Thermal Behavior of Worsted Fabrics Produced from Different Yarn Spinning Systems

Abolfazl Mirdehghan, Siamak Saharkhiz, PhD, Hooshang Nosraty, PhD

Textile Engineering Department, Amirkabir University of Technology, Tehran, Tehran IRAN

Correspondence to:
Siamak Saharkhiz email: natilus@aut.ac.ir;s.saharkhiz@yahoo.com

ABSTRACT

This paper describes an experimental study of the impact of yarn structure on the thermal properties of worsted fabric. In this study, four different spun yarn structures (Solo, Siro, and single ply and two ply Ring) were woven into four fabric structures (Plain, Twill2/1, Twill2/2 and Basket2/2) and their thermal properties were studied. In addition, the thermal behavior of finished and unfinished samples was also evaluated. Results showed that the finishing process causes an increase in thermal conductivity and warmth to weight factor and a decrease in thermal insulation. Different spinning systems, also affect the thermal properties of the worsted fabrics.

Samples with Siro yarns in the weft were found to have the highest thermal conductivity and those made from single ply weft yarn the lowest thermal conductivity. A relation between fabric thermal insulation and air permeability and thickness was also found.

INTRODUCTION

Thermal behavior of fabric is an important property related to thermal comfort. Many factors influence the thermal property of fabrics including fabric structure, thickness, weight per unit area, and bulk density.

Morris [1] investigated the thermal insulation, thickness, and volume of air per unit area of fabric for single and multiple fabric layers. Morris made a comparison between the thermal insulation and thickness values obtained by the actual measurement of multiple layers of fabrics and those obtained by adding the values of the individual fabrics involved. Bandypondhyay et al. [2] showed that there is a linear relation between the thermal resistance and the thickness of fabric as found by earlier research studies.

Hatch et al. [3] measured heat transfer through a specially selected set of jersey knit textile fabrics. They used analytical models to compute thermal comfort limits based on the experimental values and predetermined estimates of human metabolic activity. They concluded that fabric structural features, not component fibers, are the most important controllers of thermal dissipation in the presence of moisture diffusion. Their research also shows that heat transfer is highly related to fabric thickness, bulk density, and air volume fraction. Thermal transfer from a simulated sweating skin surface is strongly correlated with fabric porosity and air permeability. Ukponman [4] expressed that the weight of fabric is an important factor in its thermal property. Ukponman introduced the parameter of warmth-to-weight factor and pointed out that this factor is desirable for expressing the thermal warmth of lightweight fabrics. On the basis of equal thickness, the most open construction is the least warm and vice versa. Ukponman concluded that thermal insulation of fabric almost depends uniquely on fabric thickness. Furthermore, the warmth of fabric is governed by the entrapped air. When the surrounding air is stagnant, by increasing the amount of entrapped air in fabric, there is a raise in resistance of the fabric against transferring heat and moisture. The large additional air volume entrapped in fabric structure causes this effect, rather than the increase in fiber content.

Pac et al. [5] studied the warm-cool feeling of fabrics. They concluded that the fabrics made from two ply yarns are cooler than those from single yarns. In addition, the smaller the stitch length of the knitted fabric, the cooler the fabrics will seem to be. They pointed that rougher fabrics have smaller contact surfaces, so they seem warmer. Also a hairier fabric encapsulates more air on its surface and so seems warmer. Bouskill et al. [6] tried to quantify the relationship between clothing ventilation and thermal insulation properties. A one-layer, air-impermeable ensemble and a three-layer, air-permeable ensemble were tested using an articulated thermal manikin in a controlled climate chamber. They showed that measured air exchanges have a potential heat exchange capacity of up to 17 and 161 W/m^2 for the one and three-layer ensembles, respectively. They emphasized the need to take clothing ventilation characteristics into consideration during thermal audits and thermal risk assessments. Li et al. [7] focused on a theoretical investigation of the coupling mechanism of heat transfer and liquid moisture diffusion in porous textiles using a mathematical model. They claim that their analysis of the computational and experimental results illustrate that the heat transfer process is influenced by fabric thickness and porosity and significantly impacts moisture transport processes. Uçar and Yılmaz [8] analyzed the natural and forced convective heat transfer characteristics of rib knit fabric. In their research the effect of rib design and other fabric properties such as fabric density and air permeability on the thermal behavior have been considered. They noted that a decrease in rib number of the order of 3×3, 2×2 or 1×1 leads to a decrease in heat loss due to an increase in the amount of air entrapped between the face and the back stitch. They concluded that when the fabric design is taken into consideration, the conductive heat loss becomes more important than the heat loss due to air circulation. But, when the fabric density for each fabric design is taken into consideration, the heat loss due to air circulation becomes more important than the conductive heat loss. Wang et al. [9] investigated methods of improving the thermal conductivity of wool fabrics. They studied the relationship between electrical conductivity and thermal conductivity of Polypyrrol (PPy) coated wool fabrics. They deduced that an improvement in thermal conductivity was observed when fabrics were coated with the PPy.

This paper is an attempt to contribute to the understanding of the effect of spinning systems on the thermal behavior of worsted fabric.

EXPREMENTAL

16 worsted fabrics varying in weave construction were produced using different types of weft yarn. Weft yarns were produced by Solo, Siro, Ring (single ply and two-ply) yarn-spinning systems. The weave construction included plain, Basket 2/2, Twill 2/2 and Twill 2/1. The warp of all samples was two-ply ring spun yarn. Both warp and weft yarns were 45/55 wool-polyester with the linear density of 26 Nm.

The fineness's of wool and polyester fibers used was 22 microns and 2.33 dtex, with nominal staple lengths of 70 mm and 91 mm respectively. In order to investigate the effect of finishing process on thermal properties of samples, a part of the fabrics were finished according to industrial finishing process of worsted fabrics. The yarn parameters and fabric densities were approximately selected according to industrial spinning, weaving, and finishing treatments. Because of finishing treatment, warp and weft densities of the finished fabrics increased. *Table I* shows the specifications of the samples.

TABLE I. Fabrics properties.

	Weft	Samples Code	Weave	Weft Count (Nm)	Weight (g/m^2)	Thickness (mm)	Air Permeability (ml/s)	Fabric Sett (cm^{-1})	
								Weft	Warp
Unfinished	Ring 1	1	Plain	26	174.12	0.39	39.13	20	20
		2	Basket2/2	26	213.47	0.51	41.33	23	27
		3	Twill2/2	26	210.89	0.51	36.07	23	27
		4	Twill2/1	26	206.98	0.51	34.40	23	27
	Ring 2	5	Plain	52/2	170.35	0.38	42.20	20	20
		6	Basket2/2	52/2	210.28	0.5	40.80	23	27
		7	Twill2/2	52/2	211.84	0.5	40.60	23	27
		8	Twill2/1	52/2	206.54	0.5	35.53	23	27
	Solo	9	Plain	52/2	173.38	0.38	46.93	20	20
		10	Basket2/2	52/2	211.19	0.5	47.13	23	27
		11	Twill2/2	52/2	208.91	0.5	43.67	23	27
		12	Twill2/1	52/2	203.15	0.5	42.33	23	27
	Siro	13	Plain	52/2	172.82	0.37	52.33	20	20
		14	Basket2/2	52/2	212.33	0.5	43.47	23	27
		15	Twill2/2	52/2	208.5	0.5	49.20	23	27
		16	Twill2/1	52/2	204	0.5	48.40	23	27
Finished	Ring1	17	Plain	26	165.09	0.34	32.80	22	22
		18	Basket2/2	26	203.82	0.43	19.89	25	30
		19	Twill2/2	26	204.27	0.43	17.69	25	30
		20	Twill2/1	26	195.56	0.41	16.28	25	30
	Ring 2	21	Plain	52/2	164.34	0.34	33.53	22	22
		22	Basket2/2	52/2	202.54	0.43	22.73	25	30
		23	Twill2/2	52/2	202.32	0.42	18.04	25	30
		24	Twill2/1	52/2	193.65	0.41	16.41	25	30
	Solo	25	Plain	52/2	163.22	0.35	32.00	22	22
		26	Basket2/2	52/2	202.65	0.43	23.60	25	30
		27	Twill2/2	52/2	202.51	0.42	19.33	25	30
		28	Twill2/1	52/2	193.12	0.40	20.04	25	30
	Siro	29	Plain	52/2	163.47	0.33	42.67	22	22
		30	Basket2/2	52/2	203.58	0.43	23.93	25	30
		31	Twill2/2	52/2	202.29	0.42	23.01	25	30
		32	Twill2/1	52/2	193.95	0.40	22.51	25	30

Hairiness of weft yarns was measured according to ASTM-5647 standard using a Shirley Hairiness Meter (The number of hairs longer than 3 mm). The results are shown in *Table II.*

TABLE II. Hairiness of yarns.

Weft Yarn Type	Hairiness (hairs/100m)	CV%
Ring1	2201	18%
Ring2	1022	19.7%
Solo	1670	11.8%
Siro	1420	13.2%

Thermal conductivity was measured according to BS 4745. There are two measurement approaches in this standard, namely single plate method and two-plate method (implemented in current research).

ASTM-D1777 and ASTM-D3776 testing methods were used for measuring thickness and mass per unit area of fabric, respectively. Air permeability of the fabrics was measured by a Shirley Air Permeability Tester using ASTM-D737-96.

All samples were conditioned and tested under standard conditions at temperature of 20 ± 2°C and relative humidity of 65 ± 3%.

RESULTS AND DISCUSSION

The thickness of the samples is shown in *Figure 1*. Ishtiaque et al. [10] stated that thickness of fabrics made by Siro weft yarn is less than that of similar samples made by corresponding two-ply weft yarn. Kothari and Chital [11] showed that the thickness of fabrics made by single-ply ring weft yarn is higher than that of samples produces by two-ply ring weft yarn. As *Figure 1* shows, single-ply ring weft yarn in both finished and unfinished fabrics has the greatest thickness and Siro weft yarn results in the smallest thickness values. Fabrics made of Solo and two-ply weft yarns take thickness values in between those of Siro and single-ply. This result is confirmed by ANOVA statistical analysis (95% confidence interval).

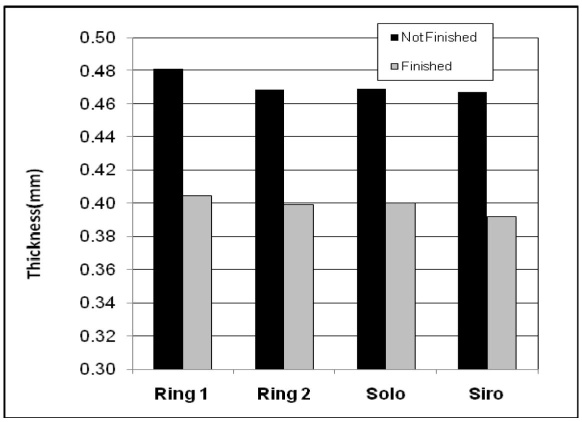

FIGURE 1. Effect of yarn types on thickness of fabrics.

By measuring the thermal insulation of the samples, the thermal conductivity (K) can be calculated from Eq. (1):

$$K = \frac{d}{R_f} \times 10^{-3} \quad (1)$$

Where K is thermal conductivity (W/m°K), R_f is thermal insulation (m^2 °K/W) and d is fabric thickness (mm).

TABLE III. Thermal insulation, thermal conductivity and warmth-to-weight factor of the samples.

Sample Code	Thermal insulation (m^2k/w)	Thermal Conductivity (w/m °k)	Warmth-to-weight Factor (m^4 °K/w.kg)
1	0.0110	0.0340	0.0669
2	0.0150	0.0334	0.0748
3	0.0150	0.0339	0.0750
4	0.0148	0.0337	0.0755
5	0.0098	0.0389	0.0596
6	0.0147	0.0341	0.0724
7	0.0144	0.0349	0.0713
8	0.0146	0.0343	0.0753
9	0.0100	0.0377	0.0615
10	0.0145	0.0344	0.0717
11	0.0143	0.0350	0.0708
12	0.0146	0.0343	0.0756
13	0.0099	0.0396	0.0603
14	0.0139	0.0358	0.0683
15	0.014	0.0357	0.0692
16	0.0135	0.0376	0.0696
17	0.0065	0.0535	0.0372
18	0.0131	0.0331	0.0615
19	0.0129	0.0338	0.0613
20	0.0112	0.0364	0.0543
21	0.0063	0.0544	0.0368
22	0.0120	0.0355	0.0562
23	0.0118	0.0359	0.0569
24	0.0109	0.0375	0.0525
25	0.0061	0.0551	0.0353
26	0.0121	0.0349	0.0575
27	0.0116	0.0356	0.0556
28	0.0102	0.0385	0.0503
29	0.0064	0.0526	0.0368
30	0.0113	0.0386	0.0533
31	0.0106	0.0398	0.0509
32	0.0101	0.400	0.0495

Ukponman [4] in his research introduced a parameter as “warmth-to-weight factor” to express thermal behavior of the fabrics as Eq. (2):

$$\text{Warmth-to-weight factor} = \frac{R_f}{m} \quad (2)$$

Where R_f is thermal insulation in Tog (0.1 m^2 °K/W) and m is weight per unit area (g/cm^2). To examine the usefulness of this factor in explanation of worsted-fabric thermal behavior, this factor is also calculated.

The experiment results and calculated parameters of fabric samples are presented in *Table III*. The one-way analysis of variance (ANOVA) was performed in order to analyze the effects of yarns and fabrics parameters on thermal properties of sample.

<u>Effect of Finishing Treatment on Thermal Properties</u>

Considering the finishing process, statistical analysis (ANOVA) showed that the thermal conductivity of the finished samples is lower than unfinished samples and their thermal insulation and warmth-to-weight factor is higher (95% confidence interval). As *Table I* depicts, finishing procedure decreases the thickness of the fabrics.

This is due to the structural changes caused by the finishing process as increase in the fabric density and reduction in thickness of fabric.

<u>Effect of Yarn Structure on Thermal Properties</u>

Figures 2 to 4 demonstrate the effect of yarn types on thermal properties of fabrics. Fabrics produced from Siro weft yarn have least thermal insulation and warmth-to-weight factor and the highest thermal conductivity. Fabrics with single ply ring weft yarn are in contrary. It also can be concluded that fabrics with Solo and two ply weft yarns have similar attributes and their corresponding thermal behavior values lay between those of Single ply and Siro weft yarn.

Our results also follow the idea that Pac presented in his research [5]. He concluded that fabrics made from two ply yarns are cooler (higher thermal conductivity) than those made from single yarns.
ANOVA analysis showed that the weft yarn type affects the thermal properties of fabric (95% confidence interval). A reason for this effect is the difference of weft structures. Yarns made in different weft systems exhibit different characteristics which affect the property of corresponding fabrics.

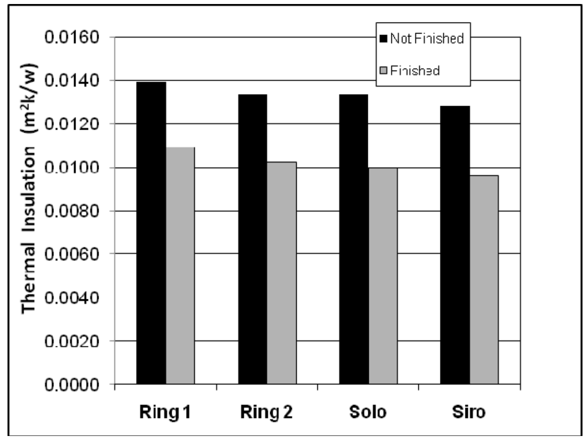

FIGURE 1. Effect of yarn types on thermal insulation of the fabrics.

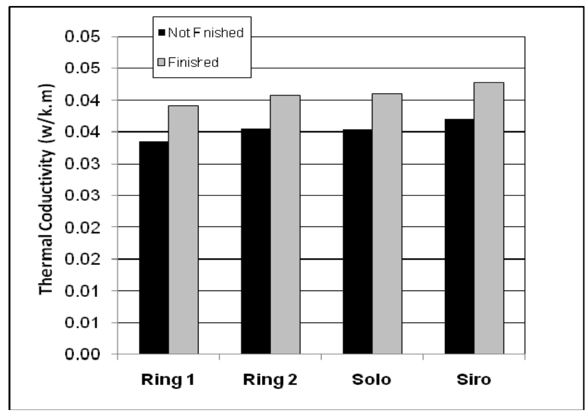

FIGURE 2. Effect of yarn types on thermal conductivity of the fabrics.

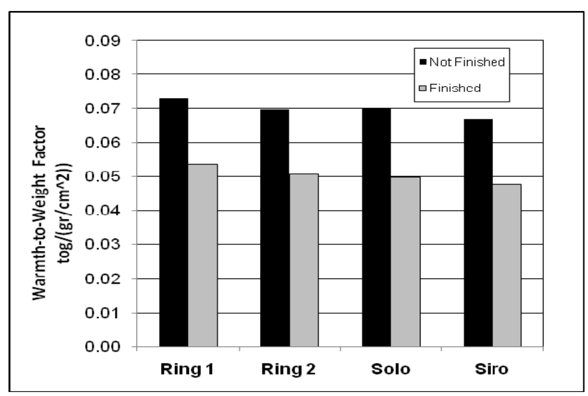

FIGURE 3. Effect of yarn types on warmth-to-weight factor of the fabrics.

The effects of yarn hairiness and cover factor on thermal property of the samples were also investigated.

The results of hairiness are shown in the *Table II.* The yarn ranks according to increase in their hairiness were as Siro, Solo, two ply and single ply yarns. The result is confirmed by ANOVA statistical analysis (95% confidence interval).

In the past, several studies have individually investigated the hairiness of yarn produced using Sirospun and Solospun technologies. Barella A. [12, 13] discussed the hairiness of Solospun and ring spun worsted yarns in his comprehensive review of yarn hairiness and stated that Solospun yarns have fewer hairs in different hair length. He reveals that Yarn produced by means of the Sirospun process are frequently less hairy compared with two ply yarns. He also reported the existence of differences in hairiness levels and consequently a slight difference in bulkiness of yarn.

Cover factor (CF) or tightness of fabric is another important factor and is defined in equation (3) as the ratio of area covered by its yarns (or fibers) to the total area of fabric (or web) [14, 15]:

$$CF = \frac{\text{area covered by yarns}}{\text{total area of the fabric (or web)}} \quad (3)$$

The end-use and performance requirements of woven fabrics, especially porosity and permeability, are strongly related to their CF.

Researchers have employed different methods to study CF of fabrics. Olsauskiene and Milasius [16] stated that CF is a basic construction parameter of woven cloth related to air permeability.

Partridge and Mukhopadhyay [17] described a mathematical model which relates air permeability to CF values for air bag fabrics. They showed that any increase of the CF leads to an approximate linear decrease in the logarithm of the air flow through the fabric. Serin and Tugru [18] explained that as the cover factor increases, the value of air permeability also decreases.

In the present work, because of the effect of the finishing process, measuring the cover factor of some of the samples was difficult and not accurate. Therefore, the air permeability of fabrics was measured as a good estimation for cover factor. The results of air permeability tests are shown in *Figure 5*.

As *Figure 5* shows, the single-ply ring weft yarn in both finished and unfinished fabrics had the greatest value and Siro weft yarn has the least value.

The air permeability values of fabrics made of solo and two-ply weft yarns in respective descending order are between Siro and single-ply. This result was confirmed by ANOVA statistical analysis (95% confidence interval).

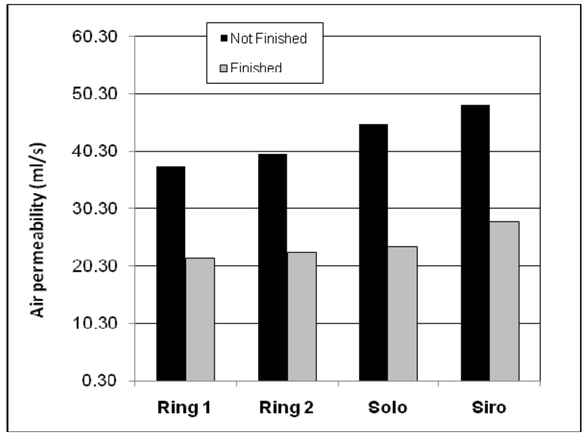

FIGURE 4. Comparison of air permeability of the fabrics.

Regarding to yarn structure, Siro yarns are less hairy and more compacted and tightly condensed. This means the existence of more space between the adjacent yarns. As a result, the air permeability of the fabric increases. The exact inverse of this fact is seen in single-ply yarns fabric.

CONCLUSION

In the present work, the effect of weft yarn structure including ring, Solo and Siro spinning systems on thermal properties of the worsted fabrics was examined. The result of the measured thermal properties of finished and unfinished samples revealed that the finishing process causes an increase in thermal conductivity and warmth to weight factor and reduction in thermal insulation. Analysis of the results from the fabrics with the same structure and different weft yarn types showed that the type of yarn affects the thermal properties of the worsted fabrics. Samples produced from Siro weft yarn had the highest measured thermal conductivity and those made from single ply weft yarn had the lowest thermal conductivity. As expected it was shown that an increase in yarn bulkiness and fabric thickness leads to increase in fabric thermal insulation. It was also shown that the thermal insulation of the fabrics is related to the air permeability of the fabrics and their thickness.

REFERENCES

[1] Morris M.A., “Thermal Insulation of Single and Multiple Layers of Fabrics“, Textile Re. J., 46, 1955, 766-773.

[2] Bandyopadhyay S.K., Ghose P.K., Bose S.K. and Mukhopadhyay U., “The Thermal Resistance of Jute and Jute- blend Fabrics“, J. Textile Inst., 78, 1987, 255-260.

[3] Hatch K.L., Woo S.S., Barker R.L., Randhakrishnaiah P., Markee N.L. and Maibach H.I., “In Vivo Cutaneous and Perceived Comfort Response to Fabric, Part: Thermo- physiological Comfort Determination for Three Experimental Knit Fabrics“, Textile Res. J., 60, 1990, 405-412.

[4] Ukponman J.O., “The Thermal-Insulation Properties of Fabrics“, Text. Progress, 1993, 23.

[5] Pac M.J., Bueno M.A., Renner M. and Kasmi S.E., “Warm-Cool Feeling Relative to Tribological Properties of Fabrics“, Textile Res. J., 71(9), 2001, 806-812.

[6] Bouskill L.M., Havenith G., Kuklane K., Parsons K.C. and Withey W.R., “Relationship between Clothing Ventilation and Thermal Insulation“, AIHA Journal, (63), 2002, 262-268.

[7] Li Y. Li, Zhu Q., and Yeung K.W., “Influence of Thickness and Porosity on Coupled Heat and Liquid Moisture Transfer in Porous Textiles“, Textile Res. J., 72(5), 2002, 435-446.

[8] Uçar N. and Yılmaz T., “Thermal Properties of 1×1, 2×2, 3×3 Rib Knit Fabrics“, FIBRES & TEXTILES in Eastern Europe, 12, 3 (47), 2004.

[9] Wang J., Kaynak A., Wang L. and Liu X., “Thermal Conductivity Studies on Wool Fabrics with Conductive Coatings“, J. Textile Inst., 97, 3, 2006, 265–269.

[10] Ishtiaque S.M., Sharma I.C. and Sharma S.U., “Structural Mechanics of Siro Yarn by Microtomy“, Indian Journal of Fibre and Textile Research, 18, 1993, 116-119.

[11] Kothari V.K., Chital A., “Tensile Properties of Single and Two-ply Cotton Yarn Woven Fabrics“, Indian Journal of Fibre and Textile Research, 28, 2003, pp 29-35.

[12] Barella A., “Yarn Hairiness”, Textile Prog., 13(1), 1983.

[13] Barella A., “The Hairiness of Yarns”, Textile Prog., 24 (3), 1993.

[14] Montserrat T., Miquel R., Jaume E., “Automatic Measurements of Partial Cover Factor and Yarn Diameters in Fabrics Using Image Processing“, Textile Res. J., 81(2), 2011, 173-186.

[15] Montserrat T., Miquel R., Jaume E., Inés A. and Ascensión R, “Objective Measure of Woven Fabric’s Cover Factor by Image Processing“, Textile Res. J., 80(1), 2010, 33-44.

[16] Olsauskiene A. and Milasius R., “Dependence of Air Permeability on Various Integrated Fabric Firmness Factors“, Mater Sci, 9(4), 2003, 401-404.

[17] Partridge J. and Mukhopadhyay S., “Mathematical Predictions of Gas Permeability for Automotive Air-Bags“, J. Appl. Polym. Sci., 77, 2000, 2104 -2112.

[18] Serin M., Tugru O., “Investigation of Air Permeability of Single Jersey Fabrics with Different Relaxation States”, Textile Res. J., 46, 1955, 766-773.

AUTHORS’ ADDRESSES

Abolfazl Mirdehghan
Siamak Saharkhiz, PhD
Hooshang Nosraty, PhD
Textile Engineering Department,
Amirkabir University of Technology
No. 454, Hafez Ave.
Tehran, Tehran 15914
IRAN