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Prediction of heat transfer and air permeability properties of light weight nonwovens using artificial intelligence

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Effects of pore sizes and distribution of pore sizes of light weight spunlace nonwovens on the heat transfer and air permeability of these fabrics have been studied. Image analysis has been applied to extract the geometrical features of the cross-section of spunlace samples (pore sizes and distribution of pore sizes) at the different layers in the thickness direction. A neural network model is also developed for the prediction of heat transfer and air permeability with respects to structural properties of light weight nonwovens. Results show that the increase in pore sizes and distribution factor of pore sizes increases the air flow rate and heat transfer properties of the nonwoven fabrics respectively. The neural network model also predicts the air permeability and heat transfer of nonwovens in terms of the measured geometrical properties.

Keywords: Air permeability, Heat transfer, Neural network, Pore size distribution, Spunlace fabrics

1 Introduction

Spunlace and hydro-entanglement are the most frequent terms applied to webs consolidated by high-velocity water jets. Carded dry laid webs are the common source of spunlace webs. The essential steps in producing hydro-entangled nonwovens are including precursor web formation, web entanglement through water jet application, de-watering and web drying and winding[1]. These fabrics are widely used in wipes, bacteria–proof cloth, surgical fabrics, interlining of garments, patient and chilled covers, apparel and tissues.

Pore structure of nonwovens has a major role in determination of heat, humidity transfers and air permeability property[2]. Simmonds *et al.*[3] have investigated the spun bonded fabrics to develop a model for producing nonwovens with the preset pore size specifications. In another research, Rawal[4] has provided a geometrical probability model to predict the distribution of pore sizes in nonwoven materials. Wiegmann and Becker[5] also introduced a method for characterization of the pore structure of nonwovens based on a virtual model.

Nonwoven materials have 3D heterogeneous structures and fibres are arranged at the preferential direction in them. The air permeability of such structures is largely dependent on orientation of the aligned fibres. Berklap[6] investigated the effect of entanglement process on the air permeability of light weight spunlace fabrics. Baczek[7] showed that increasing the mass density will lead to decrease in air permeability of spunlace fabrics. Dedov[8] presented a method to determine the air permeability rate of needle-punched nonwovens based on Darcy's law.

Thermal properties of the apparel affect most of its characteristics, such as water absorption, air permeability and sweat excretion[9]. Fan *et al.*[10] indicated that in open structure nonwovens with higher diameter fibres, heat transfer is mainly done by radiation mechanism. Obendorf *et al.*[11] have demonstrated that parameters of fabric structure, especially thickness, porosity and constitutive fibre properties, can be effective on the heat transfer. Pourdeyhimi *et al.*[12] showed that heat transfer phenomenon depends on fibre geometry. Pan *et al.*[13] have worked on thermal and moisture transport in fibrous materials with respects to influence of fibre orientation and fibre volume fraction.

There are several studies for analyzing the relationship of fabric parameters with comfort properties[14-16]. Artificial neural networks (ANN) have introduced a useful application for predicting the textile properties. Bhattacharjee *et al.*[17] has predicted the heat resistance of woven fabrics with ANN system.

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As stated above, most researchers tried to create an understanding of pore structure in nonwoven fabrics and its effects on the fabric properties. However, all of these studies are based on modeling of pore structures in a virtual environment or the development of mathematical models. In fact, these methods indirectly specify the pore size and its distribution in a fibrous structure. In addition, there are no studies for prediction of comfort properties of nonwovens based on their pores structure. Therefore in this study, we have provided a new method for direct characterization and measuring of pore sizes and its distribution in real spunlace fabrics based on image analysis method. Then, the extracted structural data are used to predict the air permeability and heat transfer properties of light weight spunlace nonwovens using an artificial neural network model.

2 Materials and Methods

2.1 Materials

Various spunlace fabrics with the different fibre components were used in this study. The nonwoven samples were supplied by Nikoo Group, Iran. These fabrics are widely used for patient and chilled apparel, tissues and cover layers.

2.2 Methods

In this study, samples of two and four layers were studied because these nonwovens are used in a layered form for patient and chilled covers. For this purpose, single layer samples were stitched together without using any chemicals.

2.2.1 Physical Characterization of Spunlace Samples

Specifications of the test samples are given in Table 1. GSM of fabrics was determined according to ASTM D-3776. Thickness of samples was measured by HANS BEER AG system with the accuracy of 10 micrometers. Table 2 shows the specification of fibre components. Fibre length was determined according to ASTM D-5103 standard method. Linear density and fineness of fibres were provided by manufacturer.

2.2.2 Measurement of Air Permeability

Shirley air permeability tester was used to measure the air flow rate through spunlace samples. All tests were done under similar conditions to eliminate the effects of temperature and humidity on the air viscosity. The tests were done under ASTM D-737 conditions. Because of the more open structure of samples, the air flow rate of test samples was not obtained using the standard circular heads of Shirley apparatus. Therefore, several heads with the different diameters were examined and diameter of 1 cm (A= 7.85×10^{-5} m^2) was selected as appropriate sample size. Air viscosity and pressure difference were taken as 1.78×10^{-5} $kgm^{-1}s^{-1}$ and 100Pa respectively and measurements were done 30 times for each sample.

2.2.3 Measurement of Heat Transfer

For measuring the heat transfer, special equipment developed previously at Isfahan University of Technology, was used. The instrument was equipped with temperature and humidity sensors to measure heat and moisture transfer. Heat transfer measurement device was consisted of an iron cylindrical test box with 120 mm diameter and 300 mm length. Test box was divided into two parts, and test sample was placed in the middle zone. A polyethylene tube was placed inside the test box, and heater was mounted on top of the box. Test box has two jaws to keep the sample without wrinkle and humidity, and heat sensors were mounted on these jaws. Internal diameter of jaws was 65 mm and the distance between two sensors in the case of without test sample was adjusted at 10 mm. One of the humidity and heat sensors was mounted at the left side (inside), and another sensor was mounted at the right side (external

Table 1—Physical properties of investigated spunlace samples

Sample	Sample ID	Fibre composition, %	Thickness µm	GSM g/m^2
PET/Viscose /Cotton	PVC1	80/10/10	210±2.66	35±2.53
PET/Viscose /Cotton	PVC2	70/15/15	220±1.71	40±2.29
PET/Viscose	PV1	80/20	190±2.84	38±2.16
PET/Viscose	PV2	50/50	230±2.06	40±2.44
PP/Viscose	PPV	40/60	310±3.53	50±2.31
Viscose	V	100	360±1.42	50±2.09
Cotton	C	100	520±2.12	50±2.20

Table 2—Fibres specifications of spunlace fabrics

Fibre	Length mm	Fineness dtex	Linear density g/cm^3
Polyester (PET)	38	1.4	1.38
Cotton	38	1.7	1.54
Viscose	38	1.6	1.54
Viscose[a]	38	2.4	1.54
Polypropylene (PP)	40	2.2	0.91

[a]Used for 100% viscose spunlace sample.

or in environment). The schematic of used instrument is shown in Fig.1. Data reading, collecting and recording were done by two humidity and two heat sensors. Outputs of sensors were analog data that digitized using A/D card and were recorded by computer. All data were recorded in specified time intervals during the test period. Test samples were cut into 80cm×80cm pieces. The samples were conditioned for two hours at a relative humidity of 48% and temperature of 35 °C, simulating to real conditions of human skin[13]. Then test sample was placed between both jaws. The proper pressure was applied to keep samples without stretching, and thirty data were collected for each sample.

2.2.4 Extracting Geometrical Parameters using Image Analysis Method

The aim of this study was to measure the pore sizes and distribution of pore sizes of light weight nonwovens. For this purpose, it needs to investigate the 3D structure of samples in the thickness direction to obtain informative data of distribution of the pore sizes throughout the whole structure. For each sample, six different sections were randomly selected for tests. Selected sections were sandwiched between two resin layers and after drying, five slices of each section were cut by using microtome device in the thickness direction. Therefore, the thirty cross-sections from different layers of spunlace fabrics were prepared for each sample. Images of cross-sections of slices were captured by polarized light microscopy and then used to determinate the pore sizes and pore sizes distribution using the image analysis method.

Matlab software was used for image analysis of captured images. At first, processed images were converted from RGB format to grayscale level. Then, the unexpected noises of captured images were removed by a 3×3 square kernel type of Median filtering method. This method was used due to high efficiency of median filter to remove so-called salt and pepper noises, which commonly occurs in polarized microscopic images due to light scattering. In this way, median filter assigns the median value of the nine pixels of a 3×3 square to the center pixel and effectively eliminates discrete, isolated strong pixel variations. After de-noising process, image segmentation was performed with Otsu method for detection of the image components. This technique is based on the threshold for portioning the pixels of an image into two classes. Using this method, images were converted to binary formats with the pixel intensity values of 0 and 1. In this step, the color of fibre components and pore regions are converted to white and black respectively. Nevertheless, there are some white pixels that are not belonging to fibres. In this case, white pixels were eliminated (converted to black pixels) if fifty or less than fifty pixels are next to each other. This threshold value was selected due to the minimum fibre diameter of fifty pixels in all samples. An image processing routine written in Matlab R 2011 A was used for finding of the edges of image components. By applying this algorithm, edge pixels of image components were white and other pixels were converted to black. In the next step, the image enhancement was done using so-called opening and closing method. This technique is a basic method for morphological noise removal. Opening eliminates the small bright spots, and closing removes the connections between neighborhood objects[18]. Finally, labeling of image components was performed with the Matlab routine and porosity information such as the mean value of pore sizes and distribution factor of

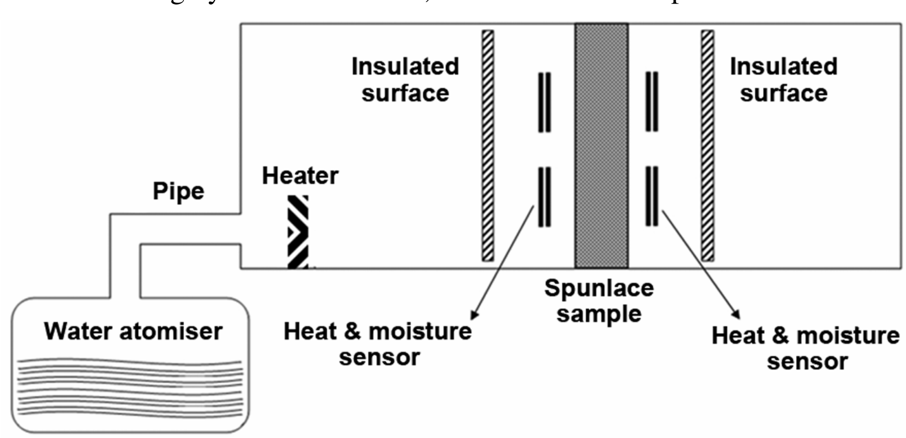

Fig. 1—Schematic diagram of measuring apparatus of heat and humidity transfer

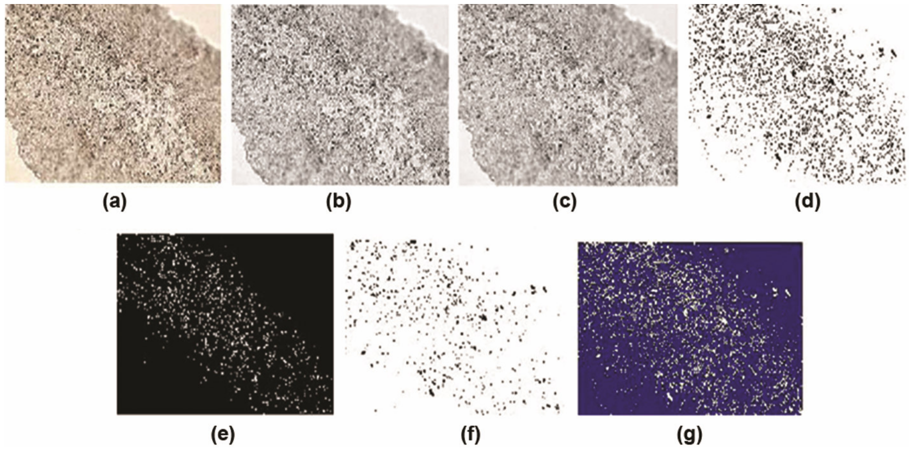

Fig.2— Step by step image processing procedure (a) original image, (b) gray scale image, (c) de-noised image, (d) binary image after segmentation, (e) edge transformed image, (f) image enhancement and (g) labeled image (×400 magnitude)

pore sizes were calculated. For this purpose, the area of each labeled pore regions are measured based on the number of their pixels. Then, the diameter of an equivalent circle of the calculated area was determined, and considered as the pore diameter. Distribution factor of pore sizes was also calculated as standard deviation of thirty measured pore sizes for each sample. The step by step image processing effects are demonstrated in Fig.2.

2.2.5 Artificial Neural Network Model

Artificial neural network (ANN) was applied for the prediction of heat transfer and air permeability properties of light weight spunlace fabrics. The developed ANN has two input and two output nodes. Input nodes were average pore sizes and distribution of pore sizes, and output nodes include the values of heat transfer constant and air flow rate. The artificial neural network was trained with the data obtained by image processing and the experimental results based on the back propagation training algorithm (BP). The ANN training process was done by Matlab software as Levenberg-Marquardt BP algorithm (TRAINLM). The developed neural network was consisted of three layers, namely input layer, hidden layer and output layer. The numbers of layers nodes were set at 2, 3 and 2 nodes for input, hidden and output layer respectively. The epoch number of training process to reach to minimum error order was set at 2000. Mean square error (MSE) was also used to control the network performance. The neural network performance was determined via comparison between preset error and difference value of actual and predicted data. For each of networks, the numbers of training, validation and test data were set at 70%, 15% and 15% respectively. These data were selected in a random manner by the written algorithm. Figure 3 shows the schematic structure of developed neural network. The ANN parameters were tuned by trial-error method many times because the available data was a few and training of ANN with small batch size of data was very difficult. The error of testing was high in most of the ANNs and tuning of parameters was very sensitive. After many attempts, all of training, validation and testing errors were reached to less than 10^{-1} and training was done successfully.

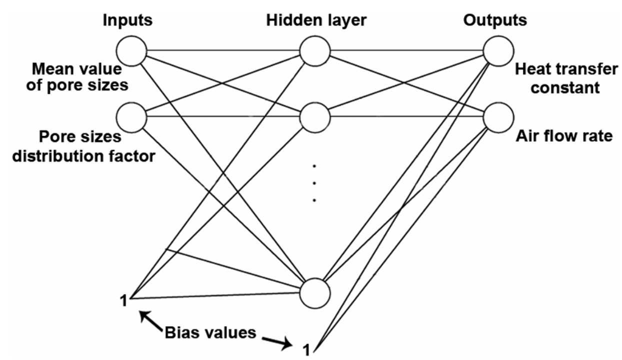

Fig. 3— Schematic diagram of developed artificial neural network

3 Results and Discussion

3.1 Image Analysis Results

The average pore sizes and distribution factors of pore sizes of all fourteen samples (two layered, and four layered) were measured using the image analysis of cross-section of samples. Image analysis results are given in Table 3. Average pore sizes are found to decrease with the increase in layers of test samples. This decrease in pore sizes can be due to increase in

Table 3— Image processing results for calculation of pore sizes and pore sizes distribution

Sample ID	Pore sizes parameters, micrometer			
	Two layered sample		Four layered sample	
	Mean value	Distribution factor	Mean value	Distribution factor
PVC1	12.50	6.30	6.06	7.38
PVC2	9.99	6.21	6.80	7.81
PV1	11.37	6.10	5.88	6.9
PV2	9.60	6.23	5.38	6.85
PPV	7.54	6.53	4.32	7.17
V	7.83	7.95	4.28	8.54
C	5.52	7.83	2.94	8.20

crossover points of fibres in four layer samples. It is also found that the distribution factor of pore sizes increases with the increase in nonwoven layers. Increase in fabric layers will lead to a more porous structure with the more different pore sizes. Thus, there will be a higher value for distribution factor of pore sizes.

3.2 Air Flow Rate and Heat Transfer Constant

The air flow rate through the samples was measured according to Darcy's law. Air permeability of a slow flow depends on structural characteristics, fluid properties and pressure drop through the material thickness. The simplified Darcy's law, considering the flow through the nonwoven materials, is expressed as follows[19]:

$$K_D = \left(\frac{\mu Q}{A}\right)\left(\frac{\Delta x}{\Delta p}\right) \quad \ldots (1)$$

where K_D is the permittivity constant (m^2); μ, the gas viscosity (kg m^{-1}s^{-1}); Q, the gas flow rate (m^{3}s^{-1}); A, the cross-sectional area of sample (m^2); Δx, the sample thickness (m); and Δp, the pressure difference across the sample thickness (Pa=Nm^{-2}). The measured values of air flow rate and heat transfer constant of samples are shown in Table 4.

It is found that air flow rate of four layered samples decreases to 32-52% in relation to two layered fabrics. Table 4 also indicates that the heat transfer property of four layered nonwovens increases to 5-26% rather than two layered fabrics. Results show that the increase in pore sizes leads to increase in air flow rate through spunlace fabrics. This is an expected behavior, because the big pore sizes will make more pathways for the air and thus increase the air permeability. It is also observed that the distribution of pore sizes has no clear trend with the air flow rate variations. The following linear equation gives the relation between air flow rate and pore sizes of investigated spunlace samples:

Table 4—Measured values for air flow rate and heat transfer constant of spunlace fabrics

Sample ID	Air flow rate × 10^{-4}, m^{3}s^{-1}		Heat transfer constant × 10^{-10}, m^2	
	2 layers	4 layers	2 layers	4 layers
PVC1	3.53±0.15	1.71±0.05	2.76±0.12	3.23±0.12
PVC2	2.82±0.13	1.92±0.05	2.72±0.11	3.42±0.14
PV1	3.21±0.15	1.66±0.04	2.67±0.14	3.02±0.06
PV2	2.71±0.09	1.52±0.07	2.73±0.11	3.00±0.08
PPV	2.13±0.25	1.22±0.01	2.86±0.17	3.14±0.07
V	2.21±0.19	1.21±0.05	3.48±0.18	3.74±0.10
C	1.56±0.07	0.83±0.02	3.43±0.21	3.59±0.13

y=(0.2823x+0.0008)×10^{-4}

There is an obvious increase in heat transfer constant of nonwovens with the increase in distribution factor of pore sizes. Pore size has no clear effect on heat transfer property of the spunlace samples. The following linear equation gives the relation between heat transfer constant and distribution factor of pore sizes of investigated nonwovens:

y=(0.4375x+0.0026)×10^{-10}

Increase in distribution factor of pore sizes can lead to increase in crossover points of fibres and fibre-to-fibre contact points. Conduction heat transfer mechanism in nonwoven materials is accomplished by fibres and trapped air. Thus, with the increasing in contact points of fibres (increase in distribution factor of pore sizes), the ideal conditions for conduction of heat transfer will be provided and heat transfer constant of test samples will increase. In addition, the role of trapped air can also be negligible because of very low thickness of samples. Therefore, the pore regions, as occupied sites by air, do not show a clear effect on heat transfer property of light weight nonwovens.

3.3 Neural Network Results

Figures 4 and 5 demonstrate the regression plots between actual and predicted values of air flow rate, and heat transfer constant of test samples respectively. The correlation coefficients of regression (R^2) between actual and predicted values are calculated as

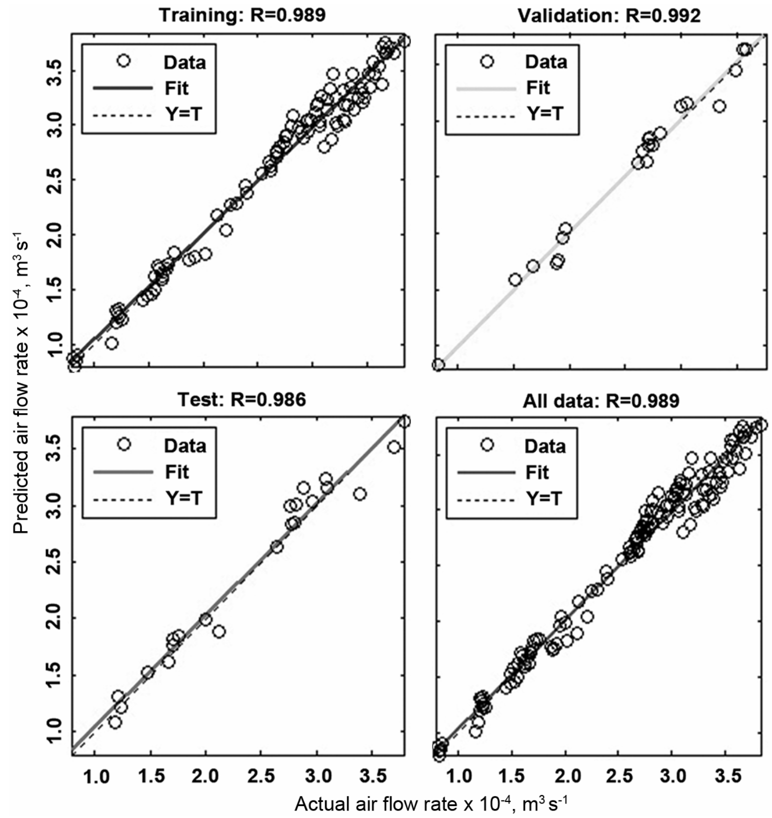

Fig. 4—Regression between predicted and actual values of the air permeability of samples

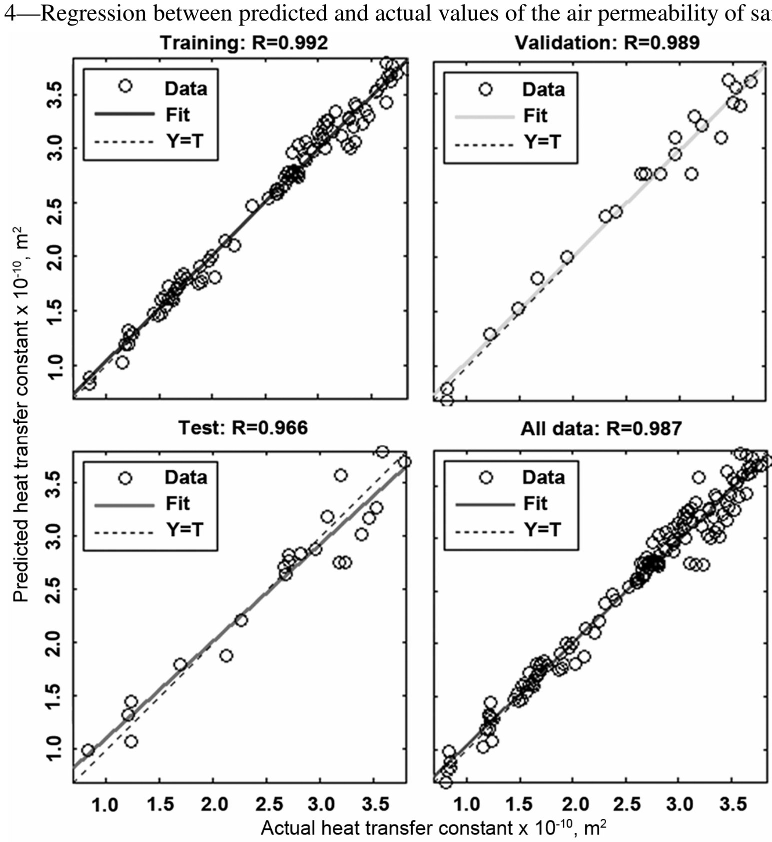

Fig. 5— Regression between predicted and actual values of heat transfer constant of samples

0.978 and 0.984 for air flow rate and heat transfer constant respectively. These values show that there is only a little difference between predicted and actual values of air flow rate and heat transfer constant of spunlace fabrics using the structural parameters of samples. In other words, the developed method is found to be useful to predict the air flow rate and heat transfer properties of light weight nonwovens using the information of cross-section profile of nonwovens.

4 Conclusion

The experimental results show that the increase in pore sizes, and distribution factor of pore sizes results in increase in air flow rate and heat transfer properties of light weight nonwovens respectively. The developed ANN also has a good performance in prediction of air permeability and heat transfer of spunlace fabrics based on pore-related factors and there is a high correlation coefficient between predicted and actual values. This method can help the manufacturer for engineering the layers with desired heat transfer and air permeability by controlling the pore structures in spunlace machine.

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