Modeling the Moisture and Heat Transfer of Warp Knitted Spacer Fabrics Using Artificial Neural Network Algorithm

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Abstract

Spacer fabrics are triple-layer structures consisting of two separate outer and one interfacing monofilament middle layers. The middle interfacing layer connects the two outer layers together. Incorporation of the middle layer imparts unique transfer properties to the fabric. In this study, models capable of predicting heat and moisture transfer of warp knitted spacer fabrics based on artificial neutral network technique were developed. The best predictive model was found by manipulation of network topology, epoch and activation functions. These models predicted transfer properties of the spacer fabrics using parameters such as fabric mass, fiber composition, porosity and thickness. Models were trained using thirty commercially available samples of warp knitted spacer fabrics. The prediction power of obtained models was evaluated with five commercially available samples out of training data. The error percentage of prediction was less than 10% for both obtained models which confirmed the validity of the developed artificial neural network models as a reliable tool in prediction the heat and moisture transfer of warp knitted spacer fabrics.

Keywords

Warp Knitted Spacer Fabrics; Artificial Neural Network; Heat and Moisture Transfer

Introduction

Research and development in the field of technical textiles in recent years has resulted in steady expansion of this class of textile structures for use in numerous varied applications. Although existing fabric formation technologies or their modifications can be employed in production of technical textiles, warp knitting is by far the most preferred manufacturing technology for production of technical textiles. Generally warp knitted spacer fabrics are comprised of two inter-connected outer layers. The inter-connection of these outer layers is achieved by a monofilament interfacing middle layer [1].

Warp knitted spacer fabrics not only have excellent transversal compressibility, but also have exceptional heat and moisture transfer together with acceptable air permeability. In applications such as automotive, medical, apparels, technical and industrial where comfort is the main selection criterion, these properties are of paramount importance.

There are many studies about the mechanical properties, simulation and numerical modeling of spacer fabrics. An experimentally validated geometrical model capable of evaluating porosity and capillarity of spacer fabrics used as absorbent fabric in medical applications was developed by Davies and Williams [2,3]. Results of Borhani et al.[4] investigation led to development of a mathematical model that described transfer mechanism of water vapor produced by sweating from the skin to the outer surface of spacer fabric. Joanne and Pui [5] studied various characteristics of spacer fabrics including low-stress mechanical properties, air permeability and thermal conductivity. It was reported that air permeability and thermal conductivity of spacer fabric were closely related to the fabric density.

Ertekin and Marmarali [6] investigated thermal comfort properties of spacer fabrics produced on double jersey machine using three different dial setting and two different spacer yarns. This research showed that fabric weight, thermal conductivity, thermal resistivity, air permeability and relative water vapor permeability properties are significantly affected by dial setting and the type of spacer yarn. Compression behavior of warp-knitted spacer

2304-9421/15/01 017-10 © 2015 DEStech Publications, Inc.
doi: 10.12783/tlist.2015.0401.02

fabrics was studied by Psilla et.al [7], Sheikhzadeh et.al [8], Liu et.al [9], and Mokhtari et.al [10]. Renkens et.al [11] worked on geometry modelling of these fabrics. Three-dimensional simulation of warp knitted spacer fabrics was also proposed by Miaoa et.al [12].

Artificial neural network technique or ANN is a data analysis method based on intelligent technology. ANN modeling methods are very popular in prediction the properties of textiles based on specific properties and also raw materials. These methods generally are very accurate and also simple in compare with analytical models. Moreover, in analytical modeling some assumptions should be considered which decrease the accuracy of proposed models.

Extensive use of ANN has been made successfully in various textile disciplines such as yarn and fabric manufacture or determination of fabric properties [13-24]. Works of Beltran et al on the pilling tendency of wool knits [13] or that of Tokarska on prediction of permeability of woven fabrics [14] are two examples of application of ANN technique in textiles. Other application of ANN modeling in the field of textiles is concerned with development of predictive model based on ANN methodology for dyeing of polyester fibers and its comparison with statistical regression and fuzzy regression [15]. ANN technique has also been used for prediction of cotton yarn hairiness [16] or tensile properties of cotton-covered nylon core yarns [17]. Artificial neural network model was proposed to predict the pilling performance of weft knitted fabrics produced from wool/acrylic blended yarns [18]. Predicting model of tensile properties and breaking elongation of ring spun yarns was developed by Ramesh et.al [21] and Majumdar et.al [22] respectively. Contrary to variety application of ANN technique in textiles, the authors did not find any study on prediction of warp spacer knitted fabrics properties by using artificial neural network modeling technique.

Therefore, in the present work, it is attempted to predict heat and moisture transfer capacity of warp knitted spacer fabrics by development of ANN models based on mass, thickness, porosity and fiber kind of warp knitted spacer fabrics.

Material and Methods

Mass and Thickness

Mass and thickness of warp knitted spacer fabrics was measured according to ASTM D3776 [25] and ASTM D1777 [26] standard test methods, respectively.

Porosity

The fabric porosity (ε) is defined as the ratio of the fabric total void volume to fabric total volume. Equation 1 denotes the dependence of fabric porosity on fabric density (ρ_{fabric}) and the fiber density (ρ_{fiber}).

$$\varepsilon = 1 - \frac{\rho_{fabric}}{\rho_{fiber}} \qquad (1)$$

Dynamic moisture and heat transfer

In order to investigate the dynamic heat and moisture transfer of fabrics, an experimental apparatus based on the research of Borhani et al. [4] was developed. The apparatus is shown schematically in Figure 1, it comprises of a controlled environmental chamber, sweating guarded hot-plate and data acquisition system. The sweating guarded hot-plate that serves as heat source consists of a hot-plate which its temperature is held constant at 37°C. A water container and a piece of animal skin are used as humidity source and human skin stimulator respectively. Humidity and temperature controllers maintain the chamber at ambient conditions i.e. 25°C, and 65% RH. The sample is inserted in apparatus in a manner that its inner side is in front of sweating animal skin without contact with it. The outer side of sample is exposed to the environment. Five humidity and temperature sensors are located above and below the test sample. The rate of sampling for temperature and humidity is 1Hz and the sampling duration was 5min. The driving forces for the movement of moisture vapor are the temperature and vapor gradients maintained between the points where the moisture vapor emerges from the simulated skin (35°C, 90%RH) and the ambient environment controlled at 25°C and 65% RH[27].

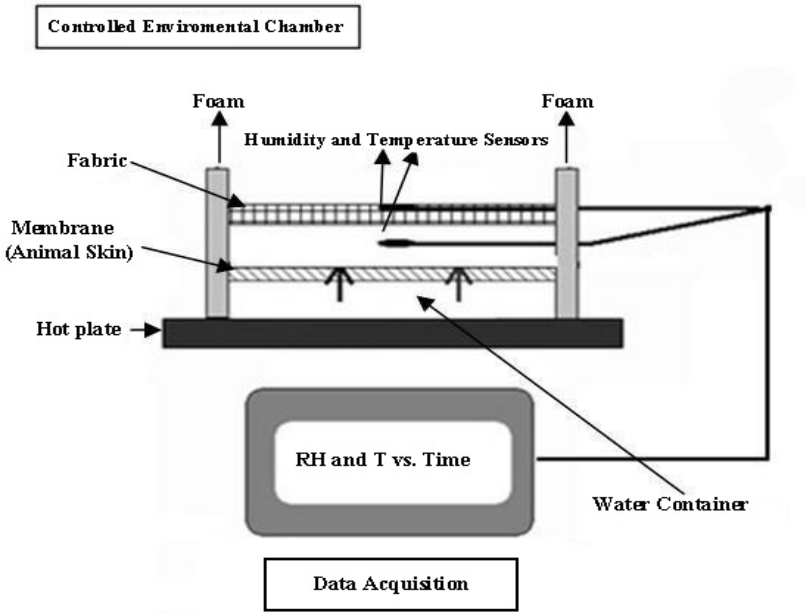
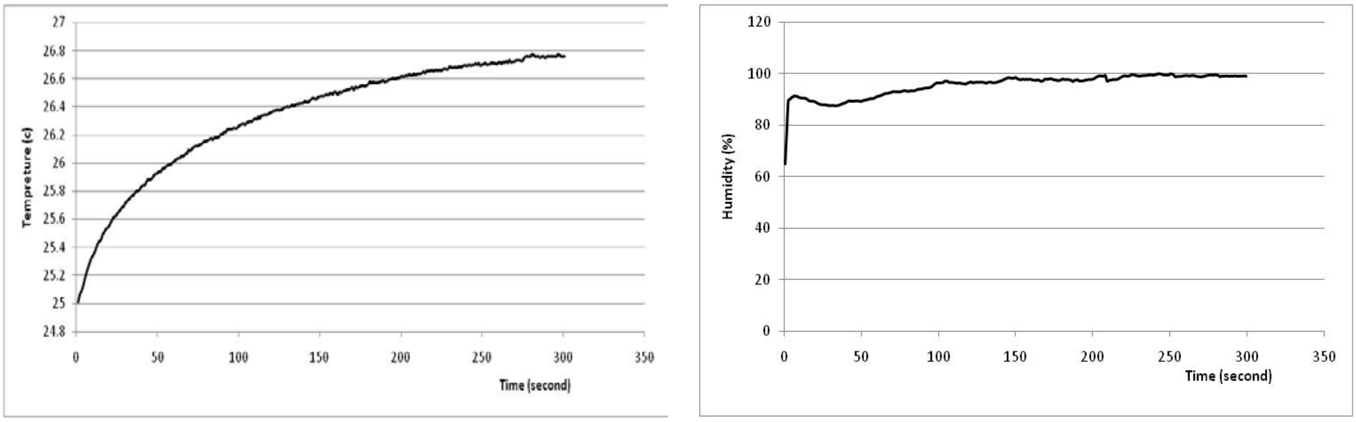


FIGURE 1. SCHEMATIC DIAGRAMOF THE TESTING APPARATUS [4]



(a) (b)

FIGURE 2. TYPICAL VARIATION OF HEAT AND MOISTURE TRANSFER THROUGH FABRIC (A). HEAT TRANSFER VS. TIME, (B). MOISTURE TRANSFER VS. TIME

In Figure2 the variation of humidity and temperature against time are shown respectively. During the initial stage of test, temperature and humidity in the inner and outer surfaces of the fabric are similar to those of environment condition. Then, evaporation of sweat from the skin simulator causes rapid increase in temperature and humidity in the microclimate and rapid increase in the temperature and humidity in the inner surface of the fabric occurs. This results in creation of a thermal gradient between the two faces of sample. Gradual reduction in the rate of heat and humidity transfer results in creation of state of balance where evaporation rate from the skin simulator equals the diffusion rate from the fabric. Ultimately temperature and humidity variation reach a static state. By considering the heat and moisture transfer curve of samples (As shown in Figure 2), moisture transfer percentage (Equation 2) and heat transfer percentage (Equation 3) can be obtained.

$$\text{Moisture Transfer Percentage} = \frac{R_{300} - R_i}{R_i} \times 100 \tag{2}$$

Where R_{300} is defined as humidity transferred through the fabric after 300 seconds and R_i is initial humidity of sample.

$$\text{Heat Transfer Percentage} = \frac{T_{300} - T_i}{T_i} \times 100 \tag{3}$$

Where T_{300} is heat transferred through the fabric after 300 seconds and T_i is initial temperature of sample.

Arttificial Neural Network Modeling

Artificial Neural Network Parameters

In this study, fiber composition, fabric thickness, weight and prosity of warp knitted spacer fabrics were selected as input parameters of Artificial Neural Network(ANN) models. Fiber type critically affects fabric heat and moisture properties. Therfore commercial fabrics made of polyester and nylon multifilament yarns were selected for training and testing process of ANN proposed models. Specifications of selected warp knitted spacer fabrics are shown in Table 1. According to Equation 4 [28], Fabric Thickness can affect moisture transfer capacity of fabric.

$$P = \frac{FL}{\Delta C} \qquad (4)$$

Where P is permeability coefficient, F is the moisture flux, L is the thickness, and is concentration gradient imposed across the sample. Equation 4 shows that permeability coefficient is directly proportional to thickness.

TABLE 1. SAMPLE SPECIFICATIONS

Input parameters				Measured Properties	
Thickness (mm)	Mass (g/m^2)	Porosity (%)	Fiber type	Heat transfer(%)	Moisture transfer(%)
1 – 6.8	131.8 -652	88-97.13	Polyester & polyamid	28.43– 94.76	70.9 –98.17

The target parameters of models were heat and moisture transfer of the warp knitted spacer fabrics. Traninig of model was performed with 30 samples and five samples was used as testing data. In Table2 the specification of testing set is presented. Therefore two separate model for moisture and heat transfer prediction based on four input parameter was proposed. Each model have four input unit (fiber composition, fabric thickness, weight and prosity of warp knitted spacer fabrics) and one output neuron (Moisture transfer percentage and Heat transfer percentage).

Training process of ANN models was carried out using backpropagation learning algorithm technique based on gradient descent and momentum rate. The learning rate and momentum values were set at 0.05 and 0.9 respectively.

Overfitting of artificial neural network models can be prevented by regularization or early stopping methods. The selection of either of these methods is dependent on the population of data. In this work due to availability of small number of data, overfitting of the model was prevented using regularization method. This method is based on modification of performance function. Equation 5 shows MSEREG function which is the modified function in Matlab software.

$$E(w) = \text{msereg} = \gamma\,\text{mse} + (1-\gamma)\text{msw} \qquad (5)$$

Where:

$$\text{msw} = \frac{1}{n}\sum_{i,j} w_{ij}^2 \qquad (6)$$

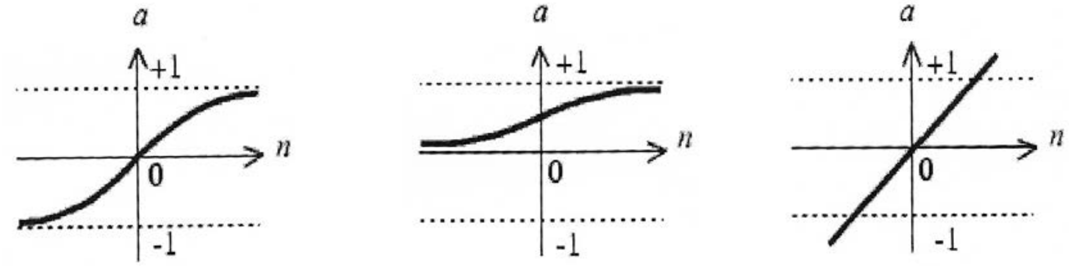
n=The number of weight connections in all layers of network.

γ = Performance ratio which determines the effectivness of MSW(Mean Saquare of connection weights) and MSE(Mean Square Error) parts [29].

This function is used instead of usual performance functions of MSE and SSE (Sum Square Error). This performance function causes the network to have smaller weights and biases, causing smaller network response and overfitting [29] .

Normalizition of input and output data was carried out in a manner that standard deviation of unity and average value of zero were obtained. Elimination of the effect of different units of input and output parameters is critically dependent on this preprocessing operation. Figure 3 shows the most common type of transfer fuctions. Nonlinearity is the main feature of sigmoid and tangent hyperbolic functions. The tangent hyperbolic (Tansig) and sigmoid (Logsig) function compress the output data between [-1,1] and [0,1] respectively. According to literatures, applying sigmoid and tangent hyperbolic function in hidden layer(s) and linear function in output layer could improve the performance of artificial neural network model [30].

Chattopadhyay reported that the artificial neural network model with one hidden layer and sigmoid transfer function in hidden layer and linear transfer function in output layer could predict each functions [31]. Parallel to obtain optimum topology of artificial neural network model, the best transfer function,and number of epoch were obtained by trail and error. Mean square error(MSE) of predicting testing data was considered as optimization criterian for judjment.



(a) (b) (c)

FIGURE 3. SCHEMATIC DIAGRAM OF THREE USED TRANFER FUNCTIONS, (A).TANGENT HYPERBOLIC(TANSIG),(B).SIGMOID(LOGSIG),(C).LINEAR

In this study two separate artifiicial neural network model for prediction the moisture and heat transfer capacities of warp knitted spacer fabrics were developed. Fabric thickness, prosity, mass, and fiber composition were selected as inputs to the modles. Each model consists of four input parameters and one outpout unit. Since fiber composition was not qunatitative parameter it was coded as 0 and 1 for nylon and polyester fiber respetively. Additionally architecture parameters, number of epoch, transfer functions for hidden layer(s) and output layer, number of hidden layer(s), and number of hidden neurons was optimized.

TABLE 2. SPECIFICATIONS OF TESTING SET SAMPLES

	Input parameters				Target parameters	
Sample code	Material	Thickness (mm)	Mass (g/m^2)	Porosity (%)	Heat transfer(%)	Moisture transfer(%)
1	Polyester	6.8	476.62	94.92	31.63	97.97
2	Polyester	4.8	304.17	95.41	40.34	98.25
3	Polyester	3.4	291.77	93.78	36.68	94.68
4	Polyester	3.9	371.16	93.10	31.63	93.6
5	Polyester	3.7	384.63	94.47	31.18	95.3

Moisture Transfer Modeling

1)Transfer Functions

As shown in Table 3, in order to obtain the best transfer functions, two structure with one and two hidden layers was selected. Various arrangments of transfer functions were considred. The number of eopchs for training was 1000. It is obvious that applying tangent hyperbolic function in hidden layer(s) and linear function in output layer results in the lowest prediction error of testing data. The lowest vlaue of prediction error on testing data was 31.06 and belongs to a network with 4-5-5-1 structure.

2) Number of Epoch

Performance of training process is most affected by number of training epoch. Overfiiting of artificial neural network occurs as training epoch increases. The former also prolongs the training process. Thus, selection of optimum number of epoch is desirable. For this reason one topology with (4-5-5-1) structure and tangent hyperbolic and linear transfer function for hidden neurons and output neuron were selected respectively. The number of epoch was changed from 500 to 1500 at 100 step. Results showed that best prediction performance of artificial neural network was obtained after 1000 epoch.

TABLE 3. BEST TRANSFER FUNCTION SELECTED FOR NEURONS OF HIDDEN AND OUTPUT LAYERS

Topology	Epoch	1st Hidden Layer	2nd Hidden Layer	Output Layer	MSE Train	MSE Test
4-7-1	**1000**	**Tansig**	**---**	**Linear**	**20.94**	**46.78**
4-7-1	1000	Logsig	---	Logsig	73.99	96.11
4-7-1	1000	Tansig	---	Tansig	36.60	50.20
4-7-1	1000	Logsig	---	Logsig	49.39	66.82
4-5-5-1	1000	Logsig	Logsig	Logsig	73.83	97.09
4-5-5-1	1000	Tansig	Tansig	Tansig	44.62	62.54
4-5-5-1	1000	Logsig	Logsig	Linear	60.53	54.05
4-5-5-1	**1000**	**Tansig**	**Tansig**	**Linear**	**45.29**	**31.06**

3)Structure of Artificial Neural Network Model

Previous researchers have shown that neural networks with one hidden layer are suitable for the majority of applications. However, when a complex relationship exsits between input and output parameters, the second hidden layer can improve the performance of the network. The number of hidden neurons and the number of hidden layers are usually adjusted by trial and error. The optimum structure of artificial neural network is both dependent on complexity of target process and the relationship between input and output parameters. In order to achieve the best topology and to evaluate artificial neural network algorithm in modeling, twelve structure as shown in Table 4 were selected. According to previous reuslts, number of epoch was selected 1000 and tangent hyperbolic and linear transfer functions were used for hidden and output neurons respectively. Preliminary evaluations revealed that networks with more than two hidden layers are not suitable for training. Trained networks were presented with different sets of data. The mean square error of test and train data were measured. Results showed that artificial neural network model with one hidden layer and ten neurons provided the least mean square error(MSE) on testing data. The MSE of testing and training data was 23.69 and 14.39 respectively.

TABLE 4. PERFORMANCE OF DIFFERENT TOPOLOGIES AFTER 1000 EPOCH ON TESTING AND TRAINING DATA SET

Sample	Transfer Function	No. of neurons in 1st Hidden Layer	No. of neurons in 2nd Hidden Layer	MSE Train	MSE Test
1	Tansig/ Linear	4	---	47.10	49.69
2	Tansig/ Linear	6	---	29.41	96.63
3	Tansig/ Linear	8	---	28.05	63.22
4	**Tansig/ Linear**	**10**	**---**	**14.35**	**23.69**
5	Tansig/ Linear	12	---	23.37	42.65
6	Tansig/ Linear	14	---	23.69	46.48
7	Tansig / Tansig / Linear	4	4	17.00	47.59
8	Tansig / Tansig / Linear	5	5	29.47	60.72
9	Tansig / Tansig / Linear	6	6	42.47	44.84
10	Tansig / Tansig / Linear	7	7	17.12	25.27
11	Tansig / Tansig / Linear	8	8	14.05	43.18
12	Tansig / Tansig / Linear	9	9	13.75	48.88

Heat Transfer Modeling

1)Transfer Functions

According to Table 5, in order to obtain the best transfer function of hidden layer(s) and output neuron(s), structures with one and two hidden layers was selected. Different transfer functions including linear, sigmoid, and tangent hyperbolic were selected for neuron(s) of hidden and output layer(s). Number of epochs was 1000. Results showed that sigmoid and linear transfer functions provide the best prediction power of heat transfer capacity of warp knitted spacer fabrics. The lowest value of error on testing data was 20.10 for an network with

4-7-1 structure.

2)Number of Epoch

In order to obtain the optimum number of epochs, this parameter was changed between 500 to 1500 at 100 step. ANN model comprised of two hidden layers with five neurons in each of them. According to previous results, the transfer functions of hidden layers and output neuron was sigmoid and linear respectively. Results showed that the best performance of ANN model was obtained at 700 epoch of training.

3)Structure of Artificial Neural Network Model

To find the best structure of ANN model twelve different structures having various numbers of hidden layers and number of hidden neurons were chosen (As shown in Table 6). Comparison of the results showed that structure with two hidden layers and eight neurons in first and second hidden layer provided the lowest prediction error on testing data. In predicting the heat transfer of testing data, the mean square error(MSE) was 6.88.

Results and Discussion

Table 7 shows both experimental and predicted values of moisture transfer of testing data accompained with prediction errors. As can be seen the maximum and minimum of prediction error are 6.32% and 4.02 % respectively. The average of prediction error is 5.01%. These results confirms the capability of artificial neural network methodology in prediction of moisture transfer of warp knitted spacer fabrics. The performance of optimized artificial neural network model in prediction of heat transfer capacity of warp knitted spacer fabrics is shown in Table 8. Results shows that average of prediction error is 6.36% and the maximum and minimum of prediction error are 9.54 % and 3.60% respectively. Again the predictive power of artificial neural network model in prediction of moisture capacity of warp knitted fabrics is confirmed.

TABLE 5. BEST TRANSFER FUNCTION SELECTED FOR HIDDEN AND OUTPUT NEURONS

Topology	1st Hidden Layer	2nd Hidden Layer	Output Layer	MSE Train	MSE Test
4-7-1	Tansig	---	Linear	6.69	31.52
4-7-1	**Logsig**	---	**Linear**	**13.57**	**20.10**
4-7-1	Tansig	---	Tansig	12.55	46.76
4-7-1	Logsig	---	Logsig	38.21	95.69
4-5-5-1	Tansig	Tansig	Linear	5.20	57.52
4-5-5-1	**Logsig**	**Logsig**	**Linear**	**7.41**	**26.37**
4-5-5-1	Tansig	Tansig	Tansig	11.17	108.54
4-5-5-1	Tansig	Logsig	Logsig	31.78	87.69

TABLE 6. PERFORMANCE OF DIFFERENT TOPOLOGIES AFTER 700 EPOCH ON TESTING AND TRAINING DATA SET

Sample	Transfer Function	No. of neurons in 1st Hidden Layer	No. of neurons in 2nd Hidden Layer	MSE Train	MSE Test
1	Logsig / Linear	---	4	21.43	21.43
2	Logsig / Linear	---	6	16.06	25.78
3	Logsig / Linear	---	8	18.23	21.07
4	Logsig / Linear	---	10	25.47	62.36
5	Logsig / Linear	---	12	22.72	72.00
6	Logsig / Linear	---	14	22.44	106.06
7	Logsig / Logsig / Linear	4	4	35.61	114.08
8	Logsig / Logsig / Linear	5	5	21.64	65.27
9	Logsig / Logsig / Linear	6	6	21.77	47.35
10	Logsig / Logsig / Linear	7	7	18.05	29.37
11	**Logsig / Logsig / Linear**	**8**	**8**	**5.83**	**6.88**
12	Logsig / Logsig / Linear	9	9	18.60	68.94

TABLE 7. POWER OF ANN MODEL IN PREDICTION OF FABRIC MOISTURE TRANSFER PROPERTY

Sample	Target Value	Predicted Value	Error	Error(%)
1	97.97	94.03	-3.94	4.02
2	98.25	93.23	-5.02	5.11
3	94.68	89.40	-5.28	5.57
4	93.63	87.68	-5.92	6.32
5	95.34	91.45	-3.85	4.04

TABLE 8. POWER OF ANN MODEL IN PREDICTION OF FABRIC HEAT TRANSFER PROPERTY

Sample	Target Value	Predicted Value	Error	Error(%)
1	31.63	32.78	1.15	3.60
2	40.334	43.38	3.04	7.53
3	36.68	40.18	3.50	9.54
4	31.63	29.55	-2.08	6.56
5	31.18	29.76	-1.42	4.57

Conclusion

In this study heat and moisture transfer properties of warp knitted spacer fabrics were predicted using artificial neural network algorithm. Strucutral parameters of fabrics were used as input of developed models. Results confirmed the ability of ANN modeling technique as an valuable method in prediction of transfer phnomenon of warp knitted spacer fabrics. It was found that topolgy with one hidden layer and ten neurons, after 700 epoch, yielded the best performance for heat transfer predcition. Similarly it was found that topology with two hidden layers and eight neurons, after 1000 epoch provided the best moisture transfer prediction. The mean square error of testing data for heat transfer and moisture transfer were found to be 23.69 and 6.88 respectively. Additionally it was concluded that the maximum predction error for hear and moisture transfer were 6.32% and 9.54% respectively.

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