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Studying Effects of Fabric Thickness, Loop Shape Factor, Fabric Tightness Factor and Aerial Weight on Thermal Conductivity of Plain Single Jersey Cotton Knitted Fabric using Box Behnken Design

Neway Seboka
Ethiopian Textile Industry Development Institute
Addis Ababa, Ethiopia

***Abstract*— The paper aims at studying the effects of fabric aerial weight, thickness, tightness factor, and loop shape factor on thermal conductivity behavior of plain single jersey knitted fabrics made with cotton yarn. 25 samples have been collected from the market. The samples are collected on the basis of their variation in the stated factors. Accordingly, statistical analysis is computed by using Design expert software version 11. For analysis Box, Behnken design (BBD) method is followed and made 30 runs of experimentation. A confidence level of 0.95 is used for prediction. The correlation coefficient between the predicted and the actual values are calculated to be 93.76%. The analysis shows fabric tightness factor and loop shape factor significantly affects the thermal conductivity of plain single jersey knitted fabrics. In addition, the interaction of fabric aerial weight & tightness factor, the interaction of fabric aerial weight & loop shape factor, and interaction of thickness & tightness factor also significantly affects the thermal conductivity behavior of the knitted fabric.**

Keywords-aerial weight, thickness, tightness factor, loop shape factor, thermal conductivity

I. INTRODUCTION

Knitted fabrics are most commonly chosen as they make the wearer feel comfortable because they have a soft texture and are flexible also. As this is the case, to make even better the comfort properties of these garments' studies have been conducted on Physiological thermal comfort and sensations of the fabrics. [1-4]

Clothing comfort is categorized into four classifications as: psychological, thermo-physiological, and tactile and garment fit comfort. Psychological comfort relates with fashion trends, the thermo-physiological comfort is concerned with air, moisture and heat movements through the fabric. Sensorial comfort is dependent on the fabric surface and that of garment fit comfort is relying on fitness of the garment material on the body. Amongst these, the thermal comfort property is dependent on fibre, yarn & fabric properties, finishing treatments, etc. For assessment measurements have to be made with thermal conductivity, thermal resistance, air permeability and water vapor permeability. [5]

Thermal conductivity of a knitted fabric is determined by the heat transfer process through the fabrics. The heat exchange process in the fabric is influenced by the fabric structure and the materials used to construct the fabric.

The thermal conductivity of natural fibres is higher as compared with protein fibres. The heat conductivity of a fabric decreases when the fabric increases in its thickness and surface mass. Specific area also affects it. Fabric texture has also a considerable influence on thermal resistance of a fabric.

A tighter/denser fabric does exhibit a decreased heat loss since the air circulation through the fabric decreases.

Özçelik et al reported on their studies that knitted fabrics made with texturized PES filaments exhibit a lower thermal conductivity property than a knitted fabric made with non-texturized PES filament yarn. [6]

The other influencing factor for heat interchange process is the fabric structure. Plain knitted fabric structures exhibit a faster and higher heat transfer than other designs produced in flat double bed knitting machines.

Cubric et al studied the factors affecting the heat conductivity properties on a single jersey knitted fabrics and reported a strong relation between fabric thickness, aerial weight and tightness factor on heat resistance of their sample fabrics. [7]

Demiryürek and Uysaltürk on the other hand compared the thermal conductivity of 1x1 rib fabric with a single jersey. They take samples made with cotton blend and polyester blended one. They have found that the rib fabric tends to have a higher thermal conductivity than the single jersey one as the rib fabric is having a higher fabric thickness, minimum air gap and a higher aerial weight. [8]

EsraTaştanÖzkan et al investigated the thermal comfort properties of polyester knitted fabrics. They found that, fabric having a higher thickness value with lower number of filaments shows the lowest thermal conductivity. [9]

It has been studied that variation in input yarn tension while making the single jersey fabric significantly affects fabric aerial weight (GSM). [10]

One way ANOVA statistical analysis technique/method has been used for showing the correlation between mechanical yarn stretch % in sizing with warp yarn breakage in looms & the same method has been followed for analyzing the relation between input yarn tension with fabric aerial weight. [11]

On the other hand using Box Behnken design, effects of fabric thickness, loop shape factor, aerial weight & tightness factor on water vapor permeability of single jersey knitted fabrics have been studied in detail. [12]

In this research, it is planned to see the effects of fabric thickness, loop shape factor, fabric tightness factor, and aerial weight on thermal conductivity of plain single jersey knitted fabrics made with 100% cotton. Design expert software is used for analyzing the significance of the factors on the thermal conductivity. For analysis Box Behnken design is used.

II. MATERIALS & METHODS

Plain knitted single jersey fabric made with 100% cotton yarn is used for experimentation. All the samples are purchased from market.

Table 1 Description of the samples

SCP describes sample made with cotton and having plain design

The characterized parameters are tested following standard testing procedures.

S. no	Experimental code	Fabric composition	Count (Ne)	Sample fabric structure	Wales/inch	Course/inch	Fabric aerial weight (GSM)	Thickness (mm)	Loop length (mm)	Fabric tightness factor ($tex^{1/2}$/loop length in mm)	Loop shape factor (CPI/WPI)
1	S_1CP	100% cotton	60	Plain single jersey	48	66	142.1	5.4	2.6	1.2	1.36
2	S_2CP	100% cotton	40	Plain single jersey	48	66	169.7	5.1	2.5	1.54	1.36
3	S_3CP	100% cotton	40	Plain single jersey	52	60	169.7	5.4	2.5	1.54	1.15
4	S_4CP	100% cotton	40	Plain single jersey	48	66	142.1	5.4	2.5	1.54	1.36
5	S_5CP	100% cotton	55	Plain single jersey	48	66	169.7	5.4	2.4	1.37	1.36
6	S_6CP	100% cotton	55	Plain single jersey	48	66	197.3	5.1	2.4	1.37	1.36
7	S_7CP	100% cotton	55	Plain single jersey	52	60	169.7	5.7	2.4	1.37	1.15
8	S_8CP	100% cotton	55	Plain single jersey	48	66	197.3	5.7	2.4	1.37	1.36
9	S_9CP	100% cotton	60	Plain single jersey	48	66	169.7	5.7	2.6	1.2	1.36
10	S_{10}CP	100% cotton	55	Plain single jersey	52	60	197.3	5.4	2.4	1.37	1.15
11	S_{11}CP	100% cotton	55	Plain single jersey	48	66	142.1	5.1	2.4	1.37	1.36
12	S_{12}CP	100% cotton	60	Plain single jersey	52	60	169.7	5.4	2.6	1.2	1.15
13	S_{13}CP	100% cotton	55	Plain single jersey	56	88	142.1	5.4	2.4	1.37	1.57

S. no	Experimental code	Fabric composition	Count (Ne)	Sample fabric structure	Wales/inch	Course/inch	Fabric aerial weight (GSM)	Thickness (mm)	Loop length (mm)	Fabric tightness factor ($tex^{1/2}$/loop length in mm)	Loop shape factor (CPI/ WPI)
14	S_{14}CP	100% cotton	55	Plain single jersey	52	60	169.7	5.1	2.4	1.37	1.15
15	S_{15}CP	100% cotton	60	Plain single jersey	56	88	169.7	5.4	2.6	1.2	1.57
16	S_{16}CP	100% cotton	55	Plain single jersey	56	88	197.3	5.4	2.4	1.37	1.57
17	S_{17}CP	100% cotton	40	Plain single jersey	48	66	197.3	5.4	2.5	1.54	1.36
18	S_{18}CP	100% cotton	55	Plain single jersey	56	88	169.7	5.7	2.4	1.37	1.57
19	S_{19}CP	100% cotton	60	Plain single jersey	48	66	197.3	5.4	2.6	1.2	1.36
20	S_{20}CP	100% cotton	55	Plain single jersey	56	88	169.7	5.1	2.4	1.37	1.57
21	S_{21}CP	100% cotton	55	Plain single jersey	52	60	142.1	5.4	2.4	1.37	1.15
22	S_{22}CP	100% cotton	55	Plain single jersey	48	66	142.1	5.7	2.4	1.37	1.36
23	S_{23}CP	100% cotton	40	Plain single jersey	48	66	169.7	5.7	2.5	1.54	1.36
24	S_{24}CP	100% cotton	60	Plain single jersey	48	66	169.7	5.1	2.6	1.2	1.36
25	S_{25}CP	100% cotton	40	Plain single jersey	56	88	169.7	5.4	2.5	1.54	1.57

A. *Experimentation*

Before testing is made, all the samples are conditioned with a room temperature of 220c & a relative humidity of 63%. The conditioning is made for 24 hrs.

Fabric thickness test: The test is conducted following ASTM D 1777.

Fabric GSM: using GSM cutter and electronic balance following ASTM D 3776 with a specimen size of $100cm^2$.

Loop length: of a knitted fabric is calculated by using the formula:

Loop length=course length/No. of loops

Tightness factor: is calculated with the formula:

Fabric tightness factor=$tex^{1/2}$/loop length

Loop shape factor: is calculated with the formula:

Loop shape factor=CPI/WPI

Fabric composition: test is made with ISO 1833:2012 test method with MLR ratio of 1g of fabric: 200 ml of (75% conc. H2SO4)

Thread density (Wales/inch & course/inch): is counted using picks glass.

III. RESULTS & DISCUSSION

Accordingly, considering the above-stated internal properties of the sample fabrics test for thermal conductivity has been carried out.

Thermal conductivity test: the test is made using ALAMBETA instrument following ISO 31092. For all the specimens, the measuring head temperature was kept 300c and the contact pressure 180Pa.

A. *Statistical analysis of factors on thermal conductivity behavior of the samples*

The statistical analysis is made using design expert software following Box Behnken design.

File Version	**11.0.3.0**		
Study Type	Response Surface	**Subtype**	Randomized
Design Type	Box-Behnken	**Runs**	30
Design Model	Quadratic	**Blocks**	No Blocks

Build Time (ms)	142.00

Table 2 Experimental results for thermal conductivity

		Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Response 1**
Std	Run	A:Fabric aerial weight GSM	B:Thickness mm	C:Fabric tightness factor	D:Loop shape factor	Thermal conductivity W/mk
17	1	142.1	5.4	1.2	1.36	0.026
15	2	169.7	5.1	1.54	1.36	0.038
6	3	169.7	5.4	1.54	1.15	0.042
19	4	142.1	5.4	1.54	1.36	0.046
27	5	169.7	5.4	1.37	1.36	0.039
26	6	169.7	5.4	1.37	1.36	0.041
2	7	197.3	5.1	1.37	1.36	0.04
22	8	169.7	5.7	1.37	1.15	0.04
4	9	197.3	5.7	1.37	1.36	0.042
14	10	169.7	5.7	1.2	1.36	0.024
10	11	197.3	5.4	1.37	1.15	0.043
1	12	142.1	5.1	1.37	1.36	0.044
5	13	169.7	5.4	1.2	1.15	0.032
28	14	169.7	5.4	1.37	1.36	0.042
11	15	142.1	5.4	1.37	1.57	0.039
29	16	169.7	5.4	1.37	1.36	0.041
21	17	169.7	5.1	1.37	1.15	0.041
7	18	169.7	5.4	1.2	1.57	0.026
25	19	169.7	5.4	1.37	1.36	0.043
12	20	197.3	5.4	1.37	1.57	0.034
20	21	197.3	5.4	1.54	1.36	0.036
24	22	169.7	5.7	1.37	1.57	0.041
18	23	197.3	5.4	1.2	1.36	0.029
23	24	169.7	5.1	1.37	1.57	0.041
9	25	142.1	5.4	1.37	1.15	0.039
30	26	169.7	5.4	1.37	1.36	0.037
3	27	142.1	5.7	1.37	1.36	0.041
16	28	169.7	5.7	1.54	1.36	0.044
13	29	169.7	5.1	1.2	1.36	0.03
8	30	169.7	5.4	1.54	1.57	0.04

Table 3 ANOVA for thermal conductivity

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0009	14	0.0001	16.09	< 0.0001	significant
A-Fabric aerial weight	0.0000	1	0.0000	2.45	0.1384	
B-Thickness	3.333E-07	1	3.333E-07	0.0810	0.7799	
C-Fabric tightness factor	0.0005	1	0.0005	126.34	< 0.0001	
D-Loop shape factor	0.0000	1	0.0000	5.18	0.0379	
AB	6.250E-06	1	6.250E-06	1.52	0.2369	
AC	0.0000	1	0.0000	10.26	0.0059	
AD	0.0000	1	0.0000	4.92	0.0424	
BC	0.0000	1	0.0000	8.74	0.0098	
BD	2.500E-07	1	2.500E-07	0.0607	0.8087	
CD	4.000E-06	1	4.000E-06	0.9717	0.3399	

A^2	5.833E-07	1	5.833E-07	0.1417	0.7119	
B^2	2.333E-06	1	2.333E-06	0.5668	0.4632	
C^2	0.0003	1	0.0003	60.80	< 0.0001	
D^2	1.190E-06	1	1.190E-06	0.2892	0.5986	
Residual	0.0001	15	4.117E-06			
Lack of Fit	0.0000	10	3.825E-06	0.8138	0.6357	not significant
Pure Error	0.0000	5	4.700E-06			
Cor Total	0.0010	29				

The Model F-value of 16.09 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case C, D, AC, AD, BC, C^2 are significant model terms.

The Lack of Fit F-value of 0.81 implies the Lack of Fit is not significant relative to the pure error. There is a 63.57% chance that a "Lack of Fit F-value" this large could occur due to noise.

The ANOVA analysis for the experimentation shows that the model is adequate and fitting. As the P-values indicate fabric tightness factor and loop shape factor significantly affects the thermal conductivity of plain single jersey knitted fabrics. Additionally, the interaction of fabric aerial weight & tightness factor, the interaction of fabric aerial weight & loop shape factor and interaction of thickness & tightness factor also significantly affects the thermal conductivity behavior of the knitted fabric.

The experimentation indicates fabrics with higher tightness factor exhibits higher thermal conductivity values. Tighter fabrics do have more number of yarns and thus a higher fibrous assembly will be there. So, the assembled fibrous materials will act as a conductive media and let the heat to pass through them. But the samples with lesser tightness factor are loose and more porous with higher air gap in the structure. As air is not a good conductive media of heat their thermal conductivity values is lower. Thus, the experiment shows fabric tightness factor directly and significantly affects fabric thermal conductivity.

The same is true for loop shape factor. As the factor increases the fabric will get denser and it will be dimensionally stable as the number of course yarns increase. The higher the yarn constituting in the fabric, the denser the fabric will be and because of the less porosity of the structure the thermal conductivity of the fabric will get higher. So, the analysis indicates loop shape factor has a direct correlation with the thermal conductivity behavior of a knitted fabric.

The interactions also show the same relation. As the fabrics' GSM and tightness factor increases, the thermal conductivity will also increase. When the fabric has a higher aerial weight and loop shape factor it will be denser and bulkier leading to higher thermal conductivity of a fabric.

For point prediction confidence level of 95% is used. The plot for predicted vs. actual values of the thermal conductivity in fig. 1 below shows that results are distributed around the regression line. This indicates that the model is unbiased and hence it is adequate & fitting. The calculated correlation coefficient between them is 93.76%.

In fig. 2 also a 3D surface graph showing the effects of fabric thickness & aerial weight on the thermal conductivity behavior is there. The other 2 factors have been kept constant with values of 1.37 & 1.36 for fabric tightness factor & loop shape factor respectively. As different mesh colors are shown in the surface graph, blue is for the lowest thermal conductivity value & red is for the highest one. Since, fabric aerial weight & thickness are not significantly affecting thermal conductivity behavior of plain single jersey knitted fabrics used in this experimentation, much color change is not observed in the surface graph.

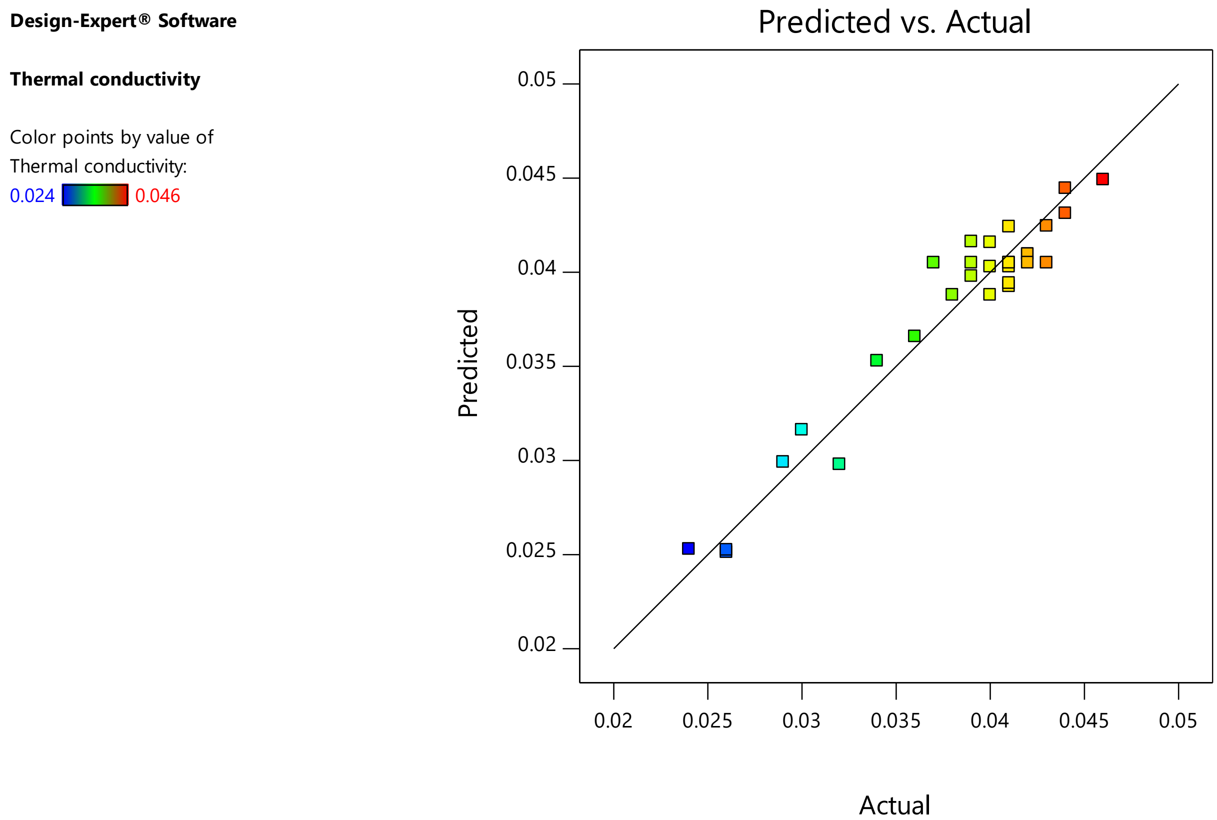

Fig. 1 Plot for predicted vs. actual values of thermal conductivity

Table 4 Calculated R^2

Std. Dev.	**0.0020**	R^2	**0.9376**
Mean	0.0380	**Adjusted R^2**	0.8793
C.V. %	5.33	**Predicted R^2**	0.7430
		Adeq Precision	13.7951

The Predicted R^2 of 0.7430 is in reasonable agreement with the Adjusted R^2 of 0.8793; i.e. the difference is less than 0.2.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. 13.795 indicate an adequate signal.

Regression Equation in Terms of Actual Factors

Thermal conductivity	=
+0.177063	
+0.000758	*Fabric aerial weight
-0.182160	*Thickness
+0.373338	*Fabric tightness factor
+0.025423	*Loop shape factor
+0.000151	*Fabric aerial weight * Thickness
-0.000693	*Fabric aerial weight * Fabric tightness factor
-0.000388	*Fabric aerial weight * Loop shape factor
+0.058824	*Thickness * Fabric tightness factor
+0.003968	*Thickness * Loop shape factor
+0.028011	*Fabric tightness factor * Loop shape factor
-3.82885E-07	*Fabric aerial weight²
+0.006481	*Thickness²
-0.209054	*Fabric tightness factor²
-0.009448	*Loop shape factor²

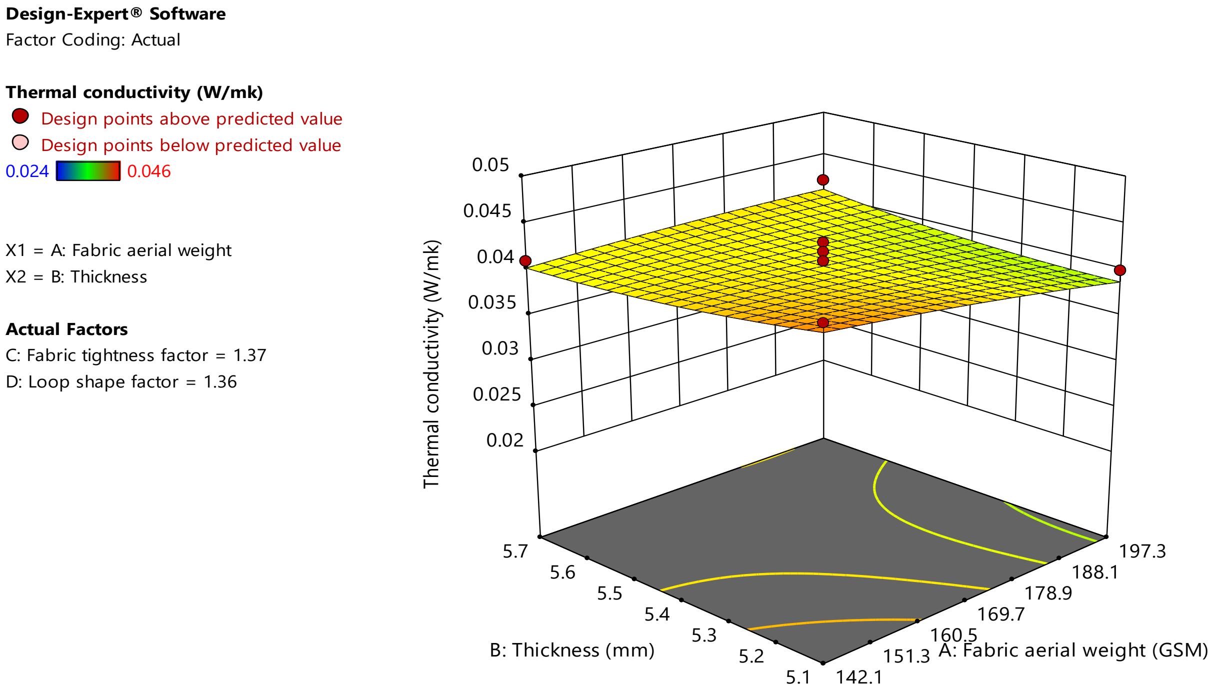

Fig. 2 3D surface for showing factor effects on thermal conductivity behavior

IV. CONCLUSION

In general, the experimentation indicates that fabric tightness factor and loop shape factor significantly affect the thermal conductivity of plain single jersey knitted fabrics. Additionally, the interaction of fabric aerial weight & tightness factor, interaction of fabric aerial weight & loop shape factor and interaction of thickness & tightness factor also significantly affects the thermal conductivity behavior of the knitted fabric. Thus, the experiment shows fabric tightness factor directly and significantly affects fabric thermal conductivity. The analysis also indicates loop shape factor has a direct correlation with the thermal conductivity behavior of a knitted fabric. By using a confidence level of 95% point prediction is made and the calculated correlation coefficient is 93.76%.

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AUTHOR PROFILE

Mr. Neway Seboka has got his BSc degree from Bahir Dar University, polytechnic campus, Ethiopia in 2012. He also received his M.Tech degree from the Indian Institute of Technology, Delhi, India in 2017. Currently, he is working as a researcher in the Ethiopian Textile Industry Development Institute. He has published more than 8 articles in peer-reviewed and reputed national and international journals.