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Thermo-physiological properties of 3D warp knitted spacer fabrics for car seat application

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Thermal comfort properties of 3-Dimensional knitted spacer fabrics have been studied in order to replace the existing polyurethane foams in the car seat and back supports. The influence of different characteristics of spacer fabrics, like structure, areal density, thickness and density on thermo-physiological performance has been studied. The potential thermal behavior is identified with the support of the thermal conductivity and resistance evaluation. The air and water vapor permeability have been measured and analyzed in-order to study the breathable performance of spacer fabrics. Advance statistical evaluation and two-way analysis of variance is used to analyze the significance of various factors on required properties. The result shows that spacer fabric with a hexagonal net structure has more open structure on surface than lock knit fabrics, which results in highly permeable to air with good thermal conductivity. It is also observed that, the hexagonal net fabrics have the ability to pass more water vapor than the fabrics with lock knit structure on the surface. These findings are the important requirements for designing the car seats with required thermal comfort properties using 3D spacer fabrics.

Keywords: 3D Spacer fabrics, Breathable fabric, Evaporative resistance, Polyester filament, Thermal conductivity, Thermal resistance, Water vapor permeability

1 Introduction

The current issue in the automotive industry is to develop the more comfortable seats. The occupant's expectation rises with the improvement in performance of both seat and back support[1]. Due to significant interface between person and seats inside the vehicle, it should be well suited for effective delivery of conditioned air and heat. Normally, a seat acts as a thermal insulator, increasing skin temperatures and reducing evaporative cooling of sweat[2]. The thermal comfort in automobiles is a comfort in automobiles is a complex task, because it involves the interaction of many factors, and vehicles are susceptible to temporal fluctuations in their thermal environments[3,4]. The micro-climatic conditions generated in the automotive seat contact area according to the type of seat material or the active heating and ventilation/cooling systems, where applicable, can considerably affect the comfort of the vehicle's occupants. Ventilating a seat has low energy costs and eliminates this insulating effect while increasing evaporative cooling[5,6]. Textile material seats use no additional energy and have similar benefits.

The heat transfer mechanisms in textile insulation layers of seats have some specific features that must be taken into account when evaluating their apparent properties[7,8]. The driver and passenger undergo multidirectional vibrations caused by the car's motion. So, the seat and back support are exposed to alternating stresses of compression and relaxation[9]. The motion of air and heat inside the seat material influences the thermo-physiological comfort of occupants including transfer and evaporation of moisture, exchange of heat within material, dry thermal insulation, air permeability and compression[10-12]. Thermal comfort requires the maintenance of whole body heat balance. Maintaining heat balance is probably the most important attribute of seats, and hence it has drawn the attention of many textile research workers[13–15]. The main problem associated with thermal comfort is the in-compatibility between the requirement of heat conservation during metabolic activity and heat dissipation at high energy level. Air permeability, being a biophysical feature of textiles, determines the ability of the air flow through the fabric. Airflow through textiles is mainly affected by

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the pore characteristics of fabrics. The pore characteristics of the fabric are mainly determined by their structure and density[16]. Water vapor permeability determines breathability of the cushion material, i.e. the ability to transmit vapor away from the body. The mechanism involved in water vapor transmission through fabric from the body to the outer surface is by diffusion and absorption - desorption method[17]. The ability of fabric to transport water vapor is an important determinant of physiological comfort[18]. There are several researches regarding the thermal comfort inside of vehicles in the scientific literature, but the number of studies which focus on analyzing the layered structures is scanty. These types of fabrics consume more fuel due to heavy weight, high cost, complex production and poor behavior under compression and in-plane shear.

So, the attention of researchers concentrates mainly on developing the advanced seat material to make the occupant's to feel thermally comfortable[19–21] by offering all the properties with low cost, less weight, and excellent compression resilience and shear behavior. The emerging natural textile materials of this decade possess most of the functional properties, e.g. three-dimensional fabrics (3D).

Spacer fabrics (3D) have two outer surfaces connected to each other with spacer yarns. This middle layer is comprised of monofilaments; the fabrics possess special characteristics such as excellent compression recovery because monofilaments between two layers act as linear springs[21]. The major application areas are automotive textiles, medical textiles, geotextiles, protective textiles, sportswear and composites[22-25].

Spacer fabrics have the ability to trap and hold air, and insulate the body because of its nature of spacer yarns between two surface layers. This, along with the ability to wick away moisture, maintains the body's microclimate and thus keeps the person dry and comfortable[26]. Spacer fabrics can accomplish all of these desirable characteristics and excellent compression recovery[27]. The thermal regulation properties of both warp and weft knit spacer fabrics are excellent when being considered for cushion materials in car upholstery[28]. Weft knitted spacer fabrics have significantly lower air permeability ratings, and are thus more able to resist air penetration than the warp knit fabric[29,30]. The lack of comprehensive studies on thermo-physiological comfort of knitted spacer fabrics are sound basis for this research. Hence, it is necessary to understand the influence of characteristics of spacer fabric on thermal and water vapor transmission properties. In this study, the effect of fabric structure, thickness, density and areal density on thermal comfort properties of 3D knitted spacer fabrics has been investigated, which is essential for vehicle seats.

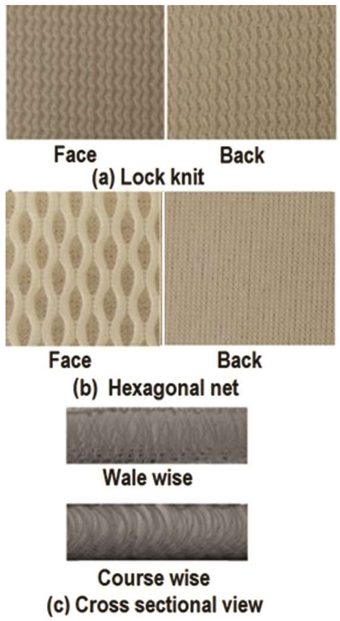
2 Materials and Methods

Twelve different spacer fabrics made up of polyester filament yarn were knitted using Raschel warp knitting machine with a gauge of E22 and 6 guide bars. The surface layer of spacer fabrics was produced with polyester multifilament yarn with same linear density; the spacer layer (connecting) was knitted using polyester monofilament with different diameters and linear densities. By adjusting guide bar movements, the fabrics were produced with two different surface structures. The first group (6 samples) was knitted using lock-knit on both the surfaces and the second group (6 samples) was produced with face layer hexagonal net and base with lock-knit structure. Among these samples, spacer fabrics with different thickness were manufactured by adjusting two needle bars. In each group, the former set was developed with 1.5, 2.5 and 3.5 mm thickness and spacer yarn diameter of 0.055 mm, but latter set was constructed with same thickness but different spacer yarn diameter (0.1mm). The loop length of the all twelve warp knit spacer fabrics was kept as 2.12 mm. The samples classification is clearly presented in Table 1. The structure and knit pattern of both lock knit and hexagonal net warp knit structures are given in Fig. 1.

Structural properties including the yarn linear density and fabric weights per unit area were determined according to ASTM D1059 standard using electronic weighing scales. The thickness of the fabrics was measured according to ASTM D1777-96 standard with the SDL digital thickness gauge at a pressure of 200 Pa. The stitch density was calculated from wales per centimeter (WPC) and course per

Table 1 — Description of warp knitted spacer fabrics [Fibre: polyester, linear density: 83 dtex, and number of filaments: 36; same for both face and back layers].

Sample	Structure	Middle layer (Spacer), dtex	Spacer yarn diameter, mm
WAS 1- WAS 3	Lock knit	33	0.055
WAS 4 – WAS 6		108	0.1
WAS 7 – WAS 9	Hexagonal net	33	0.055
WAS 10 – WAS 12		108	0.1



Lock knit	Hexagonal net

Face side
Bar 1: 1-0 0-0/ 3-2 3-3// Fully threaded
Bar 2: 2-1 1-1/ 1-0 0-0// Fully threaded
	Face side
	Bar 1: (1-0 3-3/ 3-2 1-1)x2/ (1-0 3-3/ 3-2 4-4)/ (5-4 3-3/ 3-2 4-4)x2/ (5-4 3-3/ 3-3 2-2)// 2 Empty 2 Thread
	Bar 2: (5-4 3-3/ 3-2 4-4)x2/ (5-4 3-3/ 3-2 1-2)/ (1-0 3-3/ 3-2 1-1)x2/ (1-0 3-3/ 3-2 4-4)// 2 Empty 2 Thread

Middle (Spacer) layer Bar 3: 1-0 2-1/ 2-1 1-0/ 1 Full 1 Empty Bar 4: 2-1 1-0/ 1-0 2-1/ 1 Full 1 Empty	Middle (Spacer) layer Bar 3: 1-0 2-1/ 2-1 1-0/ 1 Full 1 Empty Bar 4: 2-1 1-0/ 1-0 2-1/ 1 Full 1 Empty
Back side Bar 5: 0-0 2-1/ 1-1 1-0// Fully threaded Bar 6: 3-3 1-0/ 0-0 3-2// Fully threaded	Back side Bar 5: 0-0 2-1/ 1-1 1-0// Fully threaded Bar 6: 3-2 1-0/ 0-0 3-2// Fully threaded

Fig. 1 — Structure and knit pattern of knitted spacer fabric

centimeter (CPC) with the help of optical microscope. The density (D) of the fabric was calculated using the following relationship[31, 24]:

$$D(kg/m^3) = \frac{W}{t} \quad \text{... (1)}$$

where W is the areal density (weight per unit area); and t, the thickness. Porosity (H) was calculated using the following equation:

$$H = 1 - \frac{\rho_b}{\rho_a} \quad \text{... (2)}$$

where ρ_b is the bulk density of spacer fabrics; and ρ_a, the weighted average absolute density of polyester ($1.36 g/cm^3$) fibres in the spacer fabric, expressed in kg/m^3. The structural characteristics of warp knitted spacer fabrics are presented in the Table 2. All the experiments were carried out under standard ambient conditions and as per standard testing methods.

2.1 Air Permeability

Air permeability is described as the rate of air flow passing perpendicularly through a known area, under a prescribed air pressure differential between the two surfaces of a material. Tests were performed according to standard ISO 9237 using a Textest FX-3300 air permeability tester. The air pressure differential between the two surfaces of the material was 200 Pa.

2.2 Thermal Properties

In this study, the thermal conductivity of spacer fabric was measured using Alambeta[32]. The thermal conductivity values of spacer fabrics are presented in Table 3.

2.3 Water Vapor Permeability

The water vapor permeability of the samples has been measured using the Permetest instrument. It works on the principle of heat flux sensing. The fabric sample is placed on a measuring head over a semi-permeable foil and exposed to parallel air flow at a velocity of 1m/s. The temperature of the measuring head is maintained at room temperature (21^{o}C) for isothermal conditions. Normally, the heat loss takes place in the measuring head, when it is subjected to water flow. This instrument measures the heat loss from the measuring head due to the evaporation of water in bare condition and in the condition when covered by the fabric.

The relative water vapor permeability (RWVP) of the fabric sample is calculated by the ratio of heat loss from the measuring head with fabric (q_s) and without fabric (q_o) as below[33, 34]:

$$\text{RWVP} = \frac{q_s}{q_o} \times 100\% \quad \text{... (3)}$$

Permetest characterizes the capability of the fabric to transfer water vapor, by measuring two parameters, namely the relative water vapor permeability and the absolute evaporative resistance (R_{et}) (Table 3).

2.4 Statistical Analysis

Statistical analysis software (QC Expert - Trilobyte) was used to conduct all the statistical tests mentioned

Table 2 — Structural characteristics of warp knitted spacer fabrics

Warp spacer samples	Stitch density, stitches/cm^2				GSM, g.m^{-2}				Thickness, mm				Density kg.m^{-3}	Porosity, %
	Mean	ME	LL	UL	Mean	ME	LL	UL	Mean	ME	LL	UL		
WAS 1	120.4	1.1	119.30	121.50	262.3	0.7	261.6	263.1	1.50	0.03	1.47	1.53	174.89	87.33
WAS 2	121	1.4	119.60	122.40	354.3	0.8	353.6	355.1	2.50	0.04	2.46	2.54	141.73	89.73
WAS 3	120.3	1.3	119.00	121.60	446.0	3.1	442.9	449.1	3.50	0.03	3.47	3.53	127.42	90.77
WAS 4	119	1.2	117.80	120.20	573.1	0.7	572.4	573.8	1.50	0.02	1.48	1.52	382.06	72.31
WAS 5	120	1.1	118.90	121.10	871.9	0.6	871.3	872.5	2.50	0.01	2.49	2.51	348.77	74.73
WAS 6	120.5	0.9	119.60	121.40	1174.1	0.7	1173.4	1174.8	3.50	0.01	3.49	3.51	335.47	75.69
WAS 7	119	1.6	117.40	120.60	263.4	2.9	260.6	266.3	1.50	0.03	1.47	1.53	175.63	87.27
WAS 8	120	0.9	119.10	120.90	353.1	0.6	352.5	353.7	2.50	0.03	2.47	2.53	141.25	89.76
WAS 9	119.1	1.2	117.90	120.30	447.1	0.9	446.3	448.0	3.50	0.02	3.48	3.52	127.75	90.74
WAS 10	121	1.3	119.70	122.30	572.3	1.4	570.9	573.7	1.50	0.02	1.48	1.52	381.55	72.35
WAS 11	119.6	1.1	118.50	120.70	872.5	1.0	871.5	873.5	2.50	0.01	2.49	2.51	348.98	74.71
WAS 12	119.5	1.4	118.10	120.90	1173.3	1.4	1171.9	1174.7	3.50	0.03	3.47	3.53	335.23	75.71

ME – Margin of error, LL – Lower limit and UL – Upper limit.

Table 3 — Heat and moisture transfer properties of 3D warp knitted spacer fabrics.

Fabric	Thermal conductivity (λ)×10^{-3} W.m^{-1}k^{-1}				Thermal resistance (r) ×10^{-3} km^{2}W^{-1}				RWVP, %				Evoporative resistance Pa.m^{2}kW^{-1}			
	Mean	ME	LL	UL	Mean	ME	LL	UL	Mean	ME	LL	UL	Mean	ME	LL	UL
WAS1	47.94	0.4	47.54	48.34	64.92	0.67	64.25	65.59	51.12	0.89	50.23	52.01	7.32	0.4	6.92	7.72
WAS2	46.82	0.27	46.55	47.09	66.16	0.24	65.92	66.4	49.62	0.53	49.09	50.15	8.14	1.05	7.09	9.19
WAS3	45.61	0.78	44.83	46.39	68.42	0.39	68.03	68.81	48.7	1.3	47.4	50	8.86	0.9	7.96	9.76
WAS4	53.48	0.51	52.97	53.99	53.98	0.32	53.66	54.3	28.56	1.14	27.42	29.7	18.35	1	17.35	19.35
WAS5	52.27	0.29	51.98	52.56	56.16	0.56	55.6	56.72	27.1	1.11	25.99	28.21	20.12	1.05	19.07	21.17
WAS6	51.96	0.31	51.65	52.27	59.44	0.33	59.11	59.77	25.92	0.33	25.59	26.25	21.98	1.22	20.76	23.2
WAS7	46.78	0.86	45.92	47.64	71.34	1.02	70.32	72.36	61.28	1.64	59.64	62.92	4.92	1.09	3.83	6.01
WAS8	45.64	0.7	44.94	46.34	77.56	0.72	76.84	78.28	58.38	0.42	57.96	58.8	6.04	0.77	5.27	6.81
WAS9	44.38	0.75	43.63	45.13	82.12	0.9	81.22	83.02	57.16	0.6	56.56	57.76	6.6	0.89	5.71	7.49
WAS10	51.19	0.28	50.91	51.47	60.71	0.32	60.39	61.03	39.48	0.47	39.01	39.95	12.58	0.96	11.62	13.54
WAS11	50.45	0.2	50.25	50.65	61.13	0.81	60.32	61.94	37.88	0.76	37.12	38.64	14.4	0.74	13.66	15.14
WAS12	49.78	0.38	49.4	50.16	63.45	0.49	62.96	63.94	36.61	0.53	36.08	37.14	15.9	1.1	14.8	17

ME – Margin of error, LL – Lower limit and UL – Upper limit.

in this work. Advance statistical evaluation and two-way analysis of variance was used to analyze the significance of various factors on required properties of warp knitted spacer fabrics. Also, differences in mean values among various groups were examined for statistical significance using one-way ANOVA followed by pair comparison using Scheffe's method. For all the statistical tests, differences were considered significant at $P < 0.05$. Data were reported as mean ± standard error of mean, unless otherwise stated.

3 Results and Discussion

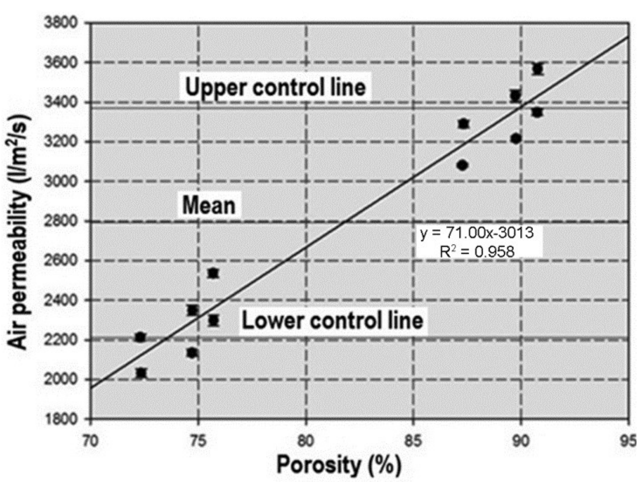
3.1 Porosity and Stitch Density

The unique characteristic of spacer fabrics is porosity, which decides air permeability, moisture transmission, and thermal comfort. The volume porosity is mostly affected by surface structure, thickness and density. In this study polyester multifilament with same linear density has been used in the outer surface layers, and polyester monofilament with two different linear densities (33 & 108 dtex) were used in spacer layer. The spacer fabric porosity is directly influenced by the vertical gaps created by a spacer layer and also depends on bulkiness. The stitch density is the surface characteristics of textile materials, which normally decides the tightness, openness and loop geometry of fabrics. The small variations in stitch density have a higher influence on the pore size and volume porosity. In this work, the stitch density is kept almost same for all the samples, because the volume porosity is directly affected by the varying thickness and areal density.

One way ANOVA was conducted to study the significance of stitch density, and it proves that there is no significant differences among the samples with p-value greater than 0.05 (p= 0.246). Figure 2 proves that the porosity has direct positive correlation with air permeability with (R^2 value 0.958). The porosity of both structures (lock knit and hexagonal) is almost same, but the significant differences in air-permeability is observed due to its different surface structure. The increase in porosity can result in a significant increase in air and water vapor permeability.

3.2 Effect of Structural Characteristics on Air Permeability

The cushions are subject to change in air movement, and velocity depends on compressive load applied by persons. If the air flow rate is too high or irregular, then local thermal discomfort appears. Thus, it's very important to control the air velocity and the flow direction in the cushioning materials. The air permeability of a fabric is closely related to the construction characteristics of the yarns, in which large volumes are occupied by air. The air permeability of a spacer fabric is defined as a measure of how well it allows the passage of air through it. The air transmission is of importance for a number of spacer fabric end uses. There are several factors affecting the air permeability of the fabric, such as fabric's structure, thickness, porosity, surface characteristics, etc. The air permeability of fabric is



ANOVA	DF	Sum of squares	Mean square	F value	Prob > F
Model	1	3.53E+06	3.53E+06	232.5397	2.98E-08
Error	10	151994	15199.4		
Total	11	3.69E+06			

Fig. 2 — Effect of porosity on air permeability

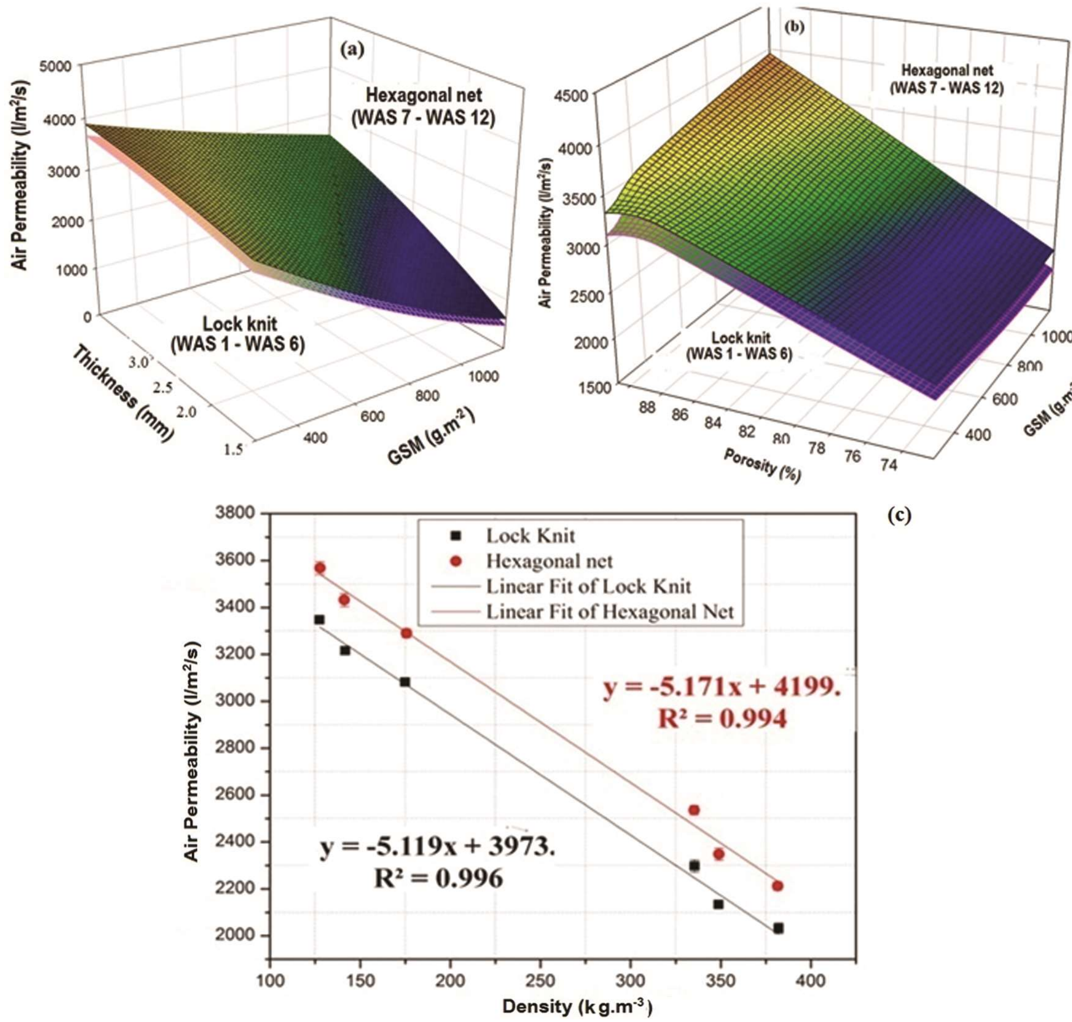
highly correlated with fabric areal density and thickness, which are related to fabric tightness. The results show that fabric thickness has a significant effect on the air permeability values of the spacer fabric, as air permeability tends to increase as thickness decreases, irrespective of yarn linear density and stitch density. As shown in Fig. 3, the lower thickness and mass per square meter also facilitate the passage of air through the fabric. It is also observed from the graph that the denser fabrics offer more resistance towards air to pass from one surface to other.

Also, it is observed from Fig. 3 that the porous fabrics with lower areal density are more permeable to air. Lock knit fabrics (WAS 1 – WAS 6) have tighter surface structure because they inter-loop the filaments very close to each other, So, it is resistant to air flow. Comparison among all the samples shows that the hexagonal net fabrics have more air permeability than lock knit fabrics with respect to thickness and areal density. Hexagonal knit fabrics (WAS 7 – WAS 12) have more open structure on the surface and produces more gaps, which results in high permeability to air. All these factors contribute towards the higher air permeability.

3.3 Influence of Structural Characteristics on Thermal Properties

Thermal resistance is a measure of a material's ability to prevent heat from flowing through it. Thermal conductivity and resistance are immensely influenced by the fabric structure and thickness. Increase in fabric thickness will result in an increase in thermal insulation, as there will be a decrease in heat losses for the space insulated by the textile. Thermal resistance is a function of the thickness and thermal conductivity of a fabric. To study the thermal performance of the above samples, characterization and analysis of thermal properties such as thermal conductivity and thermal resistance are studied.

Figure 4 demonstrates the influence of thickness and areal density on thermal properties of all the samples. It is reported that the thermal conductivity decreases with increasing thickness and areal density for both the structures. The major factors influencing the thermal behavior of fabrics are density, porosity and air permeability. As shown in Figs 5 (a) and (b), the thermal conductivity of spacer fabrics significantly increases with increase in density and decrease in air permeability. Also, it is observed that the hexagonal net fabrics (WAS 7- WAS 12) have the ability to resist more heat than the fabrics with lock knit



	ANOVA	DF	Sum of squares	Mean square	F value	Prob > F
Lock Knit	Model	1	1.75E+06	1.75E+06	1056.4929	5.34E-06
	Error	4	6634.3417	1658.5854		
	Total	5	1.76E+06			
Hexagonal	Model	1	1.78E+06	1.78E+06	747.54169	1.06E-05
	Error	4	9536.979	2384.2448		
	Total	5	1.79E+06			

Fig. 3 — Influence of structural parameters on air permeability

structure on the surface (WAS 1 – WAS 6). The open surface pores in hexagonal fabrics result in higher air permeability, and hence make the materials thermally resistant comparatively. It is also observed from Fig. 5 (c) that the spacer fabrics with low porosity result in high thermal conductivity, as the fabrics act as a barrier for air permeability. Overall findings show that the fabrics with comparatively higher thickness entrap more air within the middle layer and therefore cause higher thermal resistance with lower thermal conductivity. The amount of air entrapped in denser fabrics (WAS 4 –WAS 6 and WAS 10 – WAS 12) is high and it allows conduction of heat, causing higher thermal conductivity. Figure 5 also presents the regression model for thermal conductivity with the effect of density and air permeability. The thermal conductivity of warp knitted spacer fabric has the positive linear correlation with density and negative correlation with porosity and air permeability with the coefficient of the determinant of more than 0.9.

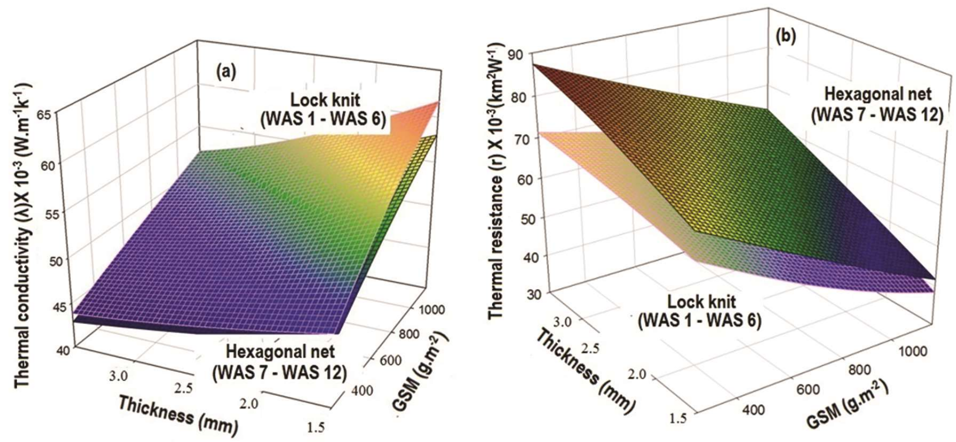
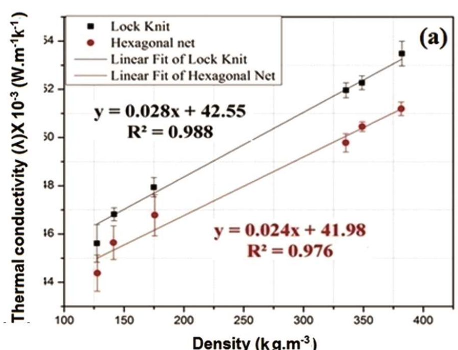
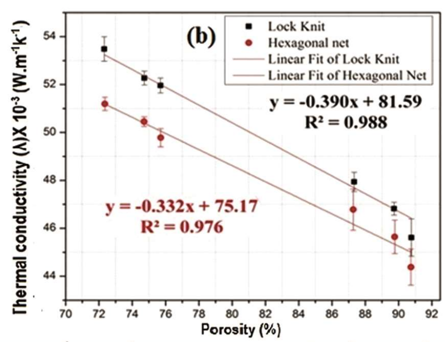


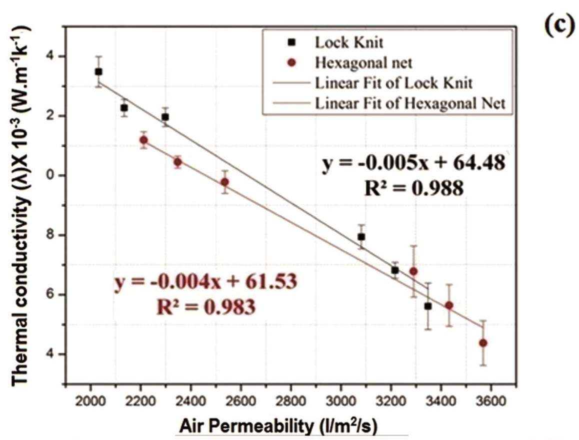
Fig. 4 — Effect of gsm and thickness on thermal properties



	ANOVA	DF	Sum of squares	Mean square	F value	Prob > F
Lock Knit	Model	1	5.35E+01	5.35E+01	355.27414	4.67E-05
	Error	4	0.60253	0.15063		
	Total	5	5.41E+01			
Hexagonal	Model	1	3.86E+01	3.86E+01	166.06597	2.09E-04
	Error	4	0.92908	0.23227		
	Total	5	3.95E+01			



.	ANOVA	DF	Sum of squares	Mean square	F value	Prob > F
Lock Knit	Model	1	5.35E+01	5.35E+01	355.27414	4.67E-05
	Error	4	0.60253	0.15063		
	Total	5	5.41E+01			
Hexagonal	Model	1	3.86E+01	3.86E+01	166.06597	2.09E-04
	Error	4	0.92908	0.23227		
	Total	5	3.95E+01			



	ANOVA	DF	Sum of squares	Mean square	F value	Prob > F
Lock Knit	Model	1	5.35E+01	5.35E+01	334.33428	5.26E-05
	Error	4	0.63982	0.15996		
	Total	5	5.41E+01			
Hexagonal	Model	1	3.89E+01	3.89E+01	240.412	1.01E-04
	Error	4	0.64647	0.16162		
	Total	5	3.95E+01			

Fig. 5 — Effect of structural characteristics and linear regression model for thermal conductivity

3.4 Effect of Structural Parameters on Water Vapor Permeability

The transmission of heat through compression is additionally disturbed by the occupant's temperature control system, that is perspiration. These properties are required in the materials; mainly mattress, shoe insole, seat and back supports should be characterized by their ability to transport moisture, irrespective of ability to maintain appropriate thermal properties. The moisture transport behavior is based on absorbing moisture by the material, and its transport to the environment. The physiological properties of seat materials are due to the two factors, namely the ability to accumulate moisture and the transmission of water vapor. The porous and elastic cushions are subject to undergo multidirectional stresses of compression and relaxation due to vibrations caused by car's motion. It results in carrying out of water vapor from one medium to another medium by means of pump effect. So, in this section the ability of spacer fabrics to transport water vapor and evaporative resistance are carefully measured and discussed. Figure 6 demonstrates the influence of thickness and areal density on physiological properties of all the samples. It is reported that the relative water vapor permeability decreases with increasing thickness and areal density for all the fabrics. The pore characteristics in the cushioning fabrics are an important factor, in which diffusion of water vapor occurs.

As shown in Fig. 7, the evaporative resistance is lower for the porous spacer fabrics with high air permeability. It is also proved that the spacer fabrics with low density result in higher water vapor permeability. Overall, it is observed that the evaporative resistance decreases with increase in porosity and decrease in thickness, density and areal density of

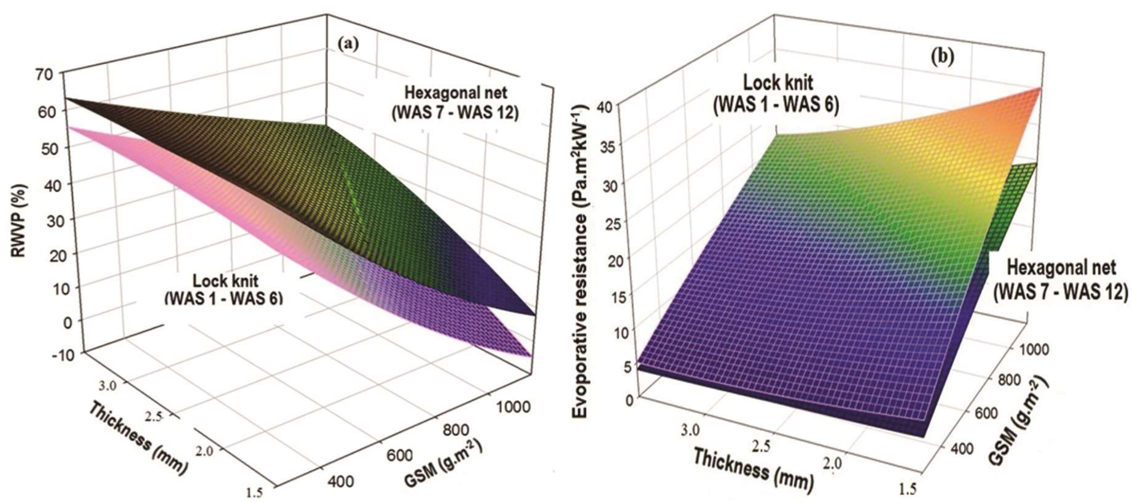


Fig. 6 — Effect of thickness and areal density on water vapor permeability

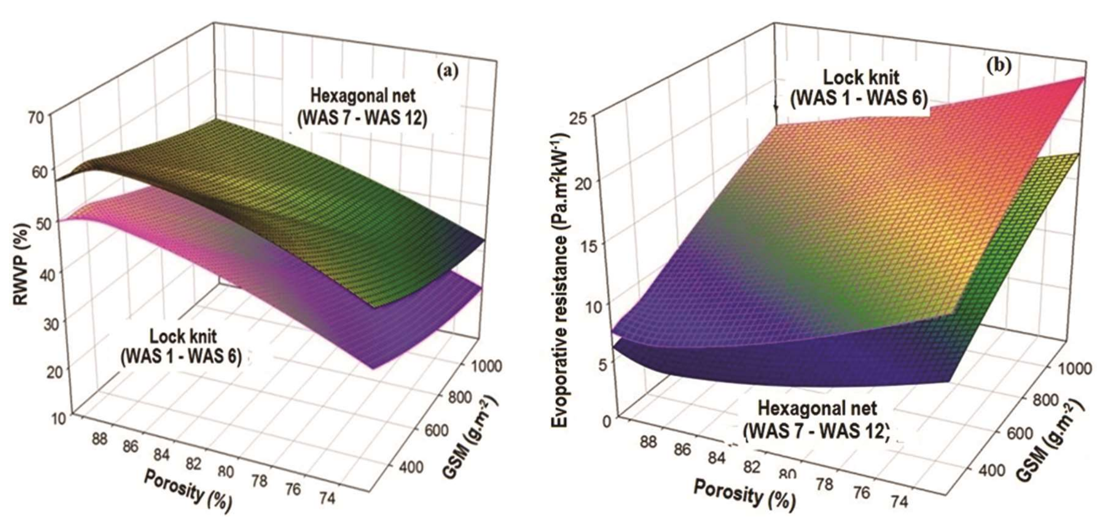
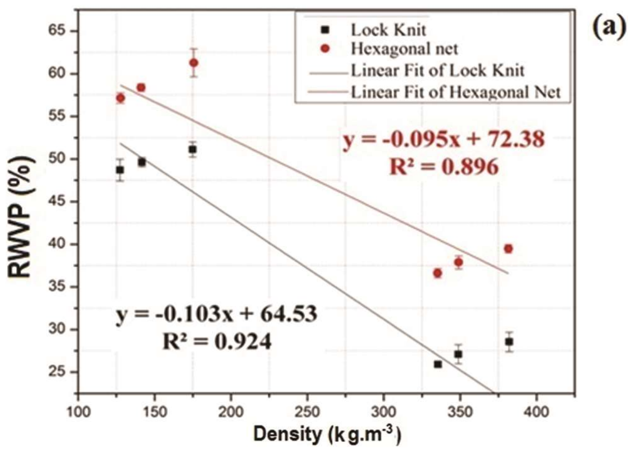


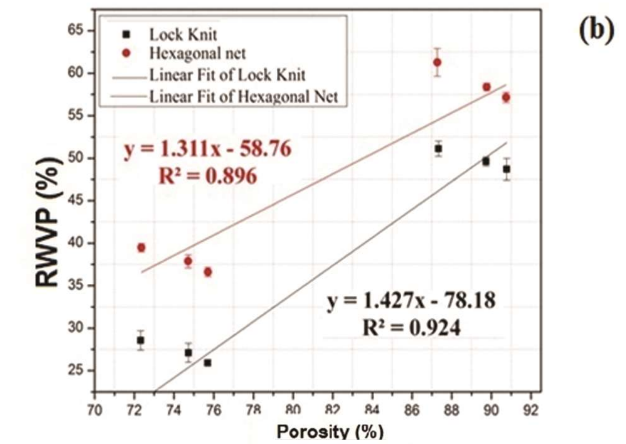
Fig. 7 — Influence of structural characteristics on water vapor permeability

spacer fabrics. It was also noticed that the hexagonal net fabrics (WAS 7- WAS 12) have ability to pass more water vapor than the fabrics with lock knit structure on the surface (WAS 1 – WAS 6). Because the open surface pores in hexagonal fabrics results in porous nature, it makes the material with higher water vapor permeability.

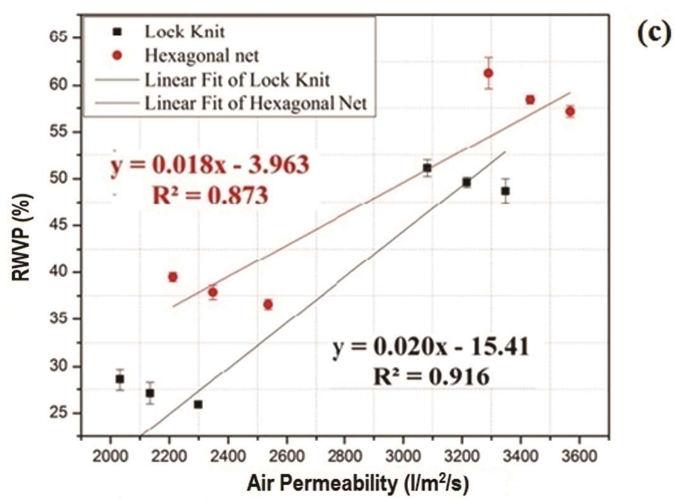
The result obtained show that the thick spacer fabrics with high density have higher evaporative resistance [Figs 8(a) and (b)]. The increase in thickness of middle (spacer) layer has the ability to entrap more air, therefore causing higher evaporative resistance with lower water vapor permeability. The spacer fabrics (WAS 1 – WAS 3 and WAS 7 –



	ANOVA	DF	Sum of squares	Mean square	F value	Prob > F
Lock Knit	Model	1	7.15E+02	7.15E+02	48.73043	2.21E-03
	Error	4	58.71211	14.67803		
	Total	5	7.74E+02			
Hexagonal	Model	1	6.02E+02	6.02E+02	34.67824	4.16E-03
	Error	4	69.43936	17.35984		
	Total	5	6.71E+02			



	ANOVA	DF	Sum of squares	Mean square	F value	Prob > F
Lock Knit	Model	1	7.15E+02	7.15E+02	48.73043	2.21E-03
	Error	4	58.71211	14.67803		
	Total	5	7.74E+02			
Hexagonal	Model	1	6.02E+02	6.02E+02	34.67824	4.16E-03
	Error	4	69.43936	17.35984		
	Total	5	6.71E+02			



	ANOVA	DF	Sum of squares	Mean square	F value	Prob > F
Lock Knit	Model	1	7.09E+02	7.09E+02	43.76966	2.70E-03
	Error	4	64.80923	16.20231		
	Total	5	7.74E+02			
Hexagonal	Model	1	5.87E+02	5.87E+02	27.65371	6.26E-03
	Error	4	84.8492	21.2123		
	Total	5	6.71E+02			

Fig. 8 — Linear regression model for water vapor permeability

WAS 9) show relatively lower density and higher porosity; therefore allows water vapor to pass through easily.

It is observed from the Fig. 8(c) that the water vapor permeability depends not only on air permeability, but it depends on surface structure, structural pores, thickness and density. Figure 8 also presents the regression model for water vapor permeability with the effect of density, porosity and air permeability. The water vapor permeability of warp knitted spacer fabric has a negative linear correlation with density and positive correlation with air permeability and porosity with R^2 value more than 0.9.

3.5 Statistical Evaluation for Thermo-physiological Behavior of Warp Knit Spacer Fabrics

The study for each thermo-physiological property (air permeability, thermal resistance, thermal conductivity, water vapor permeability and evaporative resistance) has been done by two-way analysis of variance (ANOVA) with a confidence level of 95%. In this section, the statistical significance of fabric characteristics is presented (Table 4). Statistical analysis also indicates that the structure and thickness of warp knit spacer fabrics are significantly influenced by air permeability, thermal conductivity and evaporative resistance with $F_{critical} < F_{static}$. But the insignificant differences are observed in the interaction on fabric properties.

Table 4 — Statistical evaluation (Two way Anova) for thermo-physiological properties of warp knit spacer fabrics.

Source of variability	Sum of squares	Mean square	Degrees of freedom	Std deviation	F-statistic	Critical quantile	Conclusion	p-value
Structure vs Thickness on Air permeability								
Structure	69122.7	69122.7	1	262.9119	3703	18.5128	Significant	0.00027
Thickness	73989.3	36994.7	2	192.34	1981.86	19	Significant	0.0005
Interaction	36.1151	36.1151	1	6.110101	29.6465	161.448	Insignificant	0.11563
Residuals	1.21819	1.21819	1	1.103718				
Total	143149	28629.9	5	169.2036				
Structure vs Thickness on Thermal Conductivity								
Structure	2.12415	2.12415	1	1.457446	3267.92	18.5128	Significant	0.00031
Thickness	5.5969	2.79845	2	1.672857	4305.31	19	Significant	0.00023
Interaction	0.00124	0.00124	1	0.036056	20.5853	161.448	Insignificant	0.13811
Residuals	6.02E-05	6.02E-05	1	0.007761				
Total	7.72235	1.54447	5	1.242767				
Structure vs Thickness on Thermal Resistance								
Structure	165.585	165.585	1	12.86799	23.9144	18.5128	Significant	0.03936
Thickness	51.0137	25.5069	2	5.050432	3.6838	19	Insignificant	0.2135
Interaction	13.3868	13.3868	1	3.721308	29.0159	161.448	Insignificant	0.11685
Residuals	0.46136	0.46136	1	0.679235				
Total	230.447	46.0894	5	6.788916				
Structure vsThickness on Relative Water Vapor Permeability								
Structure	124.944	124.944	1	11.17784	303.508	18.5128	Significant	0.00328
Thickness	11.1185	5.55927	2	2.35781	13.5043	19	Insignificant	0.06895
Interaction	0.80228	0.80228	1	0.907377	38.1072	161.448	Insignificant	0.10224
Residuals	0.02105	0.02105	1	0.145097				
Total	136.886	27.3772	5	5.232321				
Structure vs Thickness on Evaporative Resistance								
Structure	7.61627	7.61627	1	2.759758	676	18.5128	Significant	0.00148
Thickness	2.6284	1.3142	2	1.146386	116.645	19	Significant	0.0085
Interaction	0.00725	0.00725	1	0.150111	0.47394	161.448	Insignificant	0.61617
Residuals	0.01529	0.01529	1	0.123644				
Total	10.2672	2.05344	5	1.432983				

4 Conclusion

The conclusions induced from this research are as follows:

4.1 The porosity of both structures (lock knit and hexagonal) is almost same, but the significant differences in air-permeability are observed due to their different surface structure.

4.2 The spacer fabric with thin , porous and lower areal density facilitates hexagonal fabrics to produce more open structure on surface than lock knit fabrics. It produces more gaps which results in high permeability to air.

4.3 It is also noticed that, hexagonal net fabrics have the ability to pass more water vapor than the fabrics with lock knit structure. As the open surface pores in hexagonal fabrics result in porous nature, it makes the material with higher water vapor permeability and optimum thermal conductivity.

4.4 The two-way ANOVA confirms that the thickness and surface structure have a significant impact on the spacer fabric thermal comfort properties. It is also found that there is linear regression correlation between the fabric properties.

4.5 After deep consideration of all the properties required for car seats, the spacer fabric with a hexagonal net structure on the face (WAS 7 – WAS 9) is recommended due to their optimum water and air permeability with good thermal conductivity.

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References

1 Fung W & Hardcastle M, *Textiles in Automotive Engineering* (Woodhead Publishing, Cambridge, UK), 2001.
2 Silva M C G, *Meas Sci Technol*, 13(2002) 41.
3 Simion M, Socaciu L & Unguresan P, *Energy Procedia*, 85(2016) 472.
4 Pause B, Thermal control of automotive interiors with phase change material, *WO Pat* 02083440, 2004.
5 Madsen T L, *Int J Ind Ergonom,* 13(1994) 253.
6 Du H, Wang Y P, Yuan X H, Deng Y D & Su C Q, *J Electron Mater,* 45(2016) 1529.
7 Shishoo R, *Textile Advances in the Automotive Industry* (Woodhead Publishing Limited and CRC Press LLC), 2008.
8 Brooks J E & Parsons K C, *Ergonom.,*42(1999) 661.
9 Pamuk G & Ceken F, *Fibers Text East Eur,* 16 (4)(2008) 57.
10 Lustbader J A, *Evaluation of Advanced Automotive Seats to Improve Thermal Comfort and Fuel Economy*, paper presented at the Vehicle Thermal Management Systems Conference and Exhibition (SAE Technical Paper), 10-12 May 2005, Toronto, Canada.
11 Holmer I, Nilsson H, Bohm M & Noren O, *J Physiol Anthropol Appl Human Sci,* 14(4)(1995) 159.
12 Cengiz T G & Babalik F C, *Int J Ind Ergon,* 39(2009) 287.
13 Snycerski M & Frontczak-Wasiak I, *Autex Res J,* 2(2002) 126.
14 Khalifa T F & Hafez H S, *Int J Adv Res Sci Eng,* 4(2015) 424.
15 Arumugam V, Mishra R, Militky J & Salcova J, *J Text Inst,* 108(2017) 1095.
16 Ogulata T & Mavruz S, *Fibers Text East Eur*, 18(2010) 71.
17 Cho J U, *Adv Sci Technol Lett,* 118(2015) 54.
18 Cengiz T G & Babalık F C, *Appl Erg,* 38(2007) 337.
19 Yamashita K, Matsuo J, Tochihara Y, Kondo, Takayama S & Nagayama H, *J Physiol Anthropol Appl Hum Sci,* 24(2005) 61.
20 Prek M, *Energy,* 31(2006) 732.
21 Arumugam V, Mishra R, Militky J & Tunak M, *J Ind Text*, 46(2016) 868.
22 Bruer S H, Powel N & Smith G, *J Text Appl Tech Mangmt,* 4(2005) 1.
23 Arumugam V, Mishra R, Militky J & Novak J, *Fibers Polym,* 16(2015) 2467.
24 Mecit D & Marmarali A, *Usak University J Material Sci,* 1(2012) 71.
25 Gross D, *J Text Appl Tech Mangmt,* 4(2003) 26.
26 Bagherzadeh R, Gorji M, Latifi M, Payvandy P & Kong L X, *Fibers Polym,* 13 (2012) 529.
27 Miao X H & Ge M Q, *Fibres Text East Eur,* 16(2008) 90.
28 Armakan D M & Roye A, *Fiber Polym,* 10(2009) 116.
29 Onal L & Yildirim M, *Text Res J,* 17(2012) 1.
30 Xiaohua Y E, Hong H & Feng X, *J Ind Text,* 37(3) (2008) 213.
31 Arumugam V & Selvakumar N, *Indian J Fibre Text Res,* 37(2012) 385.
32 Lizak P & Mojumdar S C, *J Therm Anal Calorim*, 112(2013) 1095.
33 Hes L, *Indian J Fibre Text Res, 33*(2008) 239.
34 Hes L & Dolezal I, *Proceeding*s, 7th *Asian Textile Conference* (CD-ROM) (The Textile Association of India, New Delhi), 2003.