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Measurement of the Moisture and Heat Transfer Rate in Light-weight Nonwoven Fabrics Using an Intelligent Model

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Abstract
In this paper, an intelligent model of heat and moisture propagation in light nonwoven fabrics was designed by conversion of a numerical propagation model of a partial differential equation to a feed forward propagation neural network. Propagation coefficients of heat and moisture transfers were estimated from the intelligent model for nonwoven samples containing hydrophilic natural and hydrophobic synthetic fibres. The results presented that the error of the model is acceptable less than 4.7% and 7.9% for estimation of heat and moisture diffusivity coefficients, respectively. The Anova test revealed that while fibre type and fabric thickness affected heat and moisture transfer through the fabric, factors such as surface mass density, heat and the moisture transfer constant were not significant. Also it was found that the optimum transfer rate was observed in the case of samples containing viscose or a viscose and polypropylene blend in the ratio of 60%:40%, respectively.

Key words: *nonwovens, moisture transfer, heat transfer, comfort, neural network.*

Introduction

Cloth is considered to be the second human skin which protects the body against hazardous environmental factors [1]. A more demanding degree of protection is expected from cloth used by patients and children [2]. Thus characterisation of clothing properties in relation to the thermal balance of the human body and thermal comfort under steady-state conditions has been researched during the past few decades [3]. The comfort of cloth is dependent upon factors such as the heat and moisture transfer rate, sweat absorbance and sweat drying capability of the fabric. In this regard the heat and moisture transfer properties of cloth as an agent located between the body and environment become the most important functions of fabric in the dynamic of transfer [4]. Vast amounts of research into these properties of fabric, which are the most influential parameters determining human comfort in critical conditions, have been carried out (for example Barnes et al. and Woo et al. researches) [5, 6].

Fan, 1998, presented that in warm or wet environmental conditions, not only thermal characteristics but also the moisture properties of the clothing worn should be considered as an effective parameter affecting clothing comfort [7]. After that Li, 2005, simulated that at higher ambient temperature or during strenuous bodily activity, clothing worn next to the skin is saturated with body perspiration. Ideally liquid on the body surface or in the inner layer of clothing should be transferred to the outer layer so as to keep the skin dry and that the liquid can evaporate from the outer layer to the environment. Evaporation heating energy required for moisture transfer is taken up by fibres, as a result of which the body becomes both cooler and more comfortable [8]. In 2006, Park described that the cloth not only must allow moisture to be transferred from the skin, thus keeping the skin dry, but also must be capable of evaporating the moisture transferred from its outer layer so as to cool the skin and increase the level of comfort as described by the wearer [9]. It is vital for moisture to pass freely along the thickness of the fabric. Hindrance in the free passage of moisture can reduce the insulation capacity of the fabric, which in turn leads to the after chill phenomenon [10]. Moisture is transferred to the atmosphere by diffusion and wicking mechanisms, both of which are dependent on the structure, fibre composition and hygroscopicity of the layers of fabric. These factors can profoundly affect the thermal and moisture transfer ability of clothing. In thin fabrics in comparison to wicking, diffusion, which is controlled by the porosity, mass density and fibre composition of the fabric, is the predominate mechanism [11].

The effect of conditioning and fibre composition in relation to the moisture transfer rate and total absorption capacity of fabrics has been investigated in previous researches. These studies unsuccessfully attempted to evaluate the rate at which moisture is transferred from one side of the fabric to the other . Furthermore the drying rate at the inner layer of clothing, which directly affects comfort, was ignored in these researches [12]. As far as moisture transfer is concerned only the transfer between two separate layers of wet and dry fabrics and the effect of their relative position has been investigated. Despite employment of lightweight nonwoven fabrics in critical applications, the above analysis has not been applied to these thin fabrics.

In spite of researches between 1984 to 2004 for mathematical simulation in the field of fabric heat and moisture transfer, no dynamic modelling capable of predicting the parameters involved in these phenomena is available. This is due false assumptions and lack of sound evaluation of influencing factors [13 - 15].

From the results of previous researches, we can state that fibre properties and composition are very effective in heat and moisture transfer through nonwoven materials [16 - 20]. Considering this matter, in the present work the effect of the fibre composition and physical properties of thin nonwoven layers was investigated. Additionally the coefficient of diffusivity, which has hitherto remained an unsolved parameter in the field of the moisture and heat transfer of nonwoven materials, was investigated. It is well known that these classes of fabric inherently lack regularity of structure in a steady- state. Thin nonwoven fabrics are used in clothing for highly sensitive skin patients and children, where the rate of heat and moisture transfer are vitally important.

From an experimental point of view, the tools employed for moisture and heat transfer measurement in the previous researches between 1984 and 2005 were

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based on the water absorption mechanism using water sprayed on the inner layer of the clothing system [21 - 29]. These tools cannot be considered suitable for online and simultaneous measurement of evaporated moisture and heat transfer. Therefore a novel apparatus is presented in this research which is more similar to the real condition of cloth.

The aim of this research was to establish the influence of parameters affecting the moisture and thermal comfort of thin nonwoven fabrics. In order to achieve this aim, various samples of commercially available nonwoven thin fabrics used as patient and children's clothing containing a blend of fibres were used. The online moisture and heat transfer ability of the samples was evaluated under simulated perspiration conditions. Analyses of results were used to engineer suitable fabric with optimum thermal and moisture comfort. In order to minimise experimental errors, diffusivity coefficients of heat and moisture were evaluated for all of the samples, carried out by conversion of differential equations of heat and moisture to feed forward neural networks as modified intelligent models of heat and moisture propagation.

Method & material

Model and analysis

Artificial neural networks (ANNs) are defined by their structures (nodes and connections) in various layers (one layer, two layers and more), the activation function of each node and the training rule. Feed forward artificial neural networks (FFANN) are mainly two or more layered networks. In a FFANN the first layer is the primary layer, in which coefficients for connections can be constant or be updated according to the training rules designed [32]. In a standard single layer feed forward ANN, the training rule is according to that in which new weights are updated from previous ones by affecting the error between results of the network and targets estimated as "$W_{new} = W_{old} + \beta(t - y)x$ ", where "β", "t", "y" and "x" are the training rate between 0 and 1, target data, estimated output and input of the network, respectively. In general, the form of layers of the FFANN network can be more than a single layer . Each layer is defined as an independent network with a specific structure, but the training rule is the same for all the network layers. In this research, a FFANN was created based on results obtained from the experiments. Input data or the "X" matrix was made from temperature and moisture values for the bottom and top surface of the fabric, the number of which depending on the time of each experiment, being different for each sample [33].

Each differential propagation equation is defined and can be solved in specified boundary conditions by the finite differences method. In this way the partial differential equation (PDE) of propagation is defined as a time dependant equation in which the propagation in time steps is related to that in space steps with a coefficient of "α". According to the equation "$U_t = \alpha U_x$". "α" is the diffusivity coefficient that shows how much a material or energy is disposed to propagation. The physical parameter which is modelled, such as the heat or moisture, is described as the "U" parameter, where parameter "U_t" means the rate of heat or moisture in a time of t, and parameter "Uxx" means that in each location. In other words, the greater the "α", the easier the transfer process will be inside the material, or it is the rate of propagation.

Boundary conditions are defined as below:

$$U(x,0) = f(x)$$
$$U(a,t) = g_1(t) \qquad a \le x \le b \tag{1}$$
$$U(b,t) = g_2(t)$$

If boundary conditions "a" and "b" are normalised from 0 to 1, the propagation equation will have time and place steps as below, in which "T" is the time period and "N" the number of nodes in the numerical differential equation [34].

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

Heat and moisture transfer as a transient condition is the response of a moistural-thermal system which changes in time. The same methodology for a steady state problem can be employed, but the temperature and element equilibrium relations depend on time. The objective of the transient analysis is to calculate the temperatures with respect to time.

To analyse the rate of heat and moisture transmission in transient conditions, it is not possible to use simple convectional models. Also heat and moisture transfer in thin nonwoven materials is very irregular, therefore the rate of heat and moisture transfer - diffusivity coefficients - cannot be obtained by a simple experiment with a hot plate or mass transfer tool. Therefore an artificial neural network was applied to analyse the transient heat transfer and to estimate thermal diffusivity.

This method is the forward propagation of the 3-3 weighted explicit classic method. The time is explicitly forward and the space is centred. In this method, from the basic rule of $U_t = \alpha U_x$, ***Equation 3*** is given as ***Equation 4*** [35].

$$\frac{U_i^{n+1} - U_i^n}{\Delta t} = \theta\left[\frac{U_{i-1}^n - 2U_i^n + U_{i+1}^n}{(\Delta x)^2}\right] + \\ + (1-\theta)\left[\frac{U_{i-1}^{n+1} - 2U_i^{n+1} + U_{i+1}^{n+1}}{(\Delta x)^2}\right] \tag{3}$$

$$-\theta s U_{i-1}^{n+1} + (1 + 2\theta s)U_i^{n+1} + \\ -\theta s U_{i+1}^{n+1} = (1-\theta)sU_{i-1}^n + \\ + (1 - 2(1-\theta)s)U_i^n + (1-\theta)sU_{i+1}^n \tag{4}$$

where:

$$s = \frac{\alpha(\Delta t)}{(\Delta x)^2} \tag{5}$$

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

Values of moisture and temperature is represented as "U" and "θ" is a balance factor for adjusting the weight of forward and backward calculation of the PDE equation.

This equation is solved in a matrix format. If ***Equation 5*** is converted to a system of equations, it is possible to solve that system by applying the inverse matrix of forward coefficients (P^{-1}) by multiplying the secondary coefficient (V); this method is demonstrated as ***Equation 6***.

$$PU^{n+1} = VU^n \tag{6}$$

In any non-woven layer, the inner and outer sides are defined as boundary nodes, in which the temperature and moisture percent are evaluated in partial time elements of Δt separately by two equations.

With the evaluated data, it is possible to estimate the propagation equation in such a way that the transfer between the outer and inner sides is in agreement with the evaluated data for both the temperature and moisture percent. In this research, to estimate diffusivity coefficients of heat and moisture, the propagation equations were simulated with a neural network of forward-only propagation. Two neural networks were created on the basis of the results obtained from the experiments for heat and moisture separately. Input data or an X matrix were made from temperature values for the outer and inner surfaces of the layer; the number depended on the time of each experiment and was different for each sample.

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

In the neural networks designed, the inner side was defined as input nodes, and the outer side was defined as output nodes. As the structure of the neural networks designed were of a hyper dimensional nature, it was not possible to sketch them.

The weights on the node connections were the same as the coefficients in ***Equation 6***, which is weight matrix "$W = P^{-1}V$". As the neural network topology is hyper dimensional, demonstration of the network's structure is not possible.

The algorithm calculation method is as follows:

Step 1: Initialising primary values for "S" and "θ";
Step 2: Entering the data for inner and outer parts of the fabric as temperature and moisture from inner and outer sensors as U_0 and U_M;
Step 3: Calculation of equation system of ***Equation 3*** in matrix form of equation 6 from times 0 to N and layers 0 to M;
Step 4: Calculation of the difference between target values (experimental data for outer part) and values calculated (output of network) as parameter "e" or error of the network;
Step 5: Reset of parameter "S" by increasing/decreasing the formula $S_{new} = S_{old} + 0.1e$;
Step 6: Go to step 2 if "e" is greater than 0.01;
Step 7: Calculate "α"

Measurement apparatus

In order to stimulate the perspiration and dynamic transfer of heat and moisture, an apparatus was designed and developed, as shown in ***Figure 1***. This device stimulates the vaporisation of water from the skin surface. The amount of heat and moisture on both sides of the test sample was measured and recorded. The perspiration stimulator was equipped with a heating element capable of stimulating human body temperature. The heating element can precisely generate a temperature of 35 °C. A water atomiser using distilled water was also used, generating small drops of water like fog, not vapour, such as on the skin. Four electronic heat and moisture controllers were used. The switching signals for the operation of the heating element and water atomiser required were provided by the controllers. Test samples were mounted in perfectly flat form between the holding jaws. Thermal and moisture sensors were located on both sides of samples and in full contact with them. Insulated tiny surfaces were mounted on the surfaces of the sensors not in contact with the sample to ensure the measuring system. In order to minimise the data reading error, jaws were designed with an internal diameter of 65 mm. One pair controller comprising one of each type was used on each side of the mounting jaws in tandem. Each pair measures and controls the heat and moisture on each side of the test samples. A two section open-ended metallic cylinder with an internal diameter of 120 mm and length of 300 mm was used as testing capsule. The test sample is placed in the middle. At one end of this assembly atomized water droplets that can only be transferred through the test sample are fed to the capsule through a polyethylene pipe. The heating element is located on the pipe. Thus the ambient temperature of discharged water droplets from the atomiser is increased to the level required. The open end of the capsule assembly is in contact with ambient air. The analogue outputs of the controllers were digitalised using a conventional A/D converter and relevant software. Data acquisition and storage were carried out at variable but defined intervals. In order to be able to make a highly reliable comparison of data recorded from the two sets of controllers, these were calibrated.

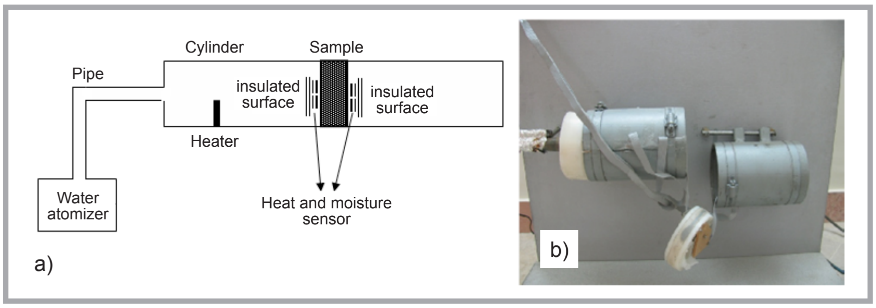

Figure 1. *Schematic drawing (a) and photograph (b) of apparatus for simulation of heat and moisture transfer similar to skin.*

80 × 80 mm experimental samples solely composed of either hydrophobic or hydrophilic fibres or their blends were cut from larger pieces of fabric. The samples were conditioned for two hours at a relative humidity of 48% and temperature of 35 °C, as determined from real conditions of human skin [30]. Samples were mounted on the jaws under a tensionless condition and excess peripheral parts were cut. An identical thermal and moisture state was followed for all of the test samples, which enabled reliable comparison to be made between the results. Attention should be drawn to the fact that in the present experiments, stimulation is faithful to the actual state, where, unlike all testing devices used in the previous research works, the perspiration process is periodical and not continuous, meaning that perspiration is generated according to skin temperature; therefore, this phenomenon does not continuously occur. In the actual situation, as the body temperature rises, sweating occurs, which is followed by perspiration, resulting in the cooling of the heated body. This cycle repeatedly takes place. Additionally in the previous works, reviewed in introduction, moisture transfer was stimulated in the liquid phase due to the formation of dew on one side of the experimental samples. It must be emphasised that in actual circumstances moisture transfer takes place in the gas phase. Thus the atomisation of water used in the present work results in the transfer of moisture under gas phase conditions without the formation of dew on the sample surface, which very nearly corresponds to the actual perspiration condition. The experiments were designed in such a manner that heated

Table 1. *Specification of spun lace samples.*

Code	Sample	Thickness, μm	Surface mass, g/m^2
PV-80/20	Polyester-Viscose (80:20)	190 ± 2.8	38 ± 2.1
PCV-80/10/10	Polyester-Viscose-Cotton (80:10:10)	210 ± 2.6	35 ± 2.5
PCV-70/15/15	Polyester-Viscose-Cotton (70:15:15)	220 ± 1.7	40 ± 2.3
PV-50/50	Polyester-Viscose (50:50)	230 ± 2.0	40 ± 2.4
PV-40/60	Polypropylene-Viscose (40:60)	310 ± 3.5	50 ± 2.3
V	Viscose	360 ± 2.1	50 ± 2.1
C	Cotton	520 ± 2	50 ± 2.2

atomised water droplets were poured at once into the cylindrical capsule, the unique design of which only allows the transfer of the atomised water droplets. Therefore the controllers can operate very accurately in an adjustable range. An auxiliary pair of identical controllers was placed at a distance of 70 mm upstream of the capsule, which enhanced the accuracy of the data collected. In the absence of the former, the internal pairs of controllers must function as both a controlling and signal changing unit. The 70mm distance between the auxiliary and controlling units allows the transfer of moisture through the fabric in a controlled manner.

Experimental works

In this work non-woven fabrics manufactured by spun lace technology were used. We experimented with samples of two and four layers because these nonwovens are used in a layered form for patient and chilled covers.

Details of the spun lace samples used are depicted in ***Table 1***. The samples are commonly used in patient and children's apparel, tissues and cover layers, which are widely produced in the spun lace fabric industry.

This type of fabric is referred to as a fibre web due to its light weight and negligible thickness. The fabric thickness was measured at an accuracy of 10 micrometers using a "HANS BEER AG" thickness tester. Fibre specifications are shown in ***Table 2***.

Table 2. *Fibers specifications of spun lace samples.*

Fiber	Length, mm	Finness, dtex
Polyester	38	1.4
Viscose	38	1.6
Viscose (in pure viscose layer)	38	2.4
Polypropylene	40	2.2
Cotton	38.1 ± 5.2	1.7 ± 0.3

Result & discussion

Samples of spun lace nonwovens of two and four layers were used in experiments. Initially the gas permeability rate and heat transfer constant of the samples were determined by Dedov's method based on Darsy's law, as shown in ***Table 3*** [31]. Heat and moisture transfer properties of the sample under sweat perspiration from human skin were stimulated. The time in which each sample was under stimulation was used in the preparation of time-based charts. Experimental data and results generated by the model were compared.

For training the networks, all the parameters evaluated for each sample were used in such a way that the initial value of "s" was selected by chance. A suitable weight of "θ" was estimated by the trial and error method 3/4.

The value of "*s*" was 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. Results of diffusivity curvatures estimated from the FFANN model and experiments are very similar, a sample of which is presented in ***Figure 2***. Also FFANN modelling results are shown in ***Table 3*** for heat and moisture diffusivity coefficients. Results present that the FFANN model estimated diffusivity coefficients of heat and moisture with good accuracy, where the maximum error for the model is less than 8%. The mean estimation error was found to be about 5% for most samples.

Results generally indicate that the rate and time required for non-woven fabric to dry are dependent on factors such as fabric permeability and the rate of moisture evaporation from the fibre (***Figure 3***).

Fabric dries due to the initial evaporation of water present on the surface . Moisture flow and distribution induces transfer of water entrapped within the fabric body to the surface. This cycle is repeated until the fabric is considered to be dry [4, 30]. Fabrics composed of a blend of polyester and viscose fibres dry more quickly than fabric composed of natural fibres, which is due to the fact that the latter not only is thicker but also contains hydrophobic fibres. Thus more moisture is retained by fabric made using natural fibres. It is a well known fact that fibres enjoy higher thermal conduction than still air [36]. Generally resistance to thermal conduction offered by fibre assemblies largely depends on the volume of the still air entrapped in the voids within the fabric, which explains the reason behind the high insulating power of the thick fibrous assemblies. Fabric thermal conduction is a function of its thickness, porosity and temperature of the two sides of the fabric. Results of statistical tests confirm the effective influence of the fabric thickness on the distribution coefficient. The volume of the sample increases as the fabric thickness is increased. Thus fabric water absorption is enhanced, which in turn leads to improved moisture transfer. Moisture absorption in high polyester content fibrous assemblies is low. Moisture and thermal transfer in these fabrics occurs at a rapid rate. This is also confirmed by the value of distribution coefficient obtained from numerical solution. The existence of a high amount of polyester fibres is responsible for low moisture absorption despite the general ability of synthetic fibres to dry rapidly. Therefore the low distribution coefficient observed must be related to the initial low absorption. More moisture is absorbed as the cellulosic proportion of the fibre blend is increased [30]. Additionally since the heat conduction coefficient is low then a relatively long time is needed for heat to be transferred. Samples containing an equal proportion of hydrophilic and hydrophobic fibres from a moisture transfer point of view lie between those composed of either hydrophilic or hydrophobic fibres. Fabric tends to dry over a longer period of time as the hydrophobic content of the fibre blend is increased, which explains why the drying time in the sample containing 40% polypropylene and 60% viscose is longer. It was also observed that this sample, despite the low heat conduction coefficient of polypropylene and viscose fibres, took longer to cool down and tended to

Table 3. Gas permeability rate & heat transfer constant and heat & moisture diffusivity coefficients for 2 & 4 layered samples.

Sample number	Sample type	Gas permeability rate, 10^{-4} m^3/s		Heat transfer constant, 10^{-10} m^2		Heat		Moisture	
		mean	standard deviation	mean	standard deviation	α, mm^2/s	error, %	α, mm^2/s	error, %
1	Polyester-viscose (80:20) - 2 layers	3.21	0.15	2.67	0.14	0.395	2.8	1.665	6.0
2	Polyester-viscose-cotton (80:10:10) - 2 layers	3.53	0.15	3.23	0.12	0.492	3.4	1.974	4.5
3	Polyester-viscose-cotton (70:15:15) - 2 layers	2.82	0.13	2.72	0.11	0.593	3.5	2.127	5.2
4	Polyester-viscose (50:50) - 2 layers	2.71	0.09	2.73	0.11	0.621	2.8	2.710	7.9
5	Polypropylene-viscose (40:60) - 2 layers	2.13	0.25	2.86	0.17	1.135	4.0	5.573	5.5
6	Viscose - 2 layers	2.21	0.19	3.48	0.18	1.416	1.8	6.751	4.3
7	Cotton - 2 layers	1.56	0.07	3.43	0.21	2.974	1.9	13.80	4.0
8	Polyester-viscose (80:20) - 4 layers	1.71	0.05	2.76	0.12	1.654	3.4	5.768	5.5
9	Polyester-viscose-cotton (80:10:10) - 4 layers	1.92	0.05	3.42	0.14	2.119	4.7	7.412	3.7
10	Polyester-viscose-cotton (70:15:15) - 4 layers	1.66	0.04	3.02	0.06	2.302	2.5	7.843	5.2
11	Polyester-viscose (50:50) - 4 layers	1.52	0.07	3.00	0.08	2.643	2.1	8.086	5.5
12	Polypropylene-viscose (40:60) - 4 layers	1.22	0.01	3.14	0.07	4.015	1.6	13.40	7.3
13	Viscose - 4 layers	1.21	0.05	3.74	0.10	6.195	2.4	16.80	8.2
14	Cotton - 4 layers	0.83	0.02	3.59	0.13	11.231	1.8	53.42	5.1

keep the heat longer. It was noted that in samples containing polyester or polypropylene and viscose the distribution coefficient was lower than for those obtained containing only cotton or viscose fibres, despite the expectation that in the samples made using a blend of hydrophobic and hydrophilic fibres absorption and transfer will be high. Results confirmed that such an expectation cannot be materialised. It was concluded that the distribution coefficient in the compounded samples was low. It is anticipated that the situation at the interface between the two types of fibres can influence transfer properties of the sample. It was noted that the coefficient of distribution largely depended upon the condition at the interface of the two types of fibres within the sample. It was also observed that the sample made solely of cotton or viscose fibres exhibited a higher coefficient of distribution, which contributed to the natural ability of these fibres to absorb moisture, being a positive factor as far as heat conduction is concerned. Therefore their improved coefficient of distribution is due to the amount of moisture absorbed by the fibres. It was found that the transfer constant in samples with cotton or viscose fibres was higher only than those of other samples containing a blend of fibres. In the former samples the fibre composition and porosity results in not only higher absorption but also the moisture absorbed is retained by the fibres for a longer period of time, which is exactly the reverse in the case of the sample containing polyester fibres. High values of the distribution coefficient in the samples made solely of polyester fibres and the low gradient of the relevant curve are indicative of a large amount of moisture transferred and a low rate of transfer, respectively. Results showed that the sample thickness influences the coefficient of distribution. The thickness of fibrous assemblies can be varied by the fibre orientation or mass per unit area. Moisture absorption is improved when the thickness of the sample in relation to the weight is increased. The increase in the value of the coefficient of distribution observed can be attributed to increases in fabric thickness. In spun lace fabric composed of polyester or a blend of viscose and cotton, fabric permeability is adversely proportional to the fabric weight, which is due to the reduction in fabric porosity and increase in air resistance presented by the fabric. Comparison of the results confirmed that generally polyester samples exhibit a higher coefficient of distribution than those made of either viscose or cotton fibres. The effect of the thickness, fibre type and surface density of the samples on their diffusivity coefficients was considered using statistical analysis. The ANOVA test presented that the thickness of the layer and fibre type affected heat and moisture transfer (P value < 0.05 & R > 0.97), but the surface mass density and heat and moisture

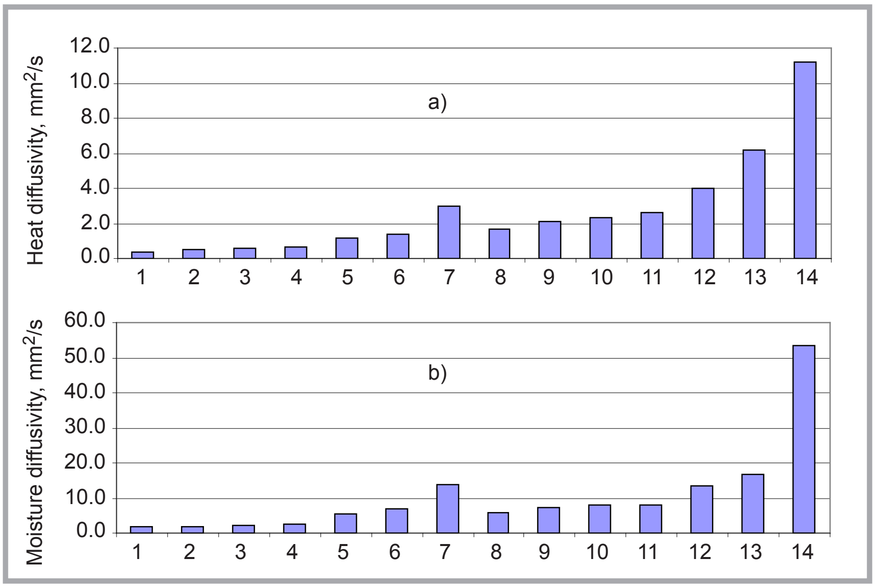

Figure 2. *Comparison graph of heat (a) and moisture (b) diffusivity for nonwoven samples; 1 - Polyester-viscose (80:20) - 2 layers, 2 - Polyester-viscose-cotton (80:10:10) - 2 layers, 3 - Polyester-viscose-cotton (70:15:15) - 2 layers, 4 - Polyester-viscose (50:50) - 2 layers, 5 - Polypropylene-viscose (40:60) - 2 layers, 6 - Viscose - 2 layers, 7 - Cotton - 2 layers, 8 - Polyester-viscose (80:20) - 4 layers, 9 - Polyester-viscose-cotton (80:10:10) - 4 layers, 10 - Polyester-viscose-cotton (70:15:15) - 4 layers, 11 - Polyester-viscose (50:50) - 4 layers, 12 - Polypropylene-viscose (40:60) - 4 layers, 13 - Viscose - 4 layers, 14 - Cotton - 4 layers.*

transfer constant were not significant (P value > 0.05 & R < 0.6).

Conclusion

Experimental data were used for evaluation of the heat and moisture transfer rate through the samples. An intelligent model of heat and moisture propagation was designed by converting a numerical propagation model of the partial differential equation to a feed forward propagation neural network. When the heat and moisture propagation were connected together, it was clear that these parameters were propagated and measured together at the same time; therefore, coefficients of heat and moisture propagation were estimated from experimental data. The results of the model were acceptable estimations of heat and moisture diffusivity coefficients. The results of the model had an acceptable error of estimation less than 4.7% and 7.9% for estimation of heat and moisture diffusivity coefficients. It is suggested that this modelling method can also be used for other kinds of transport problems in complex materials .

Besides the modelling method, heat and moisture factors were investigated as an extra evaluation. Results present that the cotton layer had high moisture diffusivity, but it has slow drying. Blended layers with more hydrophilic fibres such as polyester/viscose (80:20) slow diffusion. However, viscose and viscose/polypropylene (60%:40%) have an optimum transferring rate when both the diffusion and drying mechanisms work together.

References

1. Fanger PO. *Thermal comfort: Analysis and Applications in Environmental Engineering*, McGraw Hill, NY, 1972.
2. Li Y. The Science of Clothing Comfort. *Textile Progress* 1999; 31, 1/2.
3. Lee S, Obendorf, K. Barrier effectiveness and thermal comfort of protective clothing materials. *Journal of the Textile Institute* 2007; 98, 2: 87-97.
4. Fohr JP, Couton, D. Dynamic heat and water transfer through layered fabrics. *Textile Research Journal* 2002; 72, 1: 1-12.
5. Barnes JC, Holcombe BV. Moisture Sorption and Transport in Clothing During Wear. *Textile Research Journal* 1996; 66, 12: 777-786.
6. Woo S, Shalev I, Barker L. Heat and moisture transfer through nonwoven fabric Part I: heat transfer. *Textile Research Journal* 1994; 64, 3: 149-162.
7. Li Y, Holcombe BV. Mathematical Simulation of Heat and Moisture Transfer in a Human-Clothing-Environment System. *Textile Research Journal* 1998; 68, 6: 389-397.
8. Fan J, Cheng X. Heat and Moisture Transfer with Sorption and Phasechange Through Clothing Assemblies, Part II: Theoretical modeling, simulation, and comparison with experimental results. *Textile Research Journal* 2005; 75, 3:187-196.
9. Park J. Effect of moisture absorption of clothing on pitching speed of amateur baseball players in hot environmental conditions. *Textile Research Journal* 2006; 76, 5: 383-387.
10. Meeren PV, Cocquyt J, Flores S. Quantifying Wetting and Wicking Phenomena in Cotton Terry as Affected by Fabric Conditioner Treatment. *Textile Research Journal* 2002; 72, 5: 423-428.
11. Patnaik A, Rengasany RS, Ghosh A. Wetting and Wicking in Fibrous Materials. *Textile Progress* 2006; 38, 1.
12. Wang JH, Yasuda H. Dynamic Water Vapor and Heat Transport Through Layered Fabrics, Part I: Effect of Surface Modifications. *Textile Research Journal* 1991; 61, 1: 10-20.
13. Adlen MM, Walsh WK. Mechanisms of Transient Moisture Transport Between Fabrics. *Textile Research Journal* 1984; 54, 5: 334-343.
14. Ramachandra T, Kasavaraja N. A Study on Influencing Factors for Wetting and Wicking Behavior. *IE Journal-Tx* 2004; 84: 37-41.
15. Yoo S, Barker RL. Moisture Management Properties of Heat-resistant Workwear Fabrics, Effects of hydrophilic finishes and hygroscopic fiber blends. *Textile Research Journal* 2004; 74, 11: 995-1000.
16. Woo S, Shalev I, Barker L. Heat and moisture transfer through nonwoven fabrics Part II: Moisture diffusivity. *Textile Research Journal* 1994; 64, 4: 190-197.
17. Yoon HN, Buckley A. Improved comfort polyester Part I: Transport properties and thermal comfort of polyester/cotton blend fabrics. *Textile Research Journal* 1984; 54, 5: 289-298.
18. Mao N, Russell SJ. Directional permeability in homogeneous nonwoven structures Part I: the relationship between directional permeability and fiber orientation. *Journal of the Textile Institute* 2000; 91, 2: 235-243.
19. Mohammadi M, Banks-lee P. Determination radiative heat transfer through heterogeneous multilayer nonwoven materials. *Textile Research Journal* 2003; 73, 10: 896-900.
20. Obendorf S, Smith J. Heat transfer of nonwoven insulation material. *Textile Research Journal* 1986; 56, 9: 691-696.
21. Harnel PR, Mehta PN. A Survey and Comparison of Laboratory Test Methods for Measuring Wicking. *Textile Research. Journal* 1984; 54, 7:471-478.
22. Hu J, Yeung WK, Womg W, Xu W. Moisture Management Tester: A Method to Fabric Liquid Moisture Management Properties. *Textile Research Journal* 2005; 75, 1: 57-62.
23. Adler M, Walsh W. Mechanism of moisture transport between fabrics. *Textile Research Journal* 1984; 54, 5: 334-343.
24. Sherurell DM, Spivak SM, Hollies NR. Dynomic surface wetness of fabric in rrelation to clothing comfort. *Textile Research Journal* 1985; 55, 7: 394-399.
25. Li Y, Holcombe BV. A two stage sorption model of coupled diffusion of moisture and heat in wool fabrics. *Textile Research Journal* 1992; 62, 4: 211-217.
26. Yoo HS, Hu YS. Effect of heat and moisture transport in fabrics and garments determined with a vertical plate sweating skin model. *Textile Research Journal* 2000; 70, 6: 542-549.
27. Finn JT, Sagar JG. Effect of imposing a temperature gradient on moisture vapor transport through water resistant breathable fabrics. *Textile Research Journal* 2000; 70, 5: 460-466.
28. Fukazawa T, Kawamura H. Water vapor transport through textiles and condensation in clothes at high altitudes-combined influence of temperature and pressure simulating altitude. *Textile Research Journal* 2003; 73, 8: 657-663.
29. Fan J, Cheng X. Heat and moisture transfer with sorption and phase change through clothing assemblies, Part II: experimental investigation. *Textile Research Journal* 2005; 75, 2, 99-105.
30. Pan N, Gibson, P. *Thermal and moisture transport in fibrious materials*. Woodhead publishing Inc., England, Cambridge, 2006.
31. Dedov AV. Materials science: evaluation of the air permeability of needle punched materials. *Fibers Chemistry* 2006; 38, 3: 189-197.
32. Fausett L. *Fundamentals of Neral Network*. Prentice Hall, 1994
33. Krose B, Smagt P. *An Introduction to Neural Networks*. 8th ed The University of Amsterdam, Amsterdam, Netherland, 1996.
34. Smith GD. *Numerical Solution of Partial Differential Equations: Finite Difference Method*. Oxford Mathematical Handbook, 1986.
35. Mokhtari M, Semnani D, Sheikhzadeh M. Moisture and Heat Transfer in Hybrid Weft Knitted Fabric with Artificial Intelligence. *Journal of Applied Polymer Science* 2009; 114: 1731-1737.
36. Farnworth B, Lotens WA. Variation of water vapor resistance of microporous and hydrophobic films with relative humidity. *Textile Research Journal* 1990; 60, 1: 50-53.

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