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Study on physiological comfort of fabrics made up of structurally modified friction-spun yarns: Part I – Vapour transmission

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The effect of sheath fibre proportion, fibre fineness, and yarn fineness on physiological comfort related properties such as air permeability, water vapour permeability and thermal conductivity of Dref-III friction-spun yarn fabrics has been studied with an objective to analyse the feasibility of modified yarns for apparel end use. Samples have been prepared using polyester filament fibre as core, viscose staple fibre as secondary core and water soluble polyvinyl alcohol as sheath. It is observed that the structural modification of yarn influences the comfort related properties, effecting the vapour transmission behavior.

Keywords: Air permeability, Friction-spun yarn, Thermal conductivity, Vapour transmission, Water vapour permeability

1 Introduction

Physiological comfort is very basic and necessary property of the fabric and the fabric structure plays an important role in comfort of any garment. The comfort has been an inherent feature of the knitted textiles as it is mostly used for inner garment and the wears of delicate use such as ladies and infant dress materials. To further enhance the softness in knitted fabric twistless yarns are used instead of conventional spun yarns for making the fabric. The yarn strength largely depends on the amount of twist but it has the disadvantage of imparting a harsh feel to the fabric[1], whereas twistless yarns can overcome this disadvantage of harsh feel. Once the twistless yarn has been assembled in a fabric structure, the compacting forces created by the fabric structure itself hold the systems together[2]. Hence, it is quite possible to produce a knitted fabric made of twistless yarn. Knitted garments are in lot of demand and in future would be making a lot of scope because of their property to fit snuggly to the body and thus to provide physiological comfort. Hence, more study needs to be carried out on the modification of friction-spun yarn with improved parameters of physiological comfort, which can be used for knitted apparels. Among the modern high technologies for producing spun yarn, friction spinning has some advantage over the others due to higher productivity and flexibility in structure. But its main disadvantage is the harsh feel due to the wrapper fibres of the sheath[1]. In order to increase the comfort related properties of friction-spun yarn, a research work was carried out to achieve twistless and hollow yarns by Das and Ishtiaque[2]. Merati and Okamura[3,4] succeeded in getting the hollow yarn with enhanced comfort but they were unable to minimize harsh feel. Das *et al*.[5] also reported the properties of woven fabrics made of twistless and hollow yarns. The main objective of the present work is to achieve twistless friction-spun yarn in order to minimize harshness and subsequently enhance physiological comfort related properties. It has been considered that the physiological comfort evaluation is a function of fabric behaviour with respect to vapour and liquid transmission properties. Hence, in the present work, the effect of sheath fibre proportion, fibre fineness and yarn fineness on the vapour transmission related properties, such as air permeability, water vapour permeability and thermal conductivity, of modified Dref-III friction-spun yarns fabric has been studied.

2 Materials and Methods

A series of core-sheath type yarns was produced on Dref-III friction spinning machine. For all the yarns, the central core consisted of polyester multifilament

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yarn (75/105 den, i.e. 0.7 den/filament) followed by the secondary layer of staple viscose fibre (51 mm with 1.3, 1.5 and 1.7 den) and the sheath consisted of polyvinyl alcohol (PVA) staple fibre (51 mm×1.7 den). The idea of incorporating PVA in sheath was to have twistless yarn surface in the fabric stage to obtain very soft feel[2,5]. PVA is soluble in hot water. As the fabrics were washed in hot water the PVA in the sheath was washed out leaving the twistless viscose staple fibres on the surface. The idea of incorporating polyester multifilament in the core was to have sufficient strength of yarn as the proportion of PVA sheath was very little. This was because of the fact that the cost of PVA fibre is very high and at the same time the PVA has to be removed after fabric preparation and also one of the objectives was to optimize the proportion of PVA fibre.

Selection of raw material was done using polyester filament fibre as a core, viscose staple fibre as a secondary core and PVA as a sheath. The linear density of slivers of viscose and PVA were 3.1 ktex and 2.99 ktex respectively. Various counts taken for the study (after wash) for composition of modified friction-spun yarn were 10 Ne (59.05tex), 14Ne (49.18tex), and 18Ne (32.81tex) with different core: sheath ratio of 90:10; 87.5:12.5; and 85:15 at constant yarn delivery speed of 200 m/min and spinning drum speed of 3500 rpm.

As the removal of PVA sheath was being sought after knitted fabric formation, its percentage was kept on the lower side. For effective knitting, minimum sheath content desired is 10%. To produce the yarn of desired count, i.e. after wash, the resultant count was spun on the higher side keeping in view the percentage removal of sheath content. Following facts were considered:

Resultant count = count to be produced after wash × resultant core %
Resultant core % = 1/secondary core % + 1/primary core %
Primary core % will remain constant.

2.1 Methodology

The use of continuous polyester multifilament in the core provides the strength to the yarn. Viscose is taken as a staple fibre for secondary core and PVA staple fibre as a sheath. The amount of PVA varies from 10% to 15% of the yarn. PVA sheath allows the yarn to withstand wear and tear or provides strength during knitting. It gets dissolved at 90°C and allows staple fibre to open this yarn structure to meet the functional requirements without affecting the strength of the yarn[2]. At the end, it results in improved physiological comfort of the modified friction-spun yarn. Even after the removal of PVA, the fabrics were not affected because compacting forces created by the fabric structure itself hold the system together and also polyester multifilament core provides the strength to the yarn. These knitted fabrics were then tested for comfort properties related with vapour transmission, viz. air permeability, water vapour permeability and thermal conductivity, as given below:

Vapour transmission = f (X_1, X_2, X_3) at constant atmospheric conditions and constraints

where X_1 is the air permeability; X_2, the thermal conductivity; and X_3, the water vapour permeability.

An attempt was also made to develop regression model equations of the above-mentioned properties to predict and to reproduce the results. The knitted fabrics developed from the modified friction-spun yarns can be used for the specific apparels demanding higher vapour transmission properties relating to physiological comfort, viz. air permeability, thermal conductivity and water vapour permeability.

All yarn samples were converted into plain circular knitted fabric of 22 courses/inch and 22 wales/inch for comparative study. Harry Lucas (Germany) circular knitting machine having three and a half inch cylinder diameter with 14 inch gauge, running at the speed of 40 rpm with single feeder was used.

2.2 Washing Treatment of Fabric

Washing was performed for 45 min in boiling water followed by washing in the cold water. This procedure was repeated for 2-3 times till all the PVA got dissolved. After washing the fabrics were dried and conditioned for 24 h at 65%±2% relative humidity and 27°C±2°C temperature [ASTM D1776-90 (96)]. After that the fabrics were used for testing. Dimensional stability, in terms of relaxation shrinkage, is found to vary from 3% to 4% for all samples.

2.3 Test Method

The prepared knitted samples were conditioned and tested as per the ASTM standards: air permeability (ASTM D 737-75), thermal conductivity (ASTM 1518-77), and water vapour permeability (ASTM E 96-94).

2.3.1 Air Permeability Test

The volume of air in cm^3 which flows per second through 1 cm^2 of fabric under head of 1cm water-column is the measure of air permeability. The Shirley air permeability tester was used for measuring air permeability. A minimum of 20 observations were made for each sample. Air at 20±2ºC and 65±2% RH was used for the test. The test area was 5.07 cm^2.

2.3.2 Thermal Conductivity

SASMIRA thermal conductivity apparatus was used for measuring thermal conductivity of knitted fabrics. Thermostat was set at 50°C and then guard box was switched on. Temperature was allowed to stabilize at 50°C. After the temperature stabilization the hot plate was switched on. Once the temperature reaches at 51°C thermostats becomes operational and temperature drops to 45°C. Samples were cut using round plate template and then placed on the hot plate. Once the temperature of hot plate falls to 45°C, sample was covered with round plate. Temperature was then allowed to rise to 51ºC. When the temperature starts falling down again, time taken for the hot plate to cool down from 50°C to 49°C was measured using a standard stopwatch. Minimum 20 observations were made to find out average cooling time and the average 'Clo' value was determined. 'Clo' value in turn was converted to the more frequently used 'Tog' value using formula "0.645×Clo = Tog". Higher Tog value means lower thermal conductivity.

2.3.3 Water Vapour Permeability

Water vapour permeability (WVP) was measured by cup method. The specimen under test was sealed over the open mouth of a dish containing water and placed in the standard testing atmosphere. Evaporation takes place under standard atmospheric conditions and loss in weight of cup after 24 h was measured. After a period of time to establish equilibrium, successive weighing of the dish was made and the rate of water vapour transfer through the specimen was calculated.

The water vapour permeability index was calculated by expressing the water vapour permeability of the fabric as a percentage of the WVP of a reference fabric, which was tested alongside the test specimen. Each dish was filled with sufficient distilled water to give a 10 mm air gap between water surface and fabric. A wire sample support was placed on each dish to keep the fabric level. Contact adhesive was applied to the rim of the dish and the specimen which was 96 mm in diameter was carefully placed on top with its outside surface upper most. The cover ring was then placed over the dish and the gap between cover ring and dish was sealed with PVC tape. After a suitable time of 24 h dishes were reweighed. WVP index was calculated using the following relationship:

$$\text{Water vapour permeability index, } \% = \frac{(\text{WVP})_f}{(\text{WVP})_r} \times 100$$

where $(\text{WVP})_f$ is the water vapour permeability of the test fabric; and $(\text{WVP})_r$, the water vapour permeability of the reference fabric.

2.4 Design of Experiment

To conduct the experiments efficiently with respect to the above-mentioned variables, three factor-three level Box & Behnken design was used for designing the experiments optimally and to create respective response surfaces. To know the interaction effect of variables, quadratic model was used, so second order response equations were considered and the approximating function used are as follows[6];

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_1{*}X_2 + \beta_5 X_2{*}X_3 + \beta_6 X_3{*}X_1 + \beta_7 X_1{*}X_1 + \beta_8 X_2{*}X_2 + \beta_9 X_3{*}X_3$$

Hence, the surface represented by $Y = f(X_1, X_2, X_3)$ is known as 'response surface'. Tables 1 and 2 show three factor-three level Box & Behnken design summary and Table 3 shows regression equations, both quadratic and linear, developed for different responses. The physical parameters of fabrics made of reference and optimized friction-spun yarns are given in Table 4.

Table 1—Actual and coded values of factors in three factor-three level Box-Behnken design

Factor	Low actual value	High actual value	Low coded value	High coded value
Fibre fineness den (X_1)	1.3	1.7	-1	1
Yarn fineness tex (X_2)	32.81	59.05	-1	1
Proportion of sheath, % (X_3)	10	15	-1	1

3 Results and Discussion

3.1 Influence of Yarn Modification on Air Permeability

After the evaluation of air permeability of the respective fabric samples in the design, analysis was performed for development of a model to get the desired regression equations both linear and quadratic (Table 3). Contour plots in Figs 1(a-c) show the effect of relationship between yarn fineness and fibre fineness; proportion of sheath and fibre fineness; and proportion of sheath and yarn fineness respectively on air permeability of fabrics. It is clear from Fig. 1(a) that at constant sheath %, as the value of yarn fineness and fibre fineness increase, the air permeability increases.

It is being established[6-8] that the bending rigidity, flexural rigidity and torsional rigidity are inter-related and are sensitive to the change in the fibre fineness or diameter[9]. Flexural rigidity[10] of viscose rayon is found to be proportional to $(\text{tex})^2$. Air permeability of yarn depends on its available specific surface, which is inversely proportional to the fibre diameter[7]. Therefore, rate of flow of air will be less for finer fibres as compared to that for coarser fibres, due to the presence of higher number of finer fibres in the yarn of same cross-section. Finer the fibre, the lesser is its diameter, resulting in presence of higher number of finer fibres in the yarn cross-section and more

Table 2—Responses in three factor-three level Box-Behnken design

Responses	No. of observation	Minimum value	Maximum value
Air permeability cc/s/cm^2 (Y_1)	17	48	51.3
Water vapour permeability index % (Y_2)	17	95.2	106.1
Thermal conductivity Tog (Y_3)	17	0.3821	0.6907

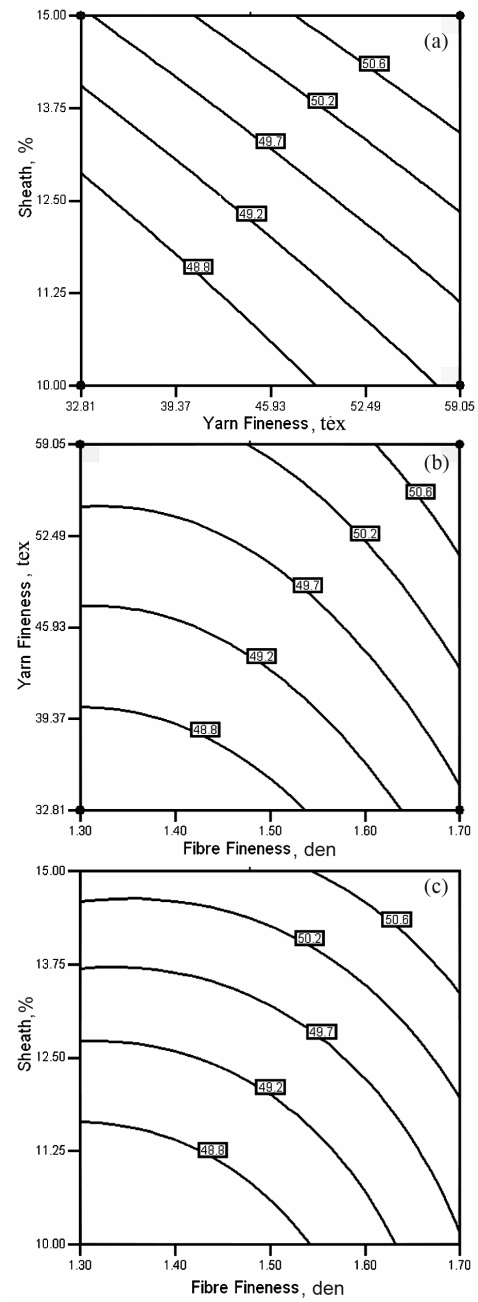

Fig. 1—Effect of yarn modification on air permeability at constant (a) fibre fineness, (b) sheath %, and (c) yarn fineness

Table 3—Response surface equations

Response	Linear regression equation	Quadratic regression equation	R^2
Air permeability (Y_1)	$37.68 + 3\,X_1 + 0.06\,X_2 + 0.37\,X_3$	$53.20 - 15.88\,X_1 + 0.04\,X_2 + 0.16\,X_3 + 7.81\,X_1^2 + 7.8\text{E-}05\,X_2^2 + 0.02\,X_3^2 - 0.01X_1X_2 - 0.3\,X_1X_3 + 0.002\,X_2X_3$	0.99
Water vapour permeability (Y_2)	$57.92 + 17.25\,X_1 + 0.05\,X_2 + 1.115\,X_3$	$95.94 + 10.96X_1 - 0.43X_2 - 2.48X_3 - 8.43X_1^2 - 0.001X_2^2 - 0.002X_3^2 + 0.20\,X_1X_2 + 1.8X_1X_3 + 0.02X_2X_3$	0.96
Thermal conductivity (Y_3)	$1.54 - 0.47\,X_1 - 0.001\,X_2 - 0.019\,X_3$	$1.73 - 0.52X_1 + 0.003X_2 - 0.06X_3 - 0.01X_1^2 - 2.87\text{E-}05X_2^2 + 0.001X_3^2 - 0.001X_1X_2 + 0.01X_1X_3 - 0.0001X_2X_3$	0.99

X_1 = Fibre fineness, X_2 = Yarn fineness, and X_3 = Sheath.

specific surface area for the same yarn cross-section. Specific area of yarn cross-section is inversely proportional to the air permeability[11].

The reason may be attributed to the higher bending rigidity of coarser fibres[8,10,12,13] which need higher energy in the form of bending, flexural and torsional rigidity to get converted into a yarn[9]. After sheath removal, the yarn will try to achieve a state of minimum energy level i.e. twistless structure. So, the higher bending rigidity of coarser fibres will result in the bulkiness of the twistless yarn while achieving a state of minimum energy level. The decrease in number of fibres in the yarn cross-section results in increase in yarn bulkiness[3,8,14] and availability of more air spaces in yarn structure, leading to increase in air permeability. It can be observed from Fig. 1(b) that at constant yarn fineness, as the proportion of sheath fibre and value of fibre fineness increases the air permeability increases. The reason may be attributed to the fact that the increase in bulkiness of yarn structure increases the availability of air passage within as well as in between yarns, leading to increase in fabric air permeability[15]. It can be observed from Fig. 1(c) that at constant fibre fineness, as the sheath % and value of yarn fineness increase, the fabric air permeability increases. The reason for increase in air permeability with the increase in sheath % has already been explained.

3.2 Influence of Yarn Modification on Water Vapour Permeability

After the evaluation of water vapour permeability of the respective fabric samples in the design, analysis was performed for development of a model to get the desired regression equations both linear and quadratic (Table 3). Contour plots in Figs 2(a-c) show the effect of inter-relationship between yarn fineness and fibre fineness; proportion of sheath and fibre fineness; and proportion of sheath and yarn fineness respectively on water vapour permeability. It can be observed from Fig. 2(a) that at constant sheath %, as the value of yarn fineness and fibre fineness increase, water vapour permeability increases. It is being established[6-8]

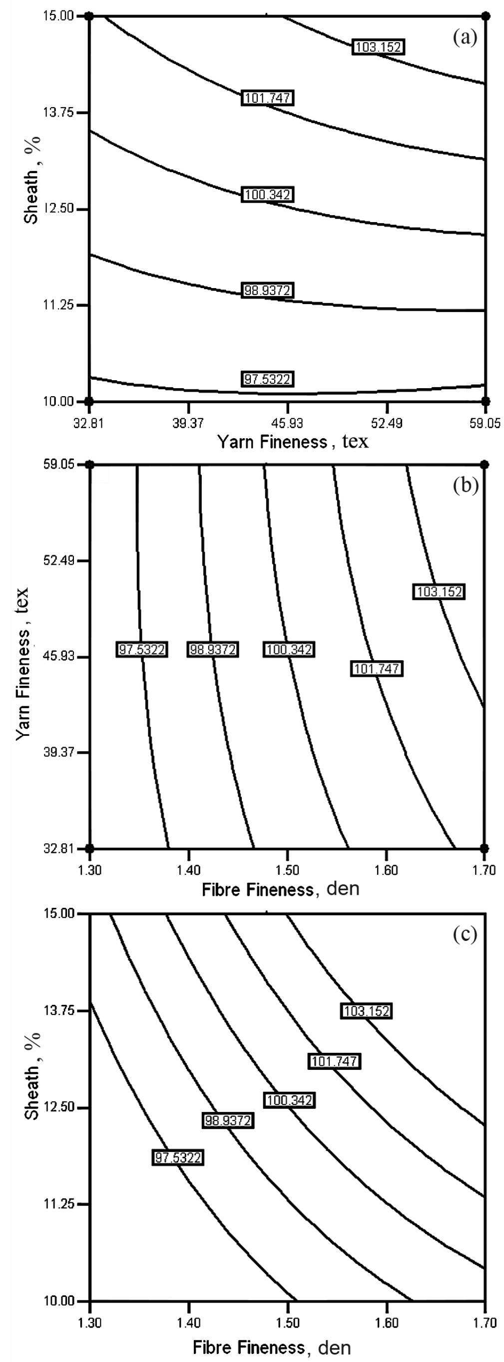

Fig. 2—Effect of yarn modification on water vapour permeability at constant (a) fibre fineness, (b) sheath %, and (c) yarn fineness

Table 4—Physical parameters of reference and optimized friction-spun yarn

Sample	Wales/inch	Courses/inch	Fabric mass g/m^2	Thickness mm	Loop length mm	Stitch density per $inch^2$
Optimized yarn	25	21	166	0.60	4.56	525
Reference yarn (100% viscose friction-spun yarn)	22	24	195	0.55	4.81	528

that the bending rigidity, flexural rigidity and torsional rigidity are inter-related and are sensitive to the change in the fibre fineness or diameter[9]. Flexural rigidity[10] of viscose rayon is found to be proportional to $(\text{tex})^2$. Water vapour permeability of yarn depends on its available specific surface, which is inversely proportional to the fibre diameter[7]. Therefore, rate of flow of water vapour will be less for finer fibres as compared to that for coarser fibres, due to the presence of higher number of finer fibres in the yarn of same cross-section. The finer the fibre, the lesser is its diameter resulting in presence of higher number of finer fibres in the yarn cross-section and more specific surface area for the same yarn cross-section. Specific area of yarn cross-section is inversely proportional to the water vapour permeability[11].

The reason may be attributed to the higher bending rigidity of coarser fibres[8,10,12,13], which need higher energy in the form of bending, flexural and torsional rigidity to get converted into a yarn[9]. After sheath removal, the yarn will try to achieve a state of minimum energy level i.e. twistless structure. So, the higher bending rigidity of coarser fibres will result in the bulkiness of the twistless yarn while achieving a state of minimum energy level. The decrease in number of fibres in the yarn cross-section results in increase in yarn bulkiness and decrease in number of fibres in yarn cross-section, resulting in increase in yarn bulkiness[3,8,14] and availability of more air spaces in yarn structure. This leads to increase in water vapour permeability by diffusion. It is clear from Fig. 2(b) that at constant yarn fineness, as sheath % and value of fibre fineness increase, water vapour permeability increases. The reason may be attributed to the decrease in compactness of yarn structure and increase in bulkiness of yarn, thus increasing the availability of air spaces in yarn structure which leads to increase in water vapour permeability[16]. It is evident from Fig. 2(c) that at constant fibre fineness, as sheath % and value of yarn fineness increase, water vapour permeability increases. The reason may be attributed to the increase in openness of fabric[16] and yarn bulkiness after sheath removal resulting in availability of more air spaces in yarn structure thus leading to increase in water vapour permeability[15].

3.3 Influence of Yarn Modification on Thermal Conductivity

After the evaluation of thermal conductivity of the respective samples in the design, analyses are performed for the development of a model to get the desired regression equation (Table 3). Contour plots in Figs 3(a-c) show the effect of inter-relationship between yarn fineness and fibre fineness; proportion of sheath and fibre fineness; and proportion of sheath and yarn fineness respectively on fabric thermal conductivity. It is being established[6-8] that the bending rigidity, flexural rigidity and torsional rigidity are inter-related and are sensitive to the change in the

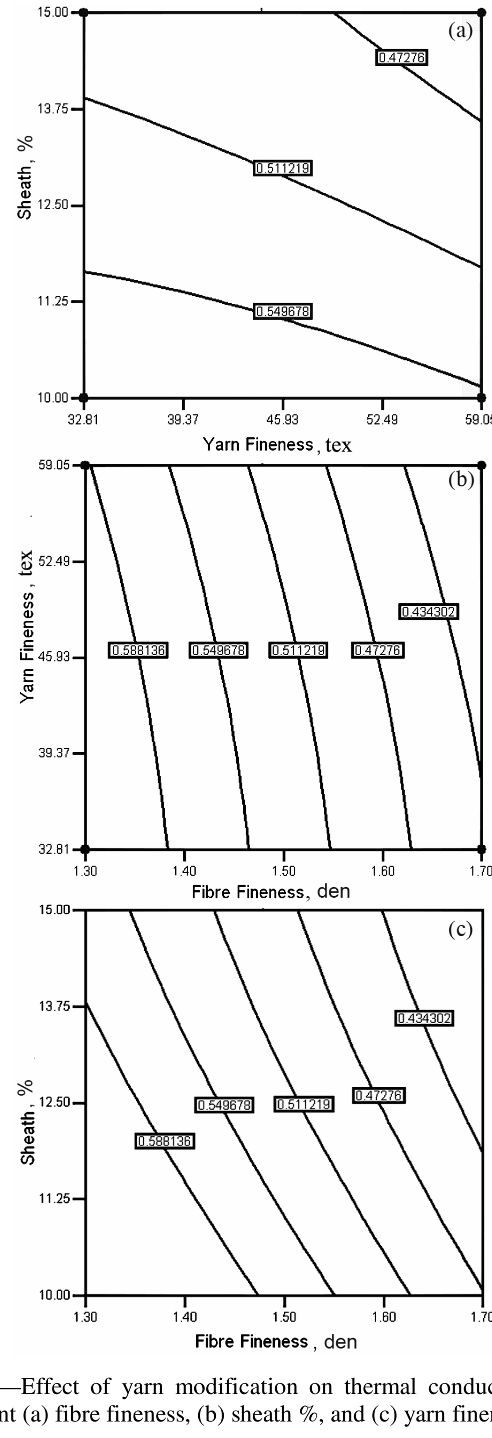

Fig. 3—Effect of yarn modification on thermal conductivity at constant (a) fibre fineness, (b) sheath %, and (c) yarn fineness

fibre fineness or diameter[9]. Flexural rigidity[10] of viscose rayon is found to be proportional to $(tex)^2$. Thermal conductivity of yarn depends on its available specific surface, which is inversely proportional to the fibre diameter[7]. Therefore, the rate of flow of water vapour will be less for finer fibres as compared to that for coarser fibres, due to the presence of higher number of finer fibres in the yarn of same cross-section. The finer the fibre, the lesser is its diameter, resulting in presence of higher number of finer fibres in the yarn cross-section and more specific surface area for the same yarn cross-section. Specific area of yarn cross-section is proportional to the thermal conductivity due to non availability of air spaces which reduces thermal conductivity[8,10].

Yarn formation needs higher energy in the form of bending, flexural and torsional rigidity to convert fibre into a yarn[9]. After sheath removal, the yarn will try to achieve a state of minimum energy level, i.e. twistless structure. So, the higher bending rigidity of coarser fibres will result in the bulkiness of the twistless yarn while achieving a state of minimum energy level. The decrease in number of fibres in the yarn cross-section results in increase in yarn bulkiness[3,8,14]. The reason may be attributed to the higher bending rigidity of coarser fibres[8,12,13] and decrease in number of fibres in yarn cross-section, resulting in increase in yarn bulkiness[3,14,16] and availability of more air space in yarn structure which leads to decrease in thermal conductivity[15]. It is evident from Fig. 3(b) that at constant sheath % and value of fibre fineness, as the yarn tex increases the fabric thermal conductivity decreases. The reason may be attributed to the fact that as the yarn tex increases the compactness of yarn structure decreases and the increase in bulkiness of yarn[3] increases the availability of air spaces in yarn structure, leading to decrease in thermal conductivity. It can be seen from Fig. 3(c) that at constant fibre fineness, as the sheath % and value of yarn fineness increase the fabric thermal conductivity decreases. The reason may be attributed to the increase in yarn bulkiness after sheath removal[3,17] which results in availability of more air spaces in yarn structure, leading to decrease in thermal conductivity[16].

4 Conclusions

4.1 For a constant sheath%, as the values of yarn fineness and fibre fineness increase the fabric air permeability increases. At constant yarn fineness, as the proportion of sheath fibre and value of fibre fineness increase the air permeability increases. With constant fibre fineness, as the sheath % and value of yarn fineness increase, the fabric air permeability increases.

4.2 With the constant sheath %, as the values of yarn fineness and fibre fineness increase, the water vapour permeability increases. For a constant yarn fineness, as sheath % and value of fibre fineness increase, the water vapour permeability increases. At constant fibre fineness, as the sheath % and value of yarn fineness increase, the water vapour permeability increases.

4.3 At constant sheath %, as the values of yarn fineness and fibre fineness increase, the thermal conductivity decreases. With constant yarn fineness, as the sheath % and value of fibre fineness increase, the fabric thermal conductivity decreases. For a constant fibre fineness, as the sheath % and value of yarn fineness increase, the fabric thermal conductivity decreases.

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