(REFEREED RESEARCH)

INVESTIGATION OF ELECTROMAGNETIC SHIELDING AND COMFORT PROPERTIES OF SINGLE JERSEY FABRICS KNITTED FROM HYBRID YARNS CONTAINING METAL WIRE

METAL TEL İÇERİKLİ KOMPOZİT İPLİKLERDEN ÖRÜLEN SÜPREM KUMAŞLARIN ELEKTROMANYETİK EKRANLAMA VE KONFOR ÖZELLİKLERİNİN İNCELENMESİ

Hüseyin Gazi ÖRTLEK[1], Cem GÜNEŞOĞLU[2*], Gamze OKYAY[1], Yunus TÜRKOĞLU[1]

[1]*Erciyes University, Department of Textile Engineering, Kayseri, Turkey*
[2]*Gaziantep University, Department of Textile Engineering, Gaziantep, Turkey*

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ABSTRACT

The aim of this study is to investigate electromagnetic shielding and comfort properties of single jersey fabrics produced from hybrid yarns containing metal wire. For this purpose, nine different hybrid yarns were produced from the combination of cotton yarns (Ne 50, Ne 60, and Ne 70) and stainless steel (SS) wires (18 micron, 35 micron, and 50 micron) by means of hollow spindle covering system. Hybrid yarns and 100 % cotton yarns used in the production of hybrid yarns were used to produce knitted fabric on the sample circular knitting machine. When the shielding effectiveness (SE) values of the sample fabrics were examined, it was found that the SE value of knitted fabrics containing SS wire were higher than that of without SS wires. It was also found that as the SS wire thickness of knitted fabric increases, thermal conductivity and thermal absorptivity values increase, but air permeability and vertical wicking values decrease.

Key Words: Metal wire, Hybrid yarn, Single jersey, Shielding effectiveness (SE), Comfort sensation.

ÖZET

Bu çalışmanın amacı, metal tel içeren kompozit ipliklerden üretilen süprem kumaşların elektromanyetik ekranlama ve konfor özelliklerini incelemektir. Bu amaç doğrultusunda, 3 farklı numarada (Ne 50, Ne 60, Ne 70) % 100 pamuk iplikleri, üç farklı incelikte (18, 35, 50 mikron) paslanmaz çelik (SS) teller, içi oyuk iğli kaplama yöntemiyle bir araya getirilerek 9 farklı tip kompozit iplik üretilmiştir. Üretilen kompozit iplikler ve kompozit ipliklerin üretiminde kullanılan % 100 pamuk iplikleri numune yuvarlak örme makinesinde kumaş formuna getirilmiştir. Üretilen kumaşların ekranlama etkinlik değerleri incelendiğinde; metal tel içeren kompozit ipliklerden örülen kumaşların, % 100 pamuk ipliklerinden örülen kumaşlardan daha yüksek ekranlama etkinlik değeri gösterdiği bulunmuştur. Ayrıca örme kumaşların içeriğindeki metal tel kalınlığı arttıkça; termal iletkenlik ve termal absorbtivite değerlerinin arttığı, hava geçirgenlik ve dikey kılcallık değerlerinin ise düştüğü görülmüştür.

Anahtar Kelimeler: Metal tel, Kompozit iplik, Süprem, Ekranlama etkinliği (SE), Konfor algısı.

[*] **Corresponding Author:** Cem Güneşlioğlu, gunesoglu@gantep.edu.tr, Tel:+ 90 352 4374937 Fax:+90 352 4375784

1. INTRODUCTION

Metal fibers used for decorative purposes in hundreds of years. For example, in the old Persian carpets, ceremonial costumes of Indians, metal fibers used to create complex and interesting patterns. The using areas of metal fibers diversify with technological developments. Whereas the metal fibers were used just decorative purposes in the past, nowadays metal fibers are begun to be used in technical areas such as prevention of static electricity and protection from electromagnetic radiation.

The usage of electrical and electronic appliances in our daily lives has grown rapidly with the development of science and technology. Many devices used in our daily life, such as, cell phones, computers, microwave ovens, televisions, base stations, printers, modems, medical devices working with different frequency and different power produce electromagnetic waves intentionally or unintentionally.

Long time interaction with devices emitting electromagnetic waves adversely affects the human health. When a high frequency electromagnetic wave enters a human body, it vibrates molecules to give out heat. In addition, it could increase the possibility of leukemia and other cancers (1). Also electromagnetic waves can affect the performance of electrical/electronic equipment by creating undesirable responses or complete operational failure.

To avoid the problems derived from electromagnetic waves shielding is required. Shielding can be stated that either to isolate a space (an apparatus, a platform, a room, etc) from external sources of electromagnetic radiation or to prevent unwanted emissions of electromagnetic waves radiated by internal sources (2). Traditionally, metals and alloys are used for shielding; however, these materials are heavy and expensive, and may be subject to thermal expansion and metal oxidation, or corrosion problems associated with their use. Conductive textile products and textile-based composite materials have started to replace metals and alloys for various shielding applications, due to their light weight, flexibility, low cost, etc.

Electromagnetic shielding textile structures can be analyzed in two groups as textiles produced using conductive yarns and textiles with the conductivity obtained by various finishing processes on textile surfaces. Conductive yarns can be analyzed under the four main groups:

1. 100 % metallic yarns, staple fiber or continuous filament
2. 100 % conductive synthetic yarns, staple fiber or continuous filament
3. Yarns produced with the mixture of staple fiber/continuous filament metal yarns with synthetic or natural fibers
4. Yarns produced with the mixture of staple fiber/continuous filament conductive synthetic yarns with synthetic or natural fibers (3).

In the literature, there are several studies on conductive yarns. Cheng et al. reported a fabrication method for conductive open-end friction core-spun yarns which are constructed from open-end friction spun yarns and SS wire as core part. Then these conductive yarns were successfully woven into a variety of woven structures in order to develop new conductive yarns and fabrics which could be suitable for shielding home electronic devices, electrical appliances from electromagnetic fields (4).

Chen et al. fabricated a serious hybrid yarns which consists of copper wire and polyamide filament as core and stainless steel wire as cover part. These hybrid yarns were used to fabricate the conducting co-weaving-knitting fabrics (CWKFs). The CWKFs were laminated with various angles in four layers, and then were heat pressed for 3 mm in thickness. Chen et al, examined the surface resistivity, electromagnetic shielding effectiveness and electrostatic discharge attenuation percentage of the CWKFs reinforced composites in their study (5).

Ueng and Cheng, reported a study to develop a spinning method of open-end friction core-spun yarn (OFCY) and its conductive fabric for shielding the electrostatic discharge and electromagnetic applications. It was stated that the electromagnetic shielding effectiveness and electrostatic discharge attenuation of the woven fabric can be tailored in a number of ways including fabric structure, density, and the amount of conductive filler material (6).

The biggest advantage of using metal wire as electro conductive filler is that the anti-electrostatic and electromagnetic shielding effect is very staple and is not influenced by environmental humidity (7). However the metal wires affect the comfort properties of fabrics. Todays, consumers prefer textile products which comfortable, easy to use and care. Therefore, fabric developed for electromagnetic shielding and electrostatic protection has to provide at least acceptable comfort properties, especially if it will be used as a garment. The aim of this study was to investigate electromagnetic shielding effectiveness and thermal comfort properties of single jersey fabric knitted from hybrid yarns containing SS wire.

2. MATERIALS AND METHODS

Initially, 9 type hybrid yarns produced by hollow spindle covering technique (Figure 1). Single jersey fabric samples were knitted from these hybrid yarns. Also a sample fabric was knitted from 100 % cotton yarn which was used for production of hybrid yarns as a control group. The codes, counts, content of hybrid yarns and the density of fabric produced are summarized in Table 1.

Table 1. Codes and properties of hybrid yarns and fabric densities

Hybrid yarn codes	Hybrid yarns count	SS wire diameter (count)	Cotton yarn count	Density of samples (g/cm³)
5000	Ne 50	--------	Ne 50	0.224
5018	Ne 45.4	18 mic. (Ne 118)	Ne 50	0.195
5035	Ne 33.1	35 mic. (Ne 77)	Ne 50	0.198
5050	Ne 23.1	50 mic. (Ne 38)	Ne 50	0.255
6000	Ne 60	--------	Ne 60	0.226
6018	Ne 35.5	18 mic. (Ne 118)	Ne 60	0.163
6035	Ne 29.7	35 mic. (Ne 77)	Ne 60	0.202
6050	Ne 20.8	50 mic. (Ne 38)	Ne 60	0.225
7000	Ne 70	--------	Ne 70	0.224
7018	Ne 47.8	18 mic. (Ne 118)	Ne 70	0.213
7035	Ne 35.2	35 mic. (Ne 77)	Ne 70	0.215
7050	Ne 24.9	50 mic. (Ne 38)	Ne 70	0.221

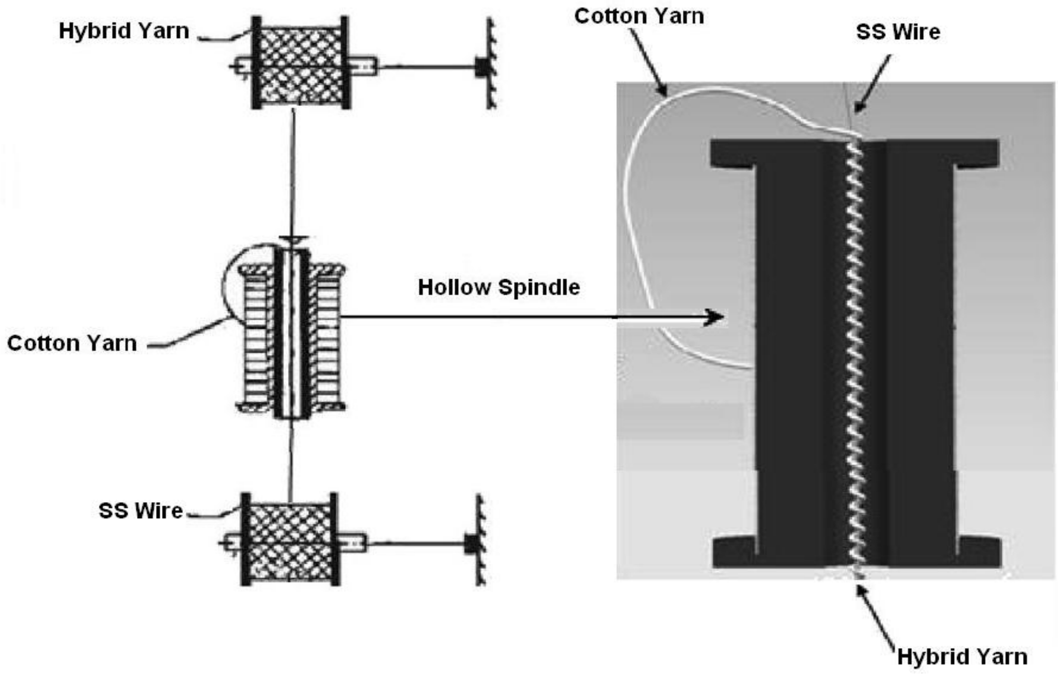

Figure 1. Hollow spindle covering technique

Visual comparisons of hybrid yarns were examined with an Olympus SZ61 stereo microscope and are given in Figure 2.

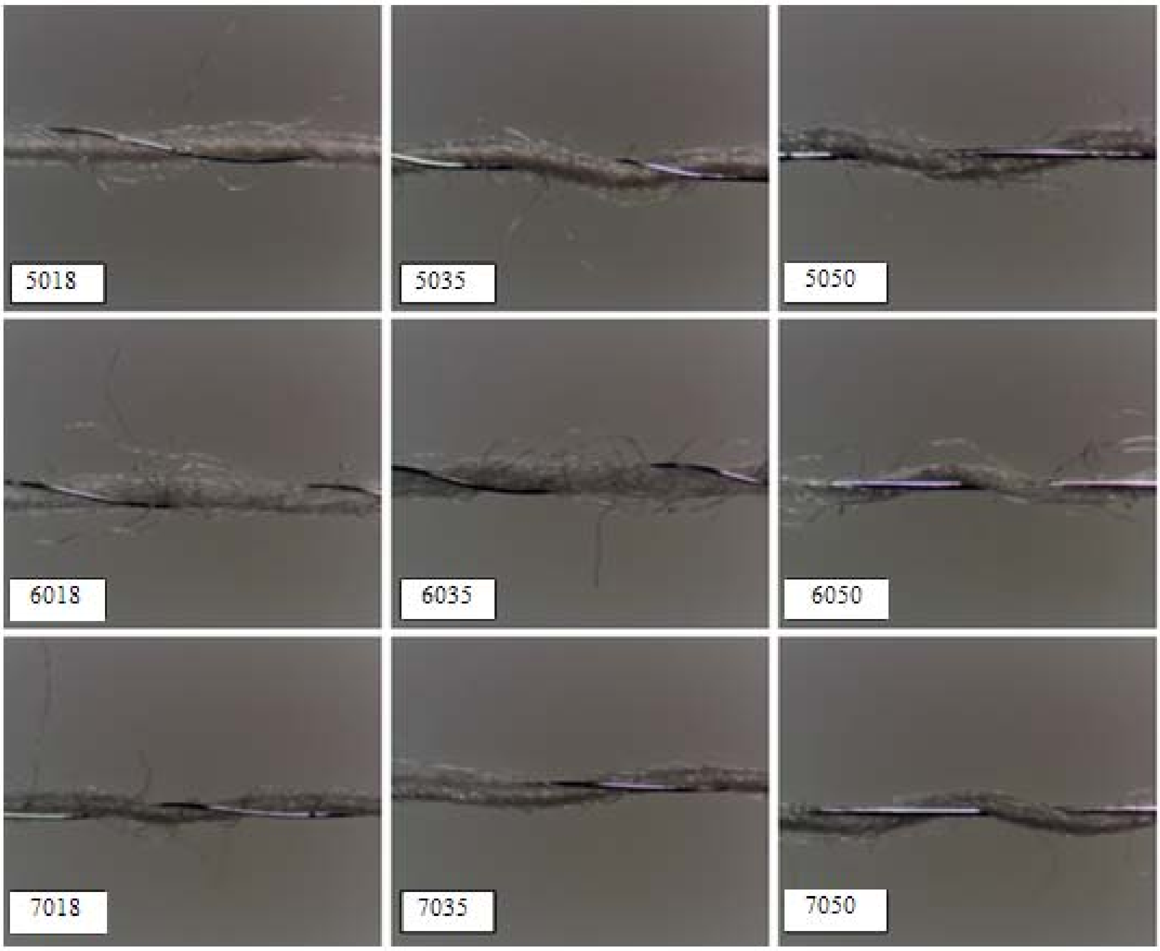

Figure 2. The longitudinal views of hybrid yarns

Single jersey fabric specimens were knitted using an automatic sample circular knitting machine (SDL Atlas). The fabric specimens are coded according to the yarns' codes which were given in Table 1. The images of fabric specimens are given in Figure 3.

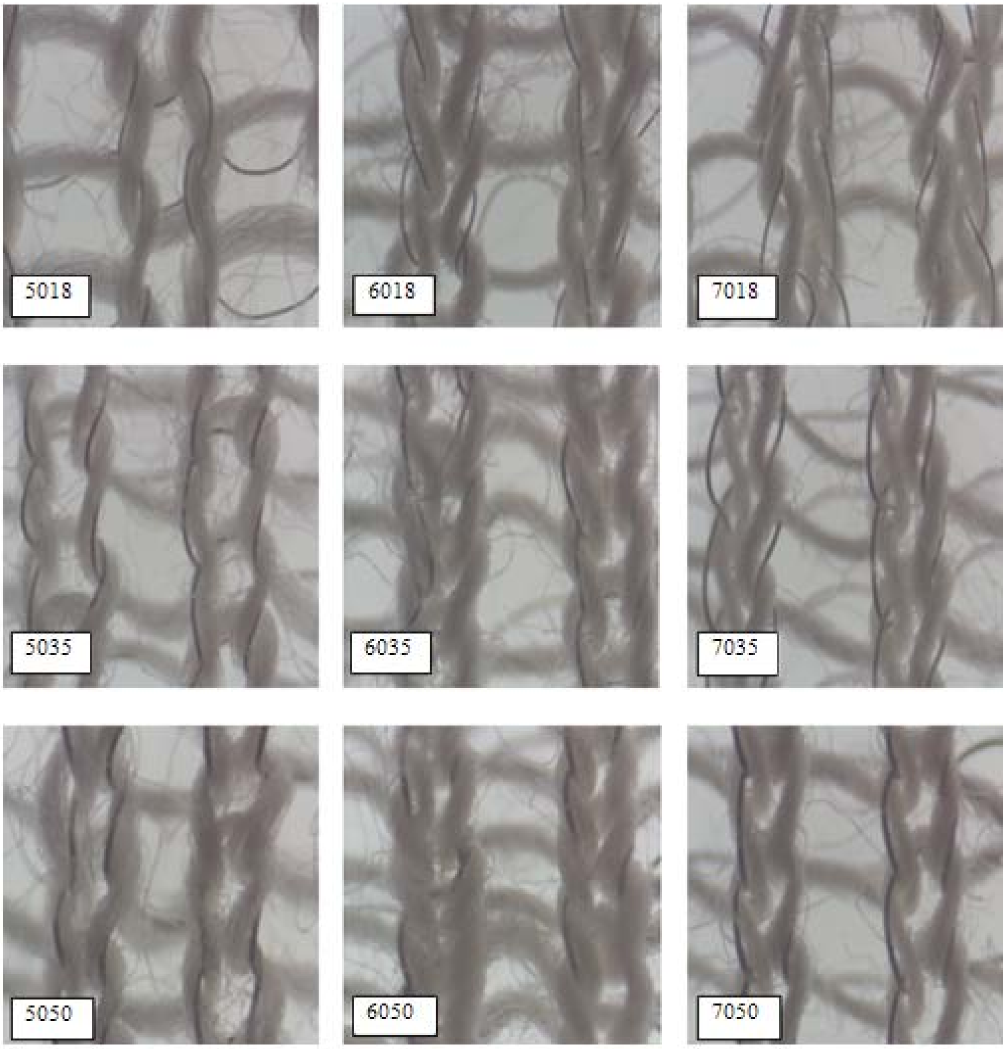

Figure 3. The images of fabric samples.

Various difficulties are met during the knitting process of hybrid yarns containing 50 micron SS wire. The images are obtained under the optical microscope show troubled areas on the fabric specimens (Figure 4).

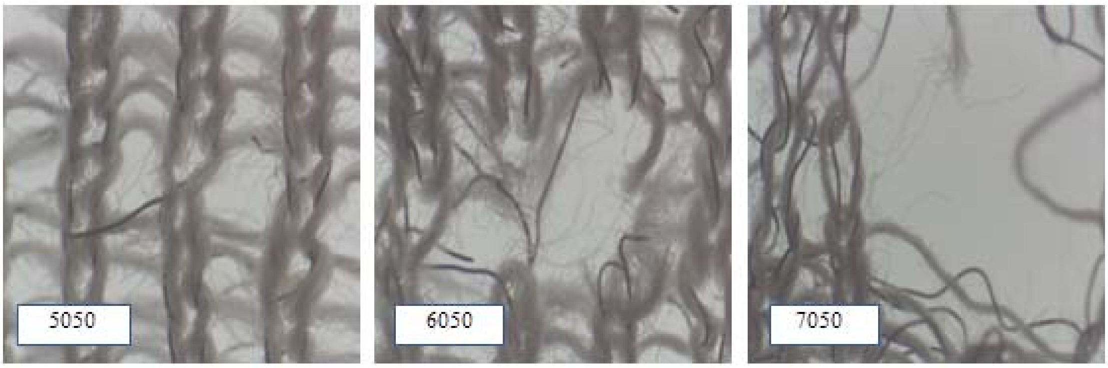

Figure 4. Some examples of mistakes occurred during the knitting of hybrid yarns containing 50 micron SS wire

These troubled areas are caused by the relatively high flexural rigidity of the 50 micron SS wire. When the images of hybrid yarns in Figure 2 were examined, relatively high flexural rigidity of 50 micron SS wires can be easily observed. Although all the hybrid yarns were produced with the same twist level and production technique (hollow spindle covering), hybrid yarns containing 18 micron and 35 micron SS wire seems like twisted yarn because of the radial torsion effect of cotton yarns as seen in Figure 2. On the other hand, when the images of hybrid yarns containing 50 micron SS wire were examined, covering effect of cotton yarn can be easily seen. It is due to the flexural rigidity increase related with the diameter of SS wires.

2.1. Measurement of Electromagnetic Shielding Effectiveness

Electromagnetic shielding effectiveness (SE) measurements of fabric specimens were made based on ASTM D 4935 standard with coaxial holder method (8). Coaxial test fixture relating to ASTM D 4935 is given in Figure 5. This standard determined the shielding effectiveness of fabric using the insertion-loss method. As seen in Figure 5, the measurement device consist of a network analyzer (R&S ZVB20) generating and receiving the electromagnetic signals and a coaxial transmission line test fixture. The shielding effectiveness is determined by comparing the difference in attenuation of a reference sample to the test sample, taking into account the insertion losses. The reference and the test measurement were performed on the same material. The shielding effectiveness was determined from equation (1)

$$SE_{dB} = 20 \log E_0/E_1 \qquad (1)$$

where the value of the electrical field component E_0 is measured with the reference specimen, whilst E_1 is measured with the test specimen.

2.2. The Investigation of Comfort Properties of Sample Fabrics

Fabric density values of the samples were obtained by simply dividing fabric weight values by the thickness. Fabric density shows high correlation with thermal conductivity and thermal absorptivity. For determining the thickness of fabric samples the Paramount thickness measurement device was used in accordance with ASTM D 1777 standard (9). Four thickness measurements were done from different part of the samples and the average of results was recorded. The weight of fabric samples were determined with ASTM D 3776 standard (10) and the measurements were repeated four times.

SDL Atlas M 021A machine was used to measure the air permeability of fabric samples. Air permeability values used in this study were measured in 20 cm² test area (20 cm² test aparatus was used), under 100 Pa pressure and for each fabric sample the measurements were repeated five times (11).

The vertical wicking values of fabric samples were determined with DIN 53924 standard (12) which depends on the measurement of distance covered by water in the sample during specific time in water tank. For this test, the mechanism offered by Wong (13) was used. The capillary action started with immersing the fabric sample vertically in distilled water and a paper gripper (≈0.679gr) provided the sufficient weight to keep the samples even. And the measurements described above were recorded as wicking performances. The mechanism for wicking measurement is shown in Figure 6.

Thermal conductivity, thermal resistance and thermal absorptivity measurements were performed with ISO EN 31092 standard by the Alambeta (Sensora/ Czech Republic) device.

2.3. Statistical Evaluation of Test Results

The relation between the measured properties and the variables was examined. The contribution of each variable, covering metal wire type with four treatment levels (0, 18, 35, 50 micron wire) and cotton yarn with three treatment levels (Ne 50/1, Ne 60/1, Ne 70/1 cotton yarn) were assessed using a completely randomized analysis of variance (ANOVA). The results were evaluated at 5% significance level. We evaluated the results based on the F-ratio (*Fs*) and the probability of the F-ratio (*p*). The lower the probability of the F-ratio and the higher the F-ratio, the stronger the contribution of the variation and the more significant the variable is. To define the exact classification of the samples, we also performed SNK (Student-Newman-Keuls) range test to designate which differs significantly from others. The samples were marked in accordance with the mean values, and any sample marked by same letter showed that they were not significantly different in the terms of the property measured. Statistical analysis has not been performed for shielding effectiveness since they have been measured at different frequency ranges.

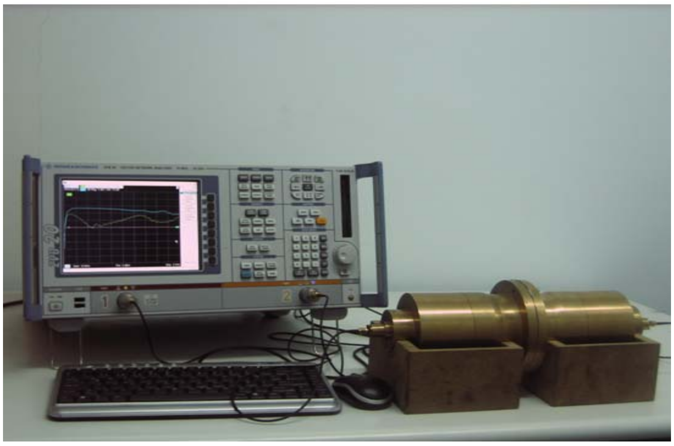

Figure 5. Photograph of SE testing apparatus.

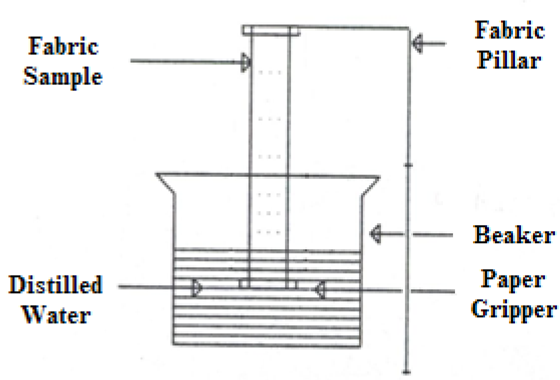

Figure 6. Capillarity measurement mechanism-vertical direction

3. RESULTS AND DISCUSSION

SE measurement results, belonging to the single jersey fabric knitted from 12 different yarn types which are summarized in Table 1, are shown graphically in Figure 7 - 11. SE results of fabric knitted from yarns coded 5000, 5050, 5035, and 5018 for incident electromagnetic waves are given in Figure 7.

Fabrics coded 5000 didn't exhibit shielding effectiveness (SE) (Figure 7) because 5000 was knitted from 100 % cotton yarn which meant no conductive filler. Besides this, it can be seen that, the SE values of 5018 are above 20 dB in the frequency range of 170 MHz-670-MHz and the SE values, of 5035 are above 20 dB in the frequency ranges of 40 MHz-190MHz. Also the SE values of 5050 are above 20 dB in the frequency range of 30 MHz-180MHz as seen in Figure 7.

Electromagnetic shielding effectiveness results of fabric knitted from yarns coded 6000, 6050, 6035, and 6018 for incident electromagnetic waves are given in Figure 8.

It was found that fabric specimen coded 6000 which were knitted 100 % cotton yarn didn't exhibit shielding effectiveness. In addition, the SE values of 6018 and 6050 were found above 15 dB respectively in the frequency ranges of 0.05-0.27 GHz and 0.03-0.21 GHz. SE values of specimen which were knitted from hybrid yarns coded 6035 were found above 20 dB in the frequency range of 0.04-0.19 GHz. The highest SE value was recorded 24.75 dB at 0.07GHz in the measurements of the specimen which were knitted from hybrid yarns coded 6035 as seen in Figure 8.

Electromagnetic shielding effectiveness results of fabric knitted from yarns coded 7000, 7050, 7035, and 7018 for incident electromagnetic waves are given in Figure 9. Fabrics coded 7000 didn't exhibit SE, similarly fabrics coded 5000 and 6000. SE value of fabric coded 7018 was found above 15 dB in the frequency range of 0.05-0.21 GHz. In addition the SE values of 7035 and 7050 were found above 15 dB respectively in the frequency ranges of 0.03-0.28 GHz and 0.03-0.41 GHz.

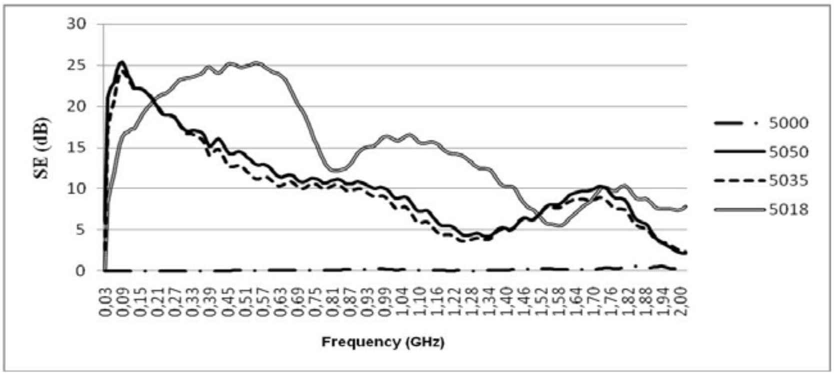

Figure 7. SE values of fabrics knitted from yarns coded 5000, 5050, 5035, 5018

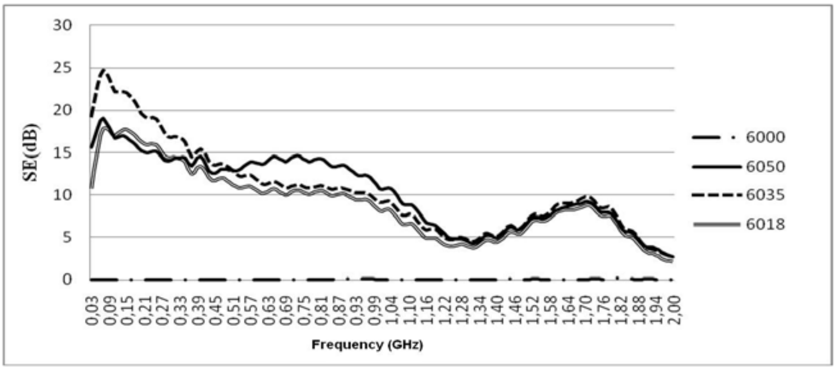

Figure 8. SE values of fabrics knitted from yarns coded 6000, 6050, 6035, 6018

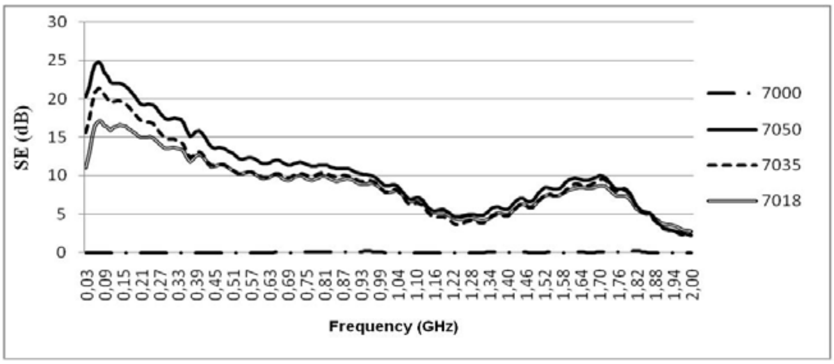

Figure 9. SE values of fabrics knitted from yarns coded 7000, 7050, 7035, 7018

SE measurement results, belonging to fabrics coded as 5050, 6050, and 7050 are shown graphically in Figure 10. The SE values of specimen coded 5050 and 7050 were found above 20 dB respectively in the frequency ranges of 0.03-0.18 GHz and 0.03-0.19 GHz. SE values of specimen which were knitted from hybrid yarns coded 6050 were found above 15 dB in the frequency range of 0.03-0.21 GHz. The highest SE value was recorded 25.37 dB at 0.07 GHz in the measurements of the specimen which were knitted from hybrid yarns coded 5050.

SE measurement results, belonging to fabrics coded as 5035, 6035, and 7035 are shown graphically in Figure 11. SE values of fabric specimen coded 5035 and 6035 were found above 20 dB in the frequency ranges of 0.04-0.19 GHz. However SE values of fabric specimen coded 7035 were found above 20 dB in relatively narrower frequency ranges of 0.06-0.09 GHz. The highest SE value was recorded 24.75 dB at 0.07 GHz in the measurements of the specimen coded 6035.

SE measurement results, belonging to fabrics coded as 5018, 6018 and 7018 are shown graphically in Figure 12. SE values of fabric specimen coded 5018 were found above 20 dB in the frequency ranges of 0.17-0.67 GHz. In addition the SE values of fabric specimens coded 6018 and 7018 were found above 15 dB respectively in the frequency ranges of 0.05-0.27 GHz and 0.05-0.21 GHz. The highest SE value was recorded 25.27 dB at 0.53 GHz in the measurements of the specimen coded 5018.

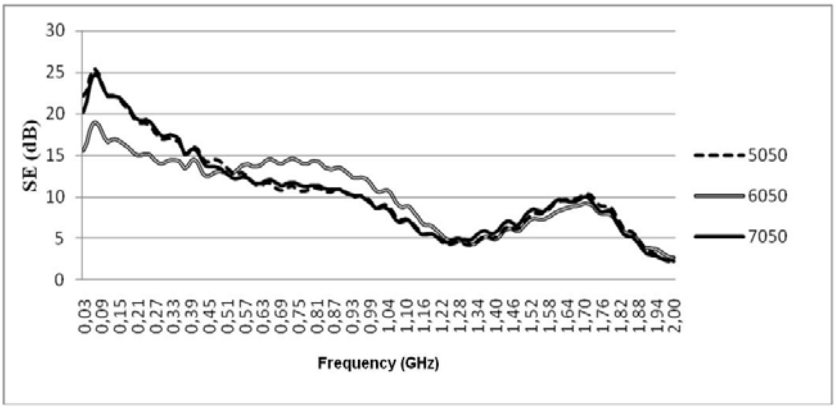

Figure 10. SE values of fabrics knitted from yarns coded 5050, 6050, 7050

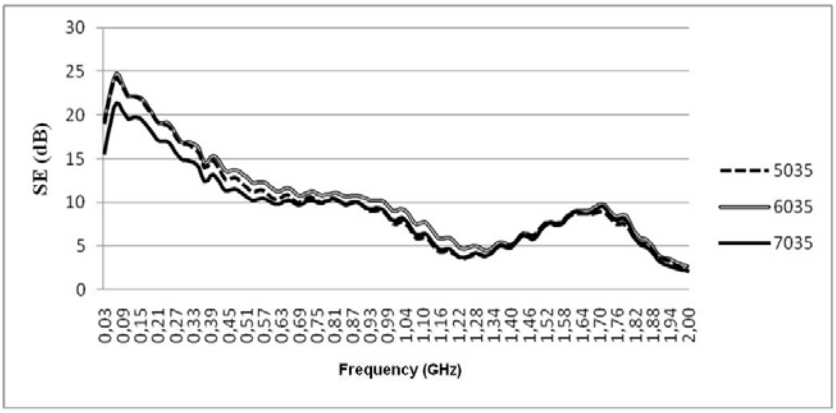

Figure 11. SE values of fabrics knitted from yarns coded 5035, 6035, 7035

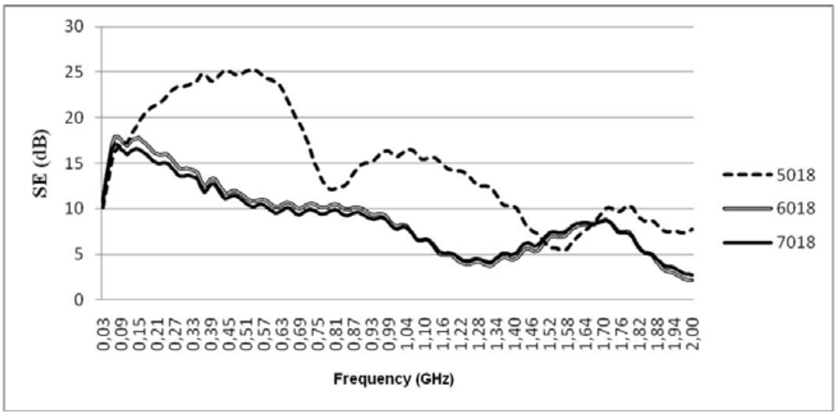

Figure 12. SE values of fabrics knitted from yarns coded 5018, 6018, 7018

Also SE measurement results of fabric specimens knitted from hybrid yarns show that SE values show generally decreasing tendency depending on the increasing frequency. The frequency and λ (wave length) of the electromagnetic waves emitted with the light speed ($3x10^8$ m/s) in space are inversely proportional. When the frequency increases the wave length decreases and depending on this, SE value decreases for the same fabric specimen.

3.1. Evaluation of Thermal Conductivity

Thermal conductivity of samples (average of 4 measurements) is shown in Figure 13.

Figure 13 shows that thermal conductivity of all fabric types increases as thickness of metal wire increases; 50 micron SS wire yields the highest thermal conductivity value at all samples. It is known that thermal conductivity of stainless steel wires increases as a function of ambient temperature and they have higher thermal conductivity than textile fibers at room temperature. Although adding metal wire causes fabric having lower density; it has enhancing effect on thermal conductivity.

Variance analysis of thermal conductivity results are shown in Table 2. The contribution of metal wire on thermal conductivity is stronger than cotton yarn, since estimated variance value (*MS*) of metal wire is bigger than that of cotton yarn as seen in Table 2. Also, the thermal conductivity values of samples varied by the change at metal wire type and cotton yarn fineness are found statistically significant; intersection of metal wire and cotton yarn effects are even significant. So, if an assessment would be done on thermal conductivity of the samples, one can say that fabric samples including metal wires either 18, 35 or 50 micron should be classified within different levels and thermal perceptions of those samples would be different from each other.

SNK test results for thermal conductivity measurements are given in Table 3. It shows that thermal conductivity of fabric samples increases gradually when thicker metal wire is included (as metal ratio increases in yarn). It is also found that although there is no difference statistically for different cotton yarn counts, coarser yarns yield higher thermal conductivity.

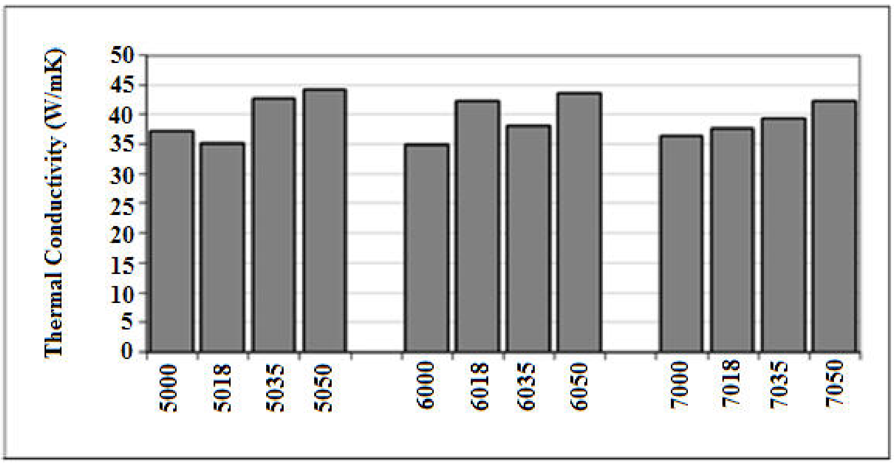

Figure 13. Thermal conductivity of samples

Table 2. Variance analysis table of thermal conductivity measurements

Variable	MS	Fs	p
Metal wire type (M)	84.005	49.724	0,000 ***
Cotton yarn type (C)	2,788	1.650	0,213 ns
M x C intersection effect	19,714	11.669	0,000 ***

Table 3. SNK ranking of thermal conductivity of samples

Variable	Treatment Level	Average Thermal Conductivity (W/mK)	Non-Significant Ranges
Metal wire type	50 micron	43.533	a
	35 micron	40.199	b
	18 micron	38.467	c
	0 micron	36.300	d
Cotton yarn type	Ne 50/1	39.975	a
	Ne 60/1	39.824	a
	Ne 70/1	39.075	a

3.2. Evaluation of Thermal Resistance

Thermal resistance (average of 4 measurements) of fabric samples is shown in Figure 14.

Figure 14 shows that increase of metal wire thickness also increases the thermal resistance. It is clear that thicker metal wire gives thicker fabric and thermal resistances of dry fabrics mainly depend on the thickness. Thus, we have found a high correlation coefficient (0,986) between thickness and thermal resistance of the samples.

Variance analysis of thermal resistance measurements is shown in Table 2. It shows the strong effect of adding metal wire as a variation source on thermal resistance of fabrics due to bigger *MS* value. The results for all variables were found statistically significant.

Table 5 shows SNK test results for thermal resistance measurements. The results reveal firstly that thicker metal wire increases thermal resistance value of fabric and this increase is statistically different range for all metal wire thickness values. Secondly, finer yarns yield lower thermal resistance as expected however only samples with Ne 50/1 yarn are found statistically different.

3.3. Evaluation of Thermal Absorptivity

Thermal absorptivity (average of 4 measurements) of fabric samples is shown in Figure 15.

Figure 15 shows that including metal wire within fabric structure increases thermal absorptivity as a general conclusion; thus those fabrics shall give colder feeling when touched. It is known that thermal absorptivity of fabric is directly proportional to thermal conductivity and inversely proportional to thermal resistance. In our study, since adding metal wire within fabric structure increased both thermal conductivity and resistance together, thermal absorptivity of our samples did not show a regular distribution. Variance analysis of thermal absorptivity results (Table 6) points that the cotton yarn count has stronger contribution than metal wire fineness. Especially, the results for cotton yarns are statistically significant.

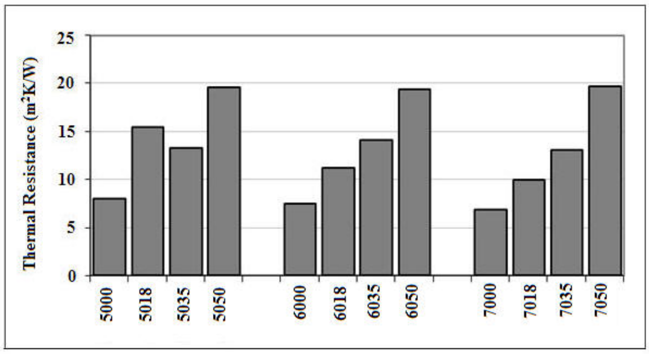

Figure 14. Thermal resistance of samples

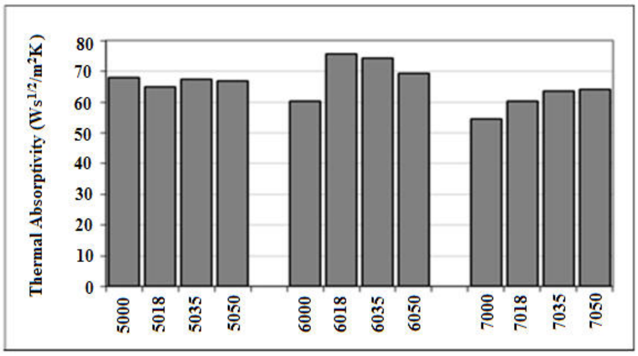

Figure 15. Thermal absorptivity of samples

Table 4. Variance analysis table of thermal resistance measurements

Variable	MS	Fs	p
Metal wire type (M)	222.412	159.886	0.0000 ***
Cotton yarn type (C)	8.709	6.261	0.0065 **
M x C intersection effect	6.043	4.344	0.0042 **

Table 5. SNK ranking of thermal resistance of samples

Variable	Treatment Level	Average Thermal Resistance (m^2K/W)	Non-Significant Ranges
	50 micron	19.540	a
Metal wire type	35 micron	13.510	b
	18 micron	12.205	c
	0 micron	7.468	d
	Ne 50/1	14.095	a
Cotton yarn type	Ne 60/1	13.038	b
	Ne 70/1	12.409	b

Table 6. Variance analysis table of thermal absorptivity measurements

Variable	MS	Fs	p
Metal wire type (M)	109.994	3.945	0.0202*
Cotton yarn type (C)	278.241	9.976	0.0007***
M x C intersection effect	52.590	1.886	0.1247 ns

SNK test results for thermal absorptivity are given in Table 7. It is found that samples without metal wire and samples knitted with finer cotton yarn (Ne 70/1) give the lowest thermal absorptivity and only samples with Ne 70/1 yarn are found statistically different.

It's shown that the SNK test results for the effect of thermal absorptivity of metal wire and cotton yarn factor levels in Table 7. SNK test average results show that thermal absorptivity values of fabric samples noninclusive metal wires are lower than fabric samples including metal wire and statistically different.

3.4. Evaluation of Air Permeability

Air permeability (average of 5 measurements) of samples is shown in Figure 16.

Figure 16 clearly shows that the thicker metal wire and the coarser cotton yarn, the lower the air permeability is. The fabrics without metal wire give the highest air permeability for all cotton yarn types. The air permeability is a function of fabric porosity, and finer yarns result higher porosity with higher air permeability. Thus, it is argued that metal wire reduced porosity at the samples. Variance analysis, given in Table 8, shows that all variables have strong contribution on air permeability and should be statistically different due to lowest *p* values as 0.000 but cotton yarn type has the strongest.

SNK results for air permeability also clearly point that as the metal wire becomes thicker and the cotton yarn gets coarser within sample structure, air permeability reduces. Samples without metal wire and with finer yarn have the highest air permeability and all treatment levels are significantly different from each other.

Table 7. SNK ranking of thermal absorptivity of samples

Factors	Factor Level	Average Thermal Absorptivity ($Ws^{1/2}/m^2K$)	Non-Significant Ranges
	35 micron	68.929	a
Metal wire type	18 micron	66.833	ab
	50 micron	66.699	ab
	0 micron	60.800	b
	Ne 60/1	69.824	a
Cotton yarn type	Ne 50/1	67.148	a
	Ne 70/1	60.474	b

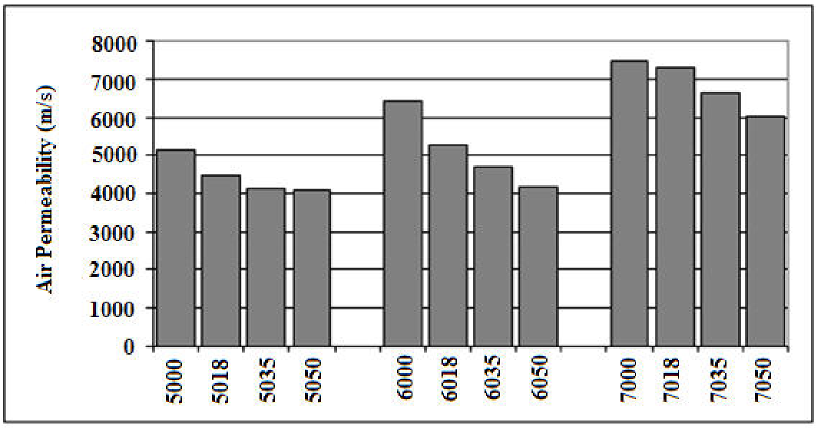

Figure 16. Air permeability of samples

Table 8. Variance analysis table of air permeability measurements

Variables	MS	Fs	p
Metal wire type (M)	4119811.111	218.429	0.0000 ***
Cotton yarn type (C)	18069352.778	958.022	0.0000***
M x C intersection effect	285219.444	15.122	0.0000 ***

Table 9. SNK ranking of air permeability of samples

Variable	Treatment Level	Average Air Permeability (mm/s)	Non-Significant Ranges
	0	6328.889	a
Metal wire type	18 micron	5708.889	b
	35 micron	5158.889	c
	50 micron	4774.444	d
	Ne 70/1	6865.000	a
Cotton yarn type	Ne 60/1	5112.500	b
	Ne 50/1	4500.833	c

3.5. Evaluation of Vertical Wicking

Vertical wicking (average of 3 measurements) of fabric samples is shown in Figure 17.

Figure 17 shows that metal wire reduces the wicking ability of samples. Wicking of textile fabrics is affected by fiber surface morphology and fiber shape since they determine the geometry, shape and portion of capillary channels where water is transferred. Thus, it is concluded that including metal wire affects the shape and geometry of capillary channels within fabric.

Variance analysis of vertical wicking measurements is given in Table 10. It is found that the largest contribution on vertical wicking belongs to metal wire type (with the biggest MS value) and cotton yarn type seems to have insignificant difference between each other. When SNK results are studied, it is obvious that samples without metal wire have significantly higher vertical wicking capacity than that of including any type of metal wire. Besides thicker metal wire and finer cotton yarn are found to reduce vertical wicking but that effect does not yield significant difference (Table 11).

4. CONCLUSION

In this study electromagnetic shielding and comfort properties of single jersey fabrics produced from hybrid yarns containing metal wire is investigated. It is found that SS wire in the structure is a parameter which affects significantly electromagnetic shielding and comfort properties of fabric samples. Fabrics including SS wire show higher SE than fabrics without metal wires. It is found that fabrics with SS wire reveal acceptable SE values (≥ 20 dB) at frequency range of 0.03 GHz – 0.21 GHz and the SE values of samples has decreasing tendency with increased frequency. This can be explained with the frequency and wave length of the electromagnetic waves emitted with the light speed ($3x10^8$ m/s) in space are inversely proportional and as the frequency increases the wave length decreases. In another words, SE value decreases for the same fabric sample because porosity of the fabric samples becomes more important with the decreasing wave length.

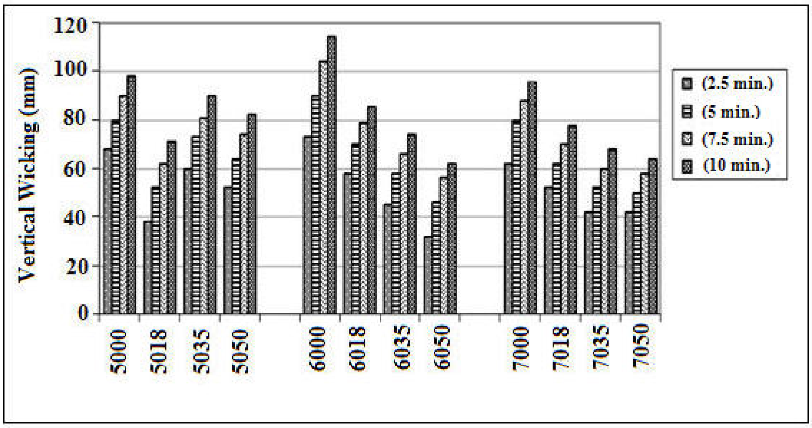

Figure 17. Vertical wicking of samples

Table 10. Variance analysis table of vertical wicking measurements

Variable	MS	Fs	p
Metal wire type (M)	1416.250	11.225	0.0001***
Cotton yarn type (C)	132.583	1.051	0.3652 ns
M x Cintersection effect	283.472	2.247	0.0732 ns

Table 11. SNK ranking of vertical wicking of samples

Variable	Treatment Level	Average Vertical Capillarity (mm)	Non-Significant Ranges
	0 mikron	81.667	a
Metal tel type	18 mikron	60.333	b
	35 mikron	59.667	b
	50 mikron	52.667	b
	Ne 50	66.167	a
Cotton yarn	Ne 60	64.750	a
	Ne 70	59.833	a

It is observed that SS wire in the hybrid yarns used for production of sample fabrics significantly affects thermal resistance and thermal conductivity of fabrics and adding metal wire increases thermal resistance and thermal conductivity values. Increasing of SS wire thickness in all fabric types reduces air permeability values. Samples without metal wire and with finer yarn have the highest air permeability. As amount of metal wire in structure of fabric increases, vertical wicking values generally decrease. Fabric without metal wire has the highest vertical wicking value.

According to experimental results, the metal wire type has also great influence on thermal conductivity, thermal resistance and vertical wicking properties of fabrics, whereas cotton yarn type is dominant factor on thermal absorptivity and air permeability properties of fabrics. This result shows that effects of metal wire and cotton yarn should be taken into account in respect to comfort perception of knitted fabrics (when considered as garment) with cotton and metal wire.

The results of measurements show that using of thick SS metal wire such as 50 micron will raise thermal resistance and thus will suppress increase of thermal conductivity and thermal absorptivity thanks to increasing fabric thickness. This structure will affect adversely property of vertical wicking which can be used to evaluate the behavior of fabric in contact with sweat.

When considering knitted garments, it has be kept in mind that amount of metal wire should be kept low in respect to physical comfort. As a result of these assessments, it can be suggested that single jersey knitted fabrics produced with 7018 and 7035 coded hybrid yarns are the most appropriate structures in terms of shielding effectiveness and thermal comfort.

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