the top of the sample and another pair for its bottom. By studying these four curves and extracting the measurable factors from them, we could observe the transfer process in each sample.

To study the statistics, each sample experiment was performed 5 times, and then the similarity was demonstrated at the significance level of 95% with the help of one-way analysis of variance (ANOVA) testing. Finally, the transmission of heat and moisture was evaluated for all the samples by differential modeling as an artificial neural network.

RESULTS AND DISCUSSION

We should study the temperature and moisture curves for the top and bottom surfaces of each fabric to observe the heat- and moisture-transfer processes in the samples and also evaluate the effect of each effective parameter, such as the hygroscopicity of the inner and outer layers, fiber fineness, and used yarn type. For example, Figures 1 and 2 show four curves of sample number 1: its bottom surface was made of PP fibers, and cotton fibers were at its top surface. (Such a sample is called PP–cotton hereafter.)

Some parameters that should be studied in the curves are as follows:

1. The initial moisture content. This is sensed on the bottom surface of the fabric because 2 or 3 s pass from the moment the fabric is wetted to the moment of contact between the fabric and sensors, and in this time, the transfer process is started, so less initial moisture content means a greater capacity of the fabric for moisture transfer.
2. The distance between the top and bottom moisture curves. Less distance shows a greater capacity for moisture transfer.
3. The temperature difference obtained between the sample and environment. A greater temperature difference shows a greater capacity of the sample for surface evaporation, and it thus provides more coolness to the skin.
4. The time that passes to reach the ambient conditions. When it takes longer to reach the ambient conditions, the sample is more suitable for providing clothing comfort, whereas for a single perspiring cycle, this kind of fabric will keep the body under comfortable conditions for a longer time.

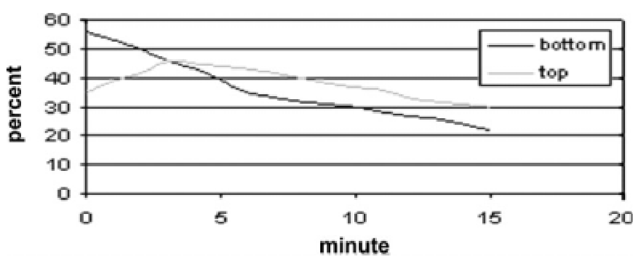

Figure 1 PP–cotton moisture curve.

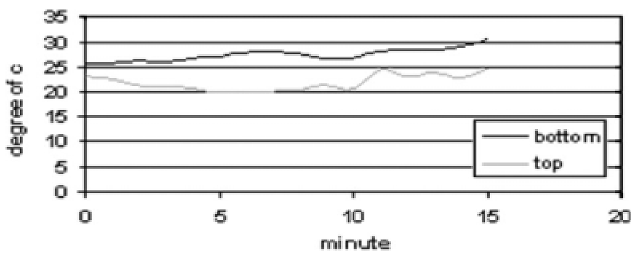

Figure 2 PP–cotton temperature curve.

Effect of the hygroscopicity of the inner and outer layers

As shown in Figure 1, the initial moisture sensed in the bottom layer of the PP–cotton sample was 55%. This means that from the moment that the sample got wet to the time that the sensors came in contact with the sample, around 45% of the water fed to the bottom layer was transferred to the top layer of the fabric. This is a sign of the high transfer ability of this sample. However, Figure 3 shows less ability of transfer for the cotton–PP sample in comparison with the PP–cotton sample.

As shown in Figure 3, the initial moisture content was around 80%, indicating the sample's low capacity for moisture transfer from the bottom layer to the top layer. On the other hand, observing these two figures (Fig. 3 versus Fig. 1), we can see that the distances between the top and bottom curves for the two samples are very different. In the PP–cotton sample, the moisture was transferred from the bottom to the top at a higher rate than in the other sample, and thus the moisture values obtained from the

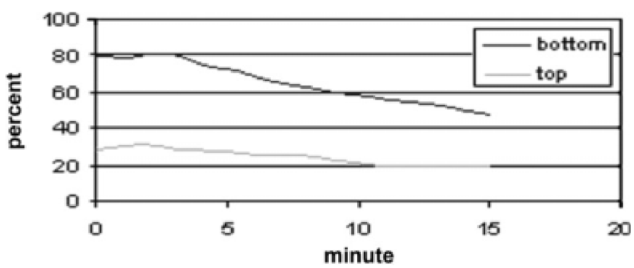

Figure 3 Cotton–PP moisture curve.

two curves for this sample were close to each other; there was less distance in comparison with the cotton–PP sample. The top moisture curve of the cotton–PP sample shows that the moisture was held in the bottom layer of the fabric and did not transfer to the upper layers, so a wearer would have a continuous feeling of wetness and clamminess and would not have the ideal feeling of coolness resulting from surface evaporation.

Temperature curves of the two samples (1 and 5) also show that the minimum temperature obtained in the PP–cotton sample was around 20°C, and it was held for a long time, but the minimum temperature obtained in the cotton–PP sample was 23°C, and it lasted for only a short time of 2 or 3 min. Thus, a dress produced by this kind of fabric would not provide a feeling of suitable coolness for the wearer at high environmental temperatures.

The results obtained for eight samples indicate that in double-surface clothing used in a hot environment or during high body activity, the most clothing comfort is obtained when the inner layer of fabric is made of fibers with low water regain but high wicking ability, such as PP or PET. It is better for the outer layer of the fabric to be made of fibers with high hygroscopicity and water-holding ability, such as cotton, to retain water and thus evaporate it over time and cool the body ideally. In this way, the inner layer of the fabric will always be dry, and clothing moisture and thermal comfort will be provided.

Effect of the fiber fineness

We used sample 2, which was made of micropolyester (micro-PET) fibers in its inner layer and cotton in its outer layer, for studying the effect of fiber fineness on the transfer process.

Temperature and moisture curves of this sample showed that the moisture-transfer and evaporating process in both layers was the same as that in the PP–cotton sample, and the only difference was in their moisture falling slope; this was sharper for the PET–cotton sample than for the PP–cotton sample (Fig. 4). Also, the initial water content sensed in the sample with microfibers was 10% lower than that in the other one (ca. 45%), and this shows the high capacity for moisture transfer in the sample containing microfibers. The only reason for the microfiber's higher transfer ability is the size of the capillary holes made within microfibers. The smaller the capillary pipe is, the stronger and quicker the wicking process will be.[15]

Another important point about microfiber samples is their temperature difference with the environment obtained from the surface evaporation of moisture, which is around 16°C. This means that in this sample, the temperature fell to 17°C (16°C below the ambient condition), and this decrease in the temperature was the highest of all the samples. The ideal coolness provided by this sample was not comparable with that of the other samples, whereas this high temperature difference was held for 17 min in one cycle of perspiration. Therefore, in clothing made of this kind of cloth, the ideal conditions would be provided for a longer time in a perspiration cycle in comparison with the other samples.

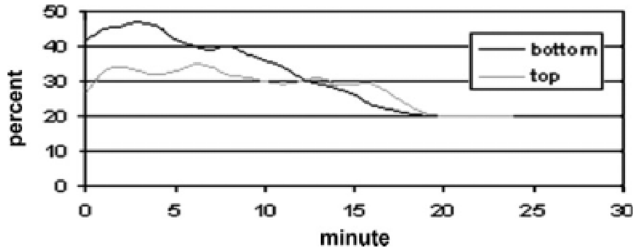

Figure 4 Micro-PET–cotton moisture curve.

The following results were obtained for a micro-PET sample:

1. Higher wicking transfer through finer capillary holes, so the inner layer was always dry.
2. Higher surface evaporation, so there was a greater temperature difference with a warm ambient temperature.
3. Retention of a low temperature for a longer time in comparison with other samples.

Effect of the use of textured or flat yarn

The next sample that was studied was knitted from PP flat yarns in the bottom layer and from cotton in the top surface, and it was compared with a textured PP–cotton sample. As the results of the experiments showed, the sample made of flat yarns had a very open structure in the bottom layer. Thus, in this sample, the wicking transfer from the bottom to the top surface of the fabric was very low, so there was not enough water for evaporation in the top surface; finally, the temperature of this sample would not be ideal for the wearer.

Comparison of eight samples

To compare the results obtained from all the samples, some parameters were extracted from temperature and moisture curves and are described as follows:

1. The slope of the moisture decline in the bottom layer and slope of the moisture increase in the top surface. More negative values of the former and more positive values of the latter when they happened simultaneously in a sample indicated high wicking ability, as shown in samples 1, 2, and 3.

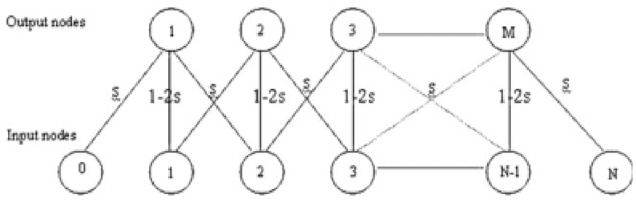

Figure 5 Designed neural network.

2. The maximum and minimum moisture sensed in the bottom layer. Lower moisture in the bottom layer indicated a higher capacity for wicking transfer; this meant a dryer inner layer and more comfort. The best result for this factor was obtained for sample 2, and the worst was obtained for sample 5.
3. The highest temperature difference with the ambient condition. Higher values indicate higher thermal comfort under hot environmental conditions. The best result was obtained for sample number 2, and the worst one was obtained for sample number 5.
4. The mean moisture difference between the top and bottom curves. A lower value indicates higher wicking transfer, as obtained for samples 1, 2, and 4.
5. The cycle time. The longer it took for each experiment to reach the ambient conditions, the more comfort was obtained (sample 2 took 25 min, whereas sample 5 took 15 min).

Summarizing all the results, we can say that ideal clothing comfort obtained through wicking transfer and surface evaporation of perspiration in a hot environment and during high body activity is provided by a kind of fabric that is made of hydrophobic and hydrophilic fibers in its inner and outer layers, respectively. The fabric should also be made from fibers with high fineness in the inner layer, and its inner layer yarns should be textured to transfer water better. These three conditions existed in sample 2 (micro-PET–cotton) simultaneously, so this sample showed the best results in the perspiration-simulation and transfer-evaluation system.

Modeling the transfer process

The computational fluid dynamics (CFD) model has been proposed to model fluid dynamic transfer in fabric, and the partial differential equation (PDE) is applied to solve this kind of model.

A one-dimensional differential propagation equation is defined and is solved with the help of specified boundary conditions and the finite differences method. In this way, the partial differential of propagation is defined as a time-dependent equation in which the propagation in time steps is related to the propagation in space steps with a coefficient of α according to $U_t = \alpha U_{xx}$[16]. U_t is propagation rate in time step and U_{xx} is propagation rate in space step.

α is a coefficient that shows how much a material is disposed to propagation. In other words, the greater α is, the easier the transfer process will be inside the material.

For propagation rate of U and propagation equation of $f(x)$, boundary conditions are defined as follows:

$$\begin{aligned} &U(x,0) = f(x) \\ &U(a,t) = g_1(t) \quad a \le x \le b \\ &U(b,t) = g_2(t) \end{aligned} \tag{1}$$

If the a and b boundary conditions are normalized from 0 to 1, the propagation equation will have time and place steps as follows:

$$\Delta x = \frac{1}{N}, \quad \Delta t = \frac{1}{T} \tag{2}$$

where T is the time period and N is the number of nodes in the numerical differential equation. In this way, a propagation equation of $f(x)$ on the basis of forward differential operators is defined as follows[16]:

$$U_i^{n+1} = sU_{i+1}^n + (1-2s)U_i^n + sU_{i-1}^n \tag{3}$$

where

$$s = \frac{\alpha \Delta t}{(\Delta x)^2}$$

TABLE II
Modeling Results

		Temperature		Moisture	
Sample number	Sample type	α	Error	α	Error
1	PP–cotton	8.05	0.0445	10.35	0.1333
2	Micro-PET–cotton	13.50	0.0970	9.25	0.0553
3	PP–PP	6.45	0.0209	7.80	0.1247
4	Micro-PET–micro-PET	6.00	0.1068	7.05	0.1183
5	Cotton–PP	8.00	0.1107	9.15	0.0803
6	Cotton–micro-PET	5.94	0.0940	10.62	0.0980
7	Cotton–cotton	7.00	0.1200	6.00	0.1120
8	Flat PP–cotton	11.85	0.0671	17.25	0.1099

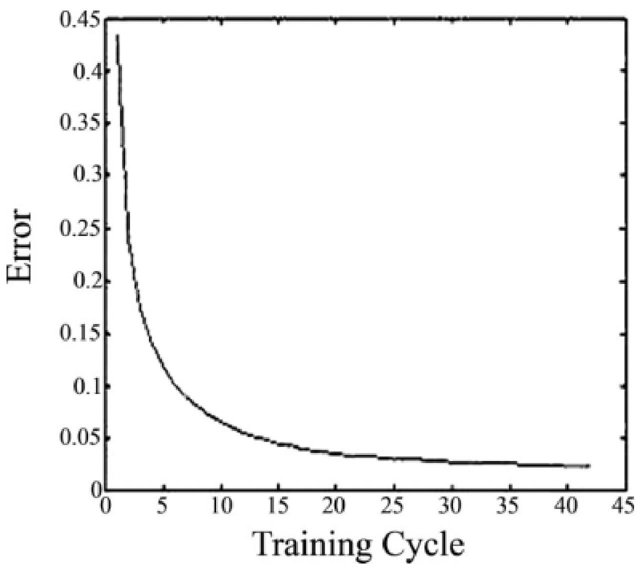

Figure 6 Error reduction curve in a cotton–PP sample.

In this equation, with the use of three nodes for the previous time step (n), it is possible to calculate the characteristics of one node in the next time step of $n + 1$.

In double-surface fabrics, the top and bottom layers are defined as boundary nodes in which temperature and moisture are evaluated in partial time elements of Δt.[16]

With the evaluated data, it is possible to estimate the propagation equation in such a way that the transfer between the top and bottom layers is in agreement with the evaluated data. In all previous research, there has not been any method to estimate an accurate propagation coefficient of α because α has been assumed by a trial and error method in complicated structures of materials such as fabrics. Our goal was to estimate the appropriate α coefficient for each sample. To do this, the propagation equation could be simulated with a neural network of forward-only propagation. A neural network was created on the basis of the results obtained from the experiments. Input data or an X matrix was made from temperature and moisture values for the bottom and top surfaces of the fabric; the number depended on the time of each experiment and was different for each sample.[17]

The connections of network nodes corresponded to the partial differential equation of propagation as forward time-centered spaces (three advanced Euler methods).[16]

In the designed neural network, the bottom layer was defined as input nodes, and the top layer was defined as output nodes (Fig. 5).

The weights on the node connections were the same as the coefficients in eq. (3). For training the network, all the evaluated parameters for each sample were used in such a way that the initial value of s was selected by chance and would be corrected continually in the system training process until the error between the actual data and network's output became minimum. At this time, the s coefficient was defined as the final network's output and was used to calculate each sample's α coefficient. Modeling results are shown in Table II, and Figure 6 shows a sample of error reduction through network training.

According to the results, a greater coefficient with respect to quantity shows a sample's greater ability to change the temperature and moisture content. This ability may result from the wicking ability of the sample or its high evaporation ability. Samples 1 and 2 showed the greater transfer coefficient between modeled samples, and this result was in agreement with those obtained by experiments. The greater α coefficient for sample 8, as stated before, was not due to its wicking ability but was instead due to its loose structure in the bottom layer.

An ANOVA test was performed for the results of the experiments and modeling to study their agreement. As shown in Table III, the parameters for the moisture reduction slope in the bottom layer, the moisture increase slope in the top layer, and moisture difference obtained in a sample as independent parameters have shown a remarkable effect on the moisture-transfer coefficient of α as a dependent parameter.

Also, the parameter of the maximum temperature difference obtained in a sample has shown a remarkable effect on the heat-transfer coefficient of α with a correlation of 95%.

The results obtained from modeling and ANOVA testing of the data indicate agreement with those obtained by experiments.

TABLE III
ANOVA Test Results

ANOVA	Moisture reduction slope in the bottom layer	Moisture increase slope in the top layer	Moisture difference obtained in the sample	Maximum temperature difference obtained in the sample
Moisture α coefficient	8.8×10^{-11}	2.15×10^{-7}	8.03×10^{-5}	—
Temperature α coefficient	—	—	—	0.5×10^{-3}

CONCLUSIONS

From the results obtained with the experiments and modeling, it is understood that in a hot environment and with high body perspiration (e.g., from working or exercising), the most thermal and moisture comfort is provided when the layer worn next to the skin absorbs the moisture from the skin surface and then delivers it to the ambient atmosphere through surface evaporation. Such a situation is more guaranteed with a kind of clothing that is made of hydrophobe fibers such as PP or PET in its inner layer and hydrophilic fibers such as cotton in its outer layer. Also, fiber fineness in the inner layer has a positive effect on the results, and if the yarns are textured, the transfer process will be better.

Among the eight tested samples, the best results were obtained with the sample made from micro-PET fibers in its inner layer and from cotton fibers in its outer layer; it fulfilled all three conditions simultaneously. This kind of fabric has shown the most comfort through ideal wicking transfer and surface evaporation of moisture.

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