FACULTY OF TEXTILE ENGINEERING TUL

EFFECT OF ELASTIC KNITTED FABRIC CONSTRUCTION PARAMETERS ON THERMO-PHYSIOLOGICAL PROPERTIES

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SUMMARY OF THE THESIS

Title of the thesis:	Effect of Elastic Knitted Fabric Construction Parameters on Thermo-physiological Properties
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Abstrakt

To enhance the dimensional stability of knitted fabrics, spandex is incorporated in the knitting machine in form of core spun yarn or by plaiting technique. The thermo-physiological properties of the fabric are one of the most important properties that affect human comfort. Therefore, the proposed study aims to investigate the effect of construction parameters of elastic single jersey knitted fabric (SJKF), namely yarn count, loop length, spandex weight percent (SWP), and plaiting technique on the geometrical and thermo-physiological properties. The elastic SJKF were produced at two levels of yarn count (25 and 35 Ne), five levels of loop length (2.7, 2.9, 3.1, 3.3, 3.4 mm), and five levels of SWP (4, 5, 6, 7, 8%) with full and half plaiting techniques. For comparison, the 100% cotton samples were produced at the same levels of yarn count and loop length. The geometrical and thermo-physiological properties, fabric stretch, fabric growth, and thermal properties at two levels of extension (15 and 30%) were measured.

The results showed that Adding spandex leads to stitch overlapping; therefore, the elastic SJKF thickness ranged between 3.9*d to 4.4*d where d is yarn diameter. The thermal conductivity and absorptivity, water vapor resistance, stitch density, and fabric weight of full and half plaited SJKF decreased when the loop length and SWP increased. While the thermal resistance and fabric thickness of the elastic SJKF increased with the loop length increasing, and decreased with SWP increasing. The thermal conductivity of full plaited knitted fabric was higher than half plaited fabric, and the thermal resistance of half plaited SJKF was higher than full plaited SJKF. The fabric growth of the full plaited SJKF was less than 100% cotton samples, while the fabric stretch of the elastic SJKF was higher than 100% cotton samples. When the fabric extension increased from 15 to 30%, the fabric thickness and the thermal conductivity, resistance, and absorptivity of full plaited decreased. The spandex incorporated in the weft knitting machine had a good impact on the geometrical and thermo-physiological properties.

Also, this study aims to present an innovated 3D geometrical model of the stitch overlapping, maximum set structure, and open structure to calculate the pore size and pore distribution through the SJKF structures by using AutoCAD software. A 3D multifiber model was developed based on actual construction parameters, such as loop length 2.9 mm, and yarn diameter 0.1662 mm. It was noticed that the overlapping structure had the smallest pore volume, followed by the maximum set, followed by the open structure.

The last aim of this study is to derive a new model that can be used to predict the thermal conductivity of the elastic SJKF based on the geometrical parameters of the loop and fibers' direction to the heat flow direction. It was marked that the predicted values of the thermal conductivity from the new model were very close to the experimental values, and the model is prepared to be used for the prediction of thermal properties of SJKF.

Content

List of Abbreviations and Nomenclature

Symbol	Description	Unit
ε	Fabric porosity	%
ρ_f	Fibre density	$Kg.m^{-3}$
ρ_c	Cotton fibre density	$Kg.m^{-3}$
ρ_s	Spandex fibre density	$Kg.m^{-3}$
ρ_{fabric}	Fabric density	$Kg.m^{-3}$
W	Fabric weight per unit area	$g.m^{-2}$
h	Fabric thickness	mm
b	Thermal absorptivity	$W. s^{1/2} m^{-2}. K^{-1}$
α_e	Twist factor	-
d	Yarn diameter	mm
c	Course spacing	mm
w	Wale spacing	mm
l	Loop length	mm
C	Specific heat capacity	$J. kg^{-1}. K^{-1}$
λ	Thermal conductivity coefficient	$W. m^{-1}. K^{-1}$
λ_{fab}	Fabric thermal conductivity coefficient	$W. m^{-1}. K^{-1}$
λ_f	Fibres thermal conductivity coefficient	$W. m^{-1}. K^{-1}$
λ_{c}	Cotton fibres thermal conductivity coefficient (0.5)	$W. m^{-1}. K^{-1}$
λ_s	Spandex fibres thermal conductivity coefficient (0.15)	$W. m^{-1}. K^{-1}$
λ_a	Thermal conductivity of air (0.026)	$W. m^{-1}. K^{-1}$
λ_{cotton}	Thermal conductivity of cotton fibres in one repeat	$W. m^{-1}. K^{-1}$
λ_{spandex}	Thermal conductivity of spandex in one repeat	$W. m^{-1}. K^{-1}$
λ_{air}	Thermal conductivity of air in one repeat	$W. m^{-1}. K^{-1}$
λ_{ser}	Thermal conductivity of fibres in series	$W. m^{-1}. K^{-1}$
λ_p	Thermal conductivity of fibres in parallel	$W. m^{-1}. K^{-1}$
F_c	Cotton fibres volume fraction	-
F_s	Spandex volume fraction	-
F_f	Total fibres volume fraction	-
F_{a}	Air volume fraction	-
A	Original distance between bench marks (100 mm)	mm
B	Distance between bench marks measured after 1 min of tension release	mm
D	Distance between bench marks measured after 60 min of tension release	mm
E	Distance between bench marks measured while specimen is under tension force	mm
SJKF	Single jersey knitted fabric	-
SWP	Spandex weight percent	%
fp	Full plaited	-
hp	Half plaited	-
WVR	Water vapour resistance	$Pa. m^2. W^{-1}$
FGW	Fabric growth in wales direction	%
FGC	Fabric growth in courses direction	%
FSW	Fabric stretch in wales direction	%
FSC	Fabric stretch in courses direction	%
ME 2	Maxwell- Eucken 2 model	-

N	total number of fibres in yarn cross-section	-
T	Yarn count	tex (g/km)
t	Cotton fibre fineness	tex (g/km)
D	Cotton fibre diameter	mm
A	Cotton fibre cross-section area	mm^2
TPI	Number of twists per inch	t/in
Nm	Yarn metric count	Nm (m/g)
Ne	English yarn count	Ne (yd/Ib)
V_{pi}	Pores volume at i^{th} section	mm^3
V_{xi}	Enclosure volume of the i^{th} section	mm^3
V_{fi}	Fibre volume of the i^{th} section	mm^3
ε_i	Theoretical porosity in the i^{th} section	%

CHAPTER 1: INTRODUCTION

The human body tries to maintain a constant core temperature of about 37°C where a rise or fall of 5°C can be fatal. The human body continuously generates heat by its metabolic processes. The heat is lost from the body by conduction, convection, radiation, evaporation, and respiration [1]. Body heat balance varies with the climate; in hot climates, the problem is one of heat dissipation, whereas in cold climates, it is one of heat conservation. Clothing plays an important role in the maintenance of heat balance as it modifies the heat loss from the skin surface and at the same time, has the secondary effect of altering the moisture loss from the skin [2]. The general clothing assemblies approximately covers around 90% of the human body. Therefore, the heat and moisture transmission behaviour of the fabric plays a very important role in maintaining thermo-physiological comfort [1].

The thermo-physiological properties of fabrics have a significant impact on the human thermal comfort [3], which is defined as a state of satisfaction with the thermal conditions of the environment [4]. The thermal comfort properties study the way in which the heat, air and water vapour are transmitted through a fabric which is heterogenous mixture of solid fibres and air. The fabric's thermo-physiological properties depend on the temperature difference between environment and skin, construction parameters of fabrics, yarns structure, yarn properties, fibre's properties, fibre's type, fabric thickness, porosity, areal density, number of fabric layers, and trapped air [5].

Textile fabrics have varying degrees of flexibility based on structural parameters [6]. Knitted fabrics are characterized by comfort compared to woven fabrics due to their high extensibility (compression and elongation of individual stitch), air permeability, and heat retention, but the dimensional stability after repeated washing especially single jersey knitted fabrics (*SJKF*) is considered the main disadvantage. To enhance the dimensional stability and maintain the dimensions during use and after repeated stresses of knitted fabrics, the spandex on form of plaiting technique or core-spun yarn are used. In plaiting technique, spandex is incorporated with cotton yarns by using a separate feeder for spandex. If the spandex and cotton yarn are knitted side-by-side in every course, with the spandex yarn always kept on one side of the cotton yarn, this is called full plaiting. When the spandex is incorporated in alternating courses, the method is called half plaiting [7].

Lycra is the trade name of elastane (spandex) yarns and has an extension-at-break greater than 200 %, and shows high recovery after unloading. These fibres exhibit rubber-like behaviour with high reversible extension as high as 400 - 800 %. Chemically, spandex is a synthetic linear macromolecule with a long chain containing at least 85 % of segmented polyurethane along with the alternating hard and soft segments linked by urethane bonds – NH – CO – O – [8][9][10][11]. Soft segment gives elasticity (stitch rearrangement), while the hard segment gives molecular interaction force to the fibre and which ensures a certain level of strength of the fibre and long-term stability. Spandex improves the dimensional stability, body fit of weft knitted fabric and freedom of body movements. Spandex proportion is one of the most important parameters of single jersey plaited fabrics and influences fabric characteristics [12].

So, there is a need to investigate the effect of spandex weight percent on the thermo-physiological comfort properties of elastic *SJKF*. The aim of this thesis is firstly, to estimate the effect of construction parameters of elastic *SJKF*, namely yarn count, loop length, and spandex weight percent on the geometrical and thermo-physiological comfort properties. Secondly a mathematical model is presented to predict thermal conductivity of elastic *SJKF*. Thirdly, a new approach to investigate the pore size and pore distribution inside the *SJKF* structure is proposed.

CHAPTER 2: OVERVIEW OF THE CURRENT STATE OF THE PROBLEM

In the last decades, a lot of researchers have been concerned with the thermo-physiological properties of knitted fabrics. The thermal properties of plain, rib and interlock produced from cotton-bamboo blended yarns were investigated [13]. It was included that the thermal conductivity of knitted fabric decreased when the yarn count increased (became finer). The thermal conductivity and thermal resistance values of interlock fabric was the maximum followed by the rib and plain fabrics. The effect of fabric parameters on the thermal properties of polyester/cotton double layer knitted interlock fabrics was analysed [14]. The results showed that the thermal resistance depended on the percentage of fibre that had higher specific heat and thermal resistance was in direct proportion with the yarn count, loop length and fabric thickness. The thermal absorptivity of the fabric decreased with fabric weight decreasing and cotton content increasing. The effect of stitch length and fabric structure on the dimensional and thermo-physiological properties of knitted fabrics made of Seacell and elastane yarns were investigated [15]. Single Jersey, Single Piqué and Double Piqué were produced from yarns composed of 20% SeaCell pure/10% SeaCell Active/70% Combed Cotton, 12 tex and bare elastane 4.4 tex at loop lengths 2, 2.5, and 3 mm. It was concluded that the thermo-physiological properties can be changed by fabric construction and the loop length had a significant effect on the thermo-physiological properties, especially the thermal conductivity and air permeability. The effect of fibre, yarn and fabric parameters was investigated on heat and moisture transport properties of single jersey plated fabrics [16]. Twelve single jersey plated knit samples were produced from cotton, polyester, nylon, and viscose yarns at three levels of loop length. Cotton yarn was used in the outer layer while filament yarns of three varying fibre types were used in the inner (next to skin). It was found that as the loop length increased, the thermal resistance, conductivity, and absorptivity decreased while the relative water vapour permeability, air permeability and water absorbency increased. The thermo-physiological properties of double-layered weft fabrics knitted from cotton or man-made bamboo yarns and synthetic polyamide, polypropylene, and polyester yarns were studied [17]. The results showed that It was established that thermal properties of double-layered knitted fabrics depend on raw material, structural parameters and knitting pattern of the fabric.

Others have been concerned with the effect of spandex on the geometrical and physical properties of elastic knitted fabric. The dimensional and physical properties of cotton/spandex single jersey fabrics were investigated and compared to 100% cotton knitted fabrics. The presence of spandex increased the fabric weight and thickness, on the contrary, it decreased air permeability, pilling grade, and spirality [18][19]. The geometrical characteristics of core-spun cotton/spandex interlock structures with high, medium and low tightness factors were studied under dry, wet, and full relaxation conditions. The elastic interlock samples had higher dimensional constants compared to 100 % cotton samples, and core cotton/spandex yarns increased tightness factors during relaxation states [20]. The effect of spandex type, the tightness factor of the base, and spandex yarn on the dimensional and physical properties of cotton/spandex single jersey fabrics were investigated. The fabrics knitted with spandex yarns that have the largest tension values under a constant draw ratio give the highest weight, courses per cm, stitches per cm^2, thickness, and lowest air permeability values [21]. The relation between spandex consumption and fabric dimensional and elastic behaviour of cotton/spandex plaited plain knitted fabrics was studied. The results showed that spandex proportion inside fabric has an incidence on fabric width, weight, and elasticity [12]. The effect of spandex yarn input tension, yarn loop length, and spandex yarn linear density on the elastic properties of spandex knitted fabrics was studied. The stitch density, fabric weight and thickness of spandex fabrics were higher, and fabric growth was lower than the knitted fabric without spandex. As the fabric loop length increased, the fabric stretch increased in both wale and course directions [22]. The effect of the extension percent of bare spandex yarns during loop formation on the geometrical, physical, and mechanical properties of plain jersey fabrics was studied. Results showed that for the full plaited (*fp)* and half plaited (*hp)* fabrics, the stitch density, fabric thickness and weight increased, while air permeability, initial elasticity modulus, and the breaking load and extension decreased considerably compared to 100% cotton knitted fabric [7]. The impact of the raw material, count of yarn, pattern and elastomeric yarn ratio on the performance and physical properties of the plain, pique, double-pique and fleeced elastic knitted fabrics was found out. Test results showed that raw material, yarn count, and elastane ratio had a significant effect on bursting strength [23]. The physical, dimensional, and mechanical properties of back plaited cotton/spandex *SJKF* were investigated and are compared to knitted fabrics made from 100% cotton, and the effect of spandex percentage was also studied. It was found that the presence of spandex in *SJKF* increased course density, fabric thickness, and fabric recovery, while fabric width, fabric porosity, and extension were decreased [24]. Plain and rib fabrics produced from 100% cotton, half-plaited and full-plaited were investigated for physical, dimensional, geometrical, and some comfort properties and compared to each other. The results showed that transfer wicking ratios of the half-plaited fabrics were the highest, whereas the transfer wicking ratios of the full-plaited fabrics were the lowest, and extension under constant load and residual deformation ratios decreased with the addition of spandex and the increase of spandex content [25]. Based on the previous research, spandex has a significant effect on the dimensional, physical and mechanical properties of knitted fabrics.

A few researchers have been concerned with the thermal comfort properties of elastic knitted fabrics. The artificial neural network (ANN) was used to predict the global thermal comfort index of stretched knitted fabric from the structural parameters as inputs [26]. The results showed that ANN was in good agreement with target and calculated input data. The thermal comfort properties of some Egyptian stretch knitted fabrics made from synthetic and spandex yarns based single jersey were statistically investigated. The results showed that both the thermal conductivity and resistance of all the selected fabric samples increased with the increase of fabric density, and the fabric temperature variation decreased with fabric thickness increasing [27]. The physical properties, strength and thermal comfort characteristics of the interlock knitted fabric produced from cotton and elastane yarns (full and half plaited) were investigated and compared to 100% cotton fabrics. It was included that the elastic fabrics produced from coarser elastane yarn had higher weight, thickness, bursting strength and puncture resistance. In terms of thermal comfort, the fabrics including coarser elastane yarn provided higher thermal conductivity and thermal absorptivity, lower air and relative water vapour permeability. As the elastane rate increased, fabric weight, thickness, bursting strength, puncture resistance, and thermal absorptivity increased, while air permeability decreased as well, and the fabrics knitted using elastane yarns presented higher thermal conductivity [28]. Based on the previous research, spandex has a significant effect on the dimensional, physical and mechanical properties of knitted fabrics. It was noticed that more researches are required to investigate and study the effect of spandex percent, loop length and spandex state (full and half plaited) on thermo-physiological properties of elastic knitted fabrics in details. Also, some data base about the thermo-physiological of elastic *SJKF* is needed to be available to the manufacturers and designers of fabrics.

CHAPTER 3: THE AIMS OF THE THESIS

The thermal comfort properties are one of the most important parameters that affect the human comfort. Last decades, researchers are interested in the thermal properties of textiles and try to find the parameters that affect consumer comfort. Based on the literature review, it was necessary in the current work to:

1. Investigate the effect of construction parameters of elastic *SJKF* (yarn count, loop length, spandex weight percent and plaiting technique) on the geometrical and thermo-physiological properties.
2. Analyse the effect of spandex percent on fabric growth and fabric stretch of *SJKF*.
3. Present a theoretical 3D model of stitch overlapping, maximum set, and open structures by using AutoCAD software to investigate the pore size and distribution for different *SJKF* structures.
4. Apply three simple mathematical models (Maxwell–Eucken 2, Schuhmeister, Militky) of thermal conductivity to investigate if these models can be used to predict the thermal conductivity of elastic *SJKF*.
5. Derive a new equation that describes the thermal conductivity of the elastic *SJKF* based on the loop geometry and the yarn and fibres inclination on the direction of heat flow.
6. To assist the manufacturers and designers to predict the thermo-physiological properties of elastic *SJKF* produced from cotton yarns.

CHAPTER 4: STUDIED MATERIAL AND USED METHODS

4.1 Studied materials

In order to investigate the effect of fabric construction parameters, two different combed yarn counts were produced (25 and 35Ne) from Egyptian cotton fibres Giza 86 (fibre fineness: 172 mtex, staple length: 32 mm) and with twist factor α_e=3.6 (838 and 709 turns per meter for yarn count 35 and 25 Ne, respectively). Then full and half plaited *SJKF* were produced with two yarn counts and five levels of spandex weight percent (*SWP)* (4, 5, 6, 7, and 8%) and five levels of the loop length (2.7, 2.9, 3.1, 3.3, and 3.4 mm) as shown in table 4.1. Spandex count was 30 and 70 dtex for full and half plaited respectively to get the same *SWP*. Spandex yarns (bare spandex) were incorporated by the plaiting technique (feeding spandex yarn at different tension with cotton yarn) where spandex yarns have a separate feeding system, plaiting roller and guide eye, as shown in figure 4.1. The adjustment of spandex percentage is obtained by adjusting and optimizing the speed of spandex delivery system. To increase spandex weight percent, the tension on spandex yarns decreased and vice versa. *SJKF* without spandex were produced at the same levels of yarn count and loop length. All samples were produced on VIGNONI SJ-B (number of feeders: 57, diameter: 19-inch, machine gauge: 24 needles/inch), and were treated according to the elastic knitted fabric finishing recipe. First, heat setting at 185 °C was applied, followed by dyeing at 95 °C and finally compacting at 90 °C.

Table 4.1: *SJKF* specifications

Yarn count			100% cotton	Full plaited					Half plaited				
	SWP (%)		0	4	5	6	7	8	4	5	6	7	8
25 Ne	Loop length (mm)	2.7	√	√	√	√	√	√	√	√	√	√	√
		2.9	√	√	√	√	√	√	√	√	√	√	√
		3.1	√	√	√	√	√	√	√	√	√	√	√
		3.3	√	√	√	√	√	√	√	√	√	√	√
		3.4	√	√	√	√	√	√	√	√	√	√	√
35 Ne	Loop length (mm)	2.7	√	√	√	√	√	√	√	√	√	√	√
		2.9	√	√	√	√	√	√	√	√	√	√	√
		3.1	√	√	√	√	√	√	√	√	√	√	√
		3.3	√	√	√	√	√	√	√	√	√	√	√
		3.4	√	√	√	√	√	√	√	√	√	√	√

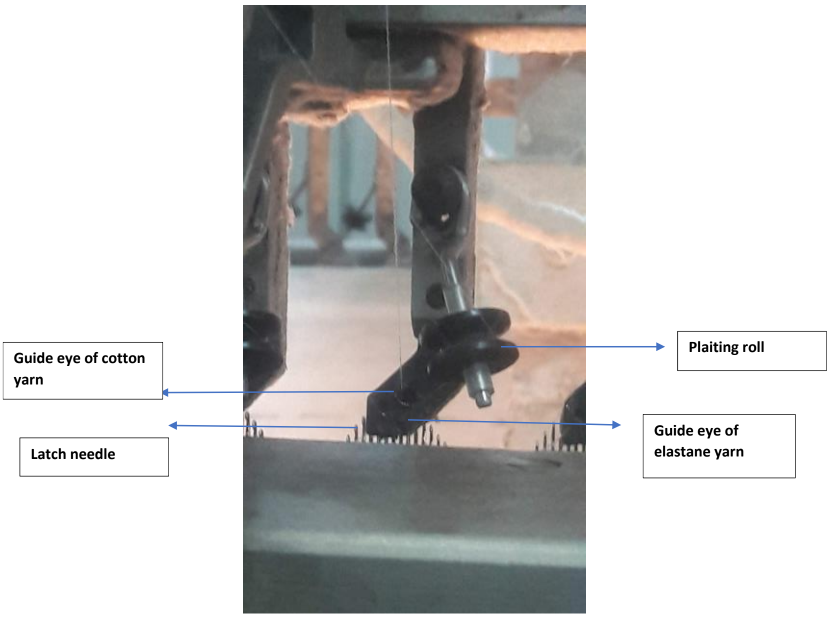
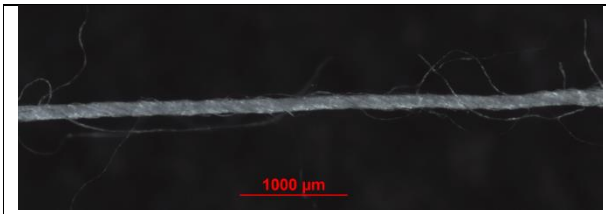


Figure 4.1. Plaiting technique in knitting machine

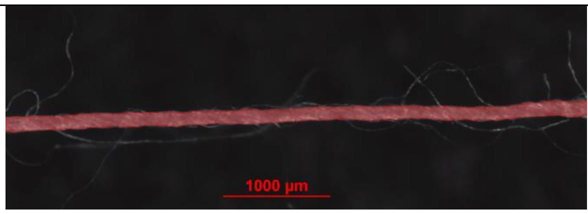
4.2 Used methods

4.2.1 Yarn diameter

Yarn diameter was measured by taking images of the yarns by the camera (ProgRes-CT3) attached to a microscope under transmitted light. The captured images were analysed by using NIS-elements software. The threshold of binary images was adjusted then binary image processing was applied, such as erosion and dilation for 70 images for each count, as shown in figure 4.2. and the yarn diameter was calculated by inserting 70 images.



a- Yarn image before processing



b- Yarn image after processing

Figure 4.2. Yarn images before and after binary processing

4.2.2 Yarn bending rigidity

The bending rigidity of yarns was measured according to internal standard No.22- 201- 01/01 [29]. Figure 4.3 shows the device used for testing, where one end of the yarn was fixed and another end was free under the yarn weight. Then the image of yarn bending was captured and analysed by using LUCIA image analysis software, as shown in figure 4.4, and the bending rigidity of yarn was obtained by applying the differential equation of the bending line [30].

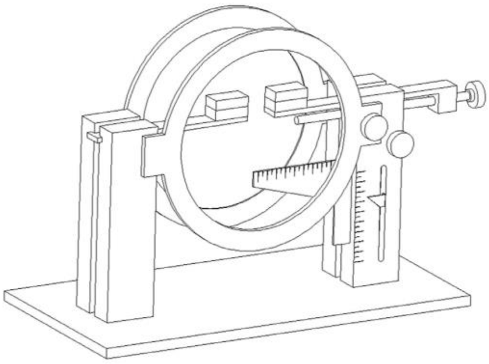


Figure 4.3 the device used for measuring yarn bending stiffness [29]

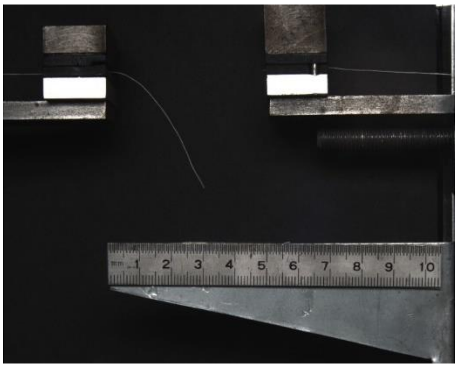


Figure 4.4 captures image of yarn bending

4.2.3 Fabric porosity

The fabric density (ρ_{fabric}) and fabric porosity (ε) were calculated from the following equations [31]:

$$\text{Fabric density, } \rho_{\text{fabric}} = \frac{W}{h} \qquad \ldots\ldots\ldots\ldots. \qquad (4.1)$$

$$\text{Fabric porosity, } \boldsymbol{\varepsilon}(\%) = \left(1 - \frac{\rho_{fabric}}{\rho_f}\right) * 100 \qquad \ldots\ldots\ldots\ldots. \qquad (4.2)$$

Where W: fabric weight per unit area (g.m^{-2}), h: fabric thickness (mm) and ρ_f: fibre density (kg.m^{-3}). ρ_f for 100% cotton is equal to 1520 kg.m^{-3}, but ρ_f for elastic knitted fabric was calculated from equation 3.3 [32].

$$\rho_f = \frac{\rho_s \, \rho_c}{\frac{SWP}{100}\,\rho_c + \left(1 - \frac{SWP}{100}\right)\rho_s} \qquad \text{…………….} \quad (4.3)$$

Where ρ_s : spandex fibre density (kg.m^{-3}), ρ_c: cotton fibre density (kg.m^{-3}).

4.2.4 Thermo-physiological properties

Thermal conductivity, resistance and absorptivity and fabric thickness were measured by using Alambeta tester (non-destructive instrument) [33] according to the standard ISO 8301 [34]. Relative water vapour permeability was tested by Permetest instrument, which is the so-called skin model that simulates dry and wet human skin in terms of its thermal feeling [35][36] according to ISO 11092 [37]. Air permeability was measured by FX 3300-20 Labotester III according to EN ISO 9237 [38]. Fabric growth and fabric stretch were measured according to ASTM D2594 – 04 [39] as follows:

4.2.5 Fabric growth and fabric stretch

Flexi-frame was designed according to the standard, as shown in figure 4.5. Fabric samples were cut with the dimension of 125 mm*400 mm, folded in half lengthwise forming a loop and sewed, then bench marks 100 mm were placed on samples. Fabric sample was hanged on rods of flexi-frame, as shown in figure 4.6, then extensions 15% and 30% were applied in wales and course direction, respectively, by moving a movable board down. After an extension was applied for 2 hrs. ±5 min, the sample was free from flexi-frame and put on the table, and the length between bench marks was measured after 1 min and 60 min. To measure the fabric stretch, the tension force (10, 15, 20, and 25 N) were applied, as shown in figure 4.7, and the length between bench marks was measured after applying weight by a ruler or from monitor.

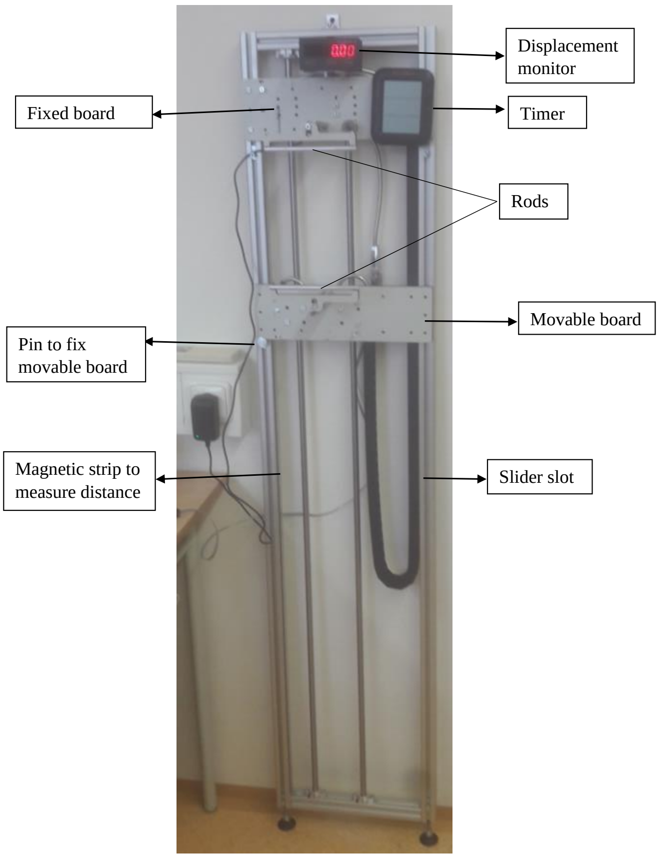


Figure 4.5. Flexi-frame

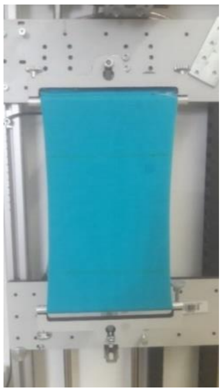


Figure 4.6. Hanged sample

Figure 4.7. Applied tension force

The Fabric growth and fabric stretch were calculated from the following equations:

$$Fabric\ Growth_{1\ min}\ (\%) = \frac{B - A}{A} * 100 \qquad \text{… … … … [4.4]}$$

$$Fabric\ Growth_{60\ min}\ (\%) = \frac{D - A}{A} * 100 \qquad \text{… … … … [4.5]}$$

$$Fabric\ Stretch\ (\%) = \frac{E - A}{A} * 100 \qquad \text{… … … … [4.6]}$$

Where A is the original distance between bench marks (100 mm), B is the distance between bench marks measured after 1 min of tension force release, D is the distance between bench marks measured after 60 min of tension release. Recovery, E is the distance between bench marks measured while the specimen is under tension force.

4.2.6 Thermal properties under extension

Thermal properties (thermal conductivity, resistance and absorptivity) and fabric thickness were measured under two levels of extension 15 and 30% for loose fitting knitted fabric as mentioned on the standard test method ASTM D2594 – 04. The thermal properties of compression knitted fabric under extensions ranged between 0 to 60% was investigated [40][41]. The extensions were applied by embroidery frame of diameter 15 cm, as shown in figure 4.8. To obtain 15 and 30% extension, two circles with diameters 13 and 11.5 cm were marked respectively on the samples. Then the samples were extended to get the desired extension.

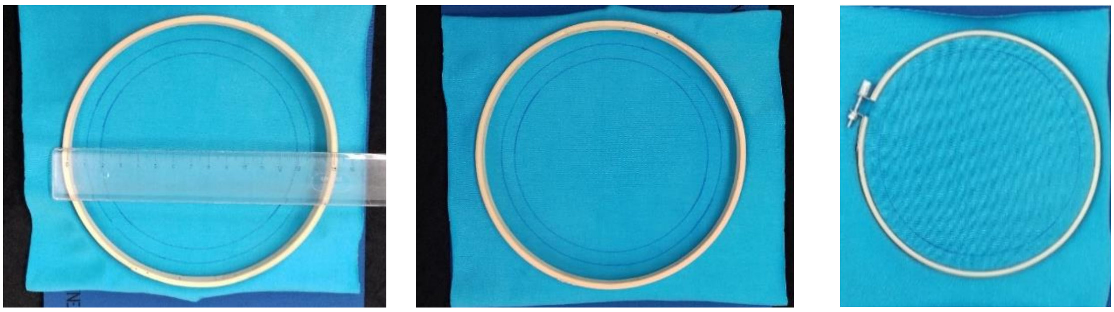


Figure 4.8. Applied extension by using embroidery frame

To determine the significance effects of the yarn count, loop length, *SWP* and plaiting technique on all tested properties of elastic *SJKF* at 95% significant level, the general factorial analysis was applied by using Minitab program. Table 4.2 shows the factors information. Multi-way ANOVA was applied to investigate the effect of *SWP*, relation time, and direction of applied tension on fabric growth and stretch also, to investigate the effect of extension percent on the thermal conductivity.

Table 4.2. Factors information of factorial design

Factor	Levels	Values
Plaiting technique	2	full plaiting, half plaiting
Yarn count (Ne)	2	25 - 35
Loop length (mm)	5	2.7 - 2.9 - 3.1 - 3.3 - 3.4
Spandex weight percent (%)	5	4- 5 - 6 - 7 - 8

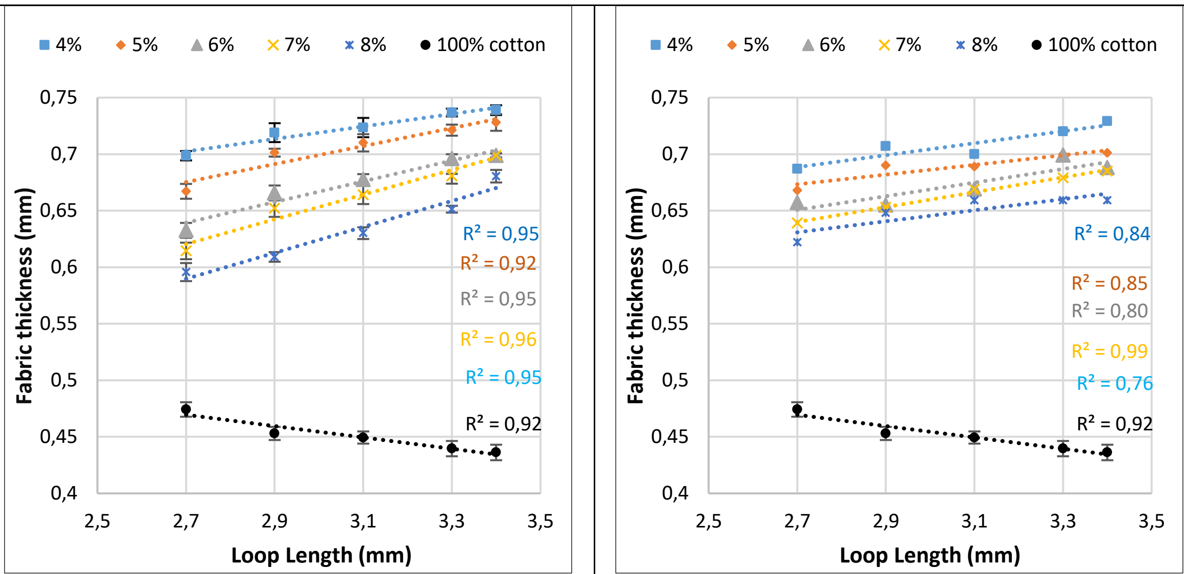
CHAPTER 5: SUMMARY OF THE ACHIEVED RESULTS

In order to investigate the effect of loop length and *SWP* on the geometrical and thermo-physiological properties, the produced *fp* and *hp SJKF* from yarn count 35 Ne at five levels of loop length and *SWP* will be shown. The same effects and trends were found for samples produced from yarn count 25 Ne.

5.1 Geometrical properties

5.1.1 Fabric thickness

Figures (5.1-a) and (5.1-b) display the effect of loop length on fabric thickness of full and half plaited *SJKF*, respectively, at five levels of *SWP* (4, 5, 6, 7, and 8%). The theoretical fabric thickness equals twice the yarn diameter for open and normal structures (jamming condition or maximum set), as shown in figure (5.2-a:d). For open structure, wale spacing (*w*) is more than 4 *d*, and course spacing (*c*) is more than 2*√3**d* where *d* is the yarn diameter (mm). While for normal structure, *w* is equal to 4*d, and *c* is equal to 2*√3**d*. The elastic fabric thickness of experimental samples ranged between 3.58**d* (0.596 mm) to 4.44**d* (0.739 mm). So, it could be interpreted that spandex leads to stitch overlapping (*c* < 2*√3**d*, *w* < 4**d*, but it was assumed to be equal to 4**d* for geometrical modelling), as shown in figure (5.2-e:g). Also, adding spandex leads to stitch legs overlapping, as shown in figure (5.2-h), which significantly increases the fabric thickness. The fabric thickness of *fp* knitted samples was higher than 100% cotton by 47% at loop length 2.7 mm and *SWP* 4% and 69% at loop length 3.4 mm and *SWP* 8% as shown in figure (5.1-a) and figure 5.3.

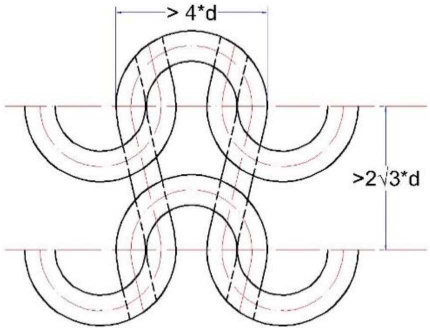


a- Full plaited (35 Ne)

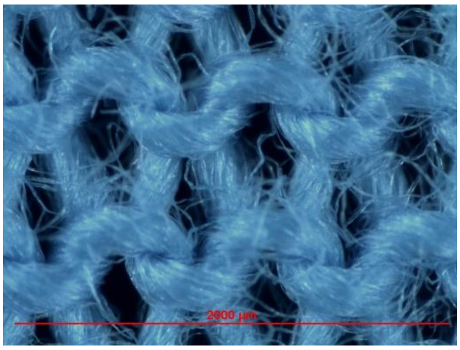
b- Half plaited (35 Ne)

Figure 5.1. Effect of loop length on the fabric thickness

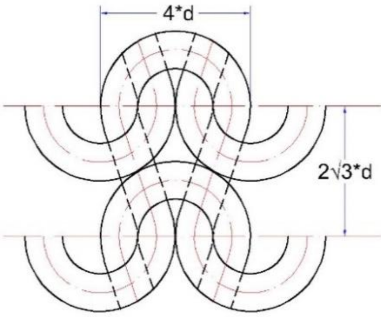
In general, for *fp* and *hp*, the fabric thickness decreased with the increase of the *SWP* from 4 to 8% by 17% at loop length 2.7mm for *fp* and by 7% at the loop length 2.7mm for *hp*. It could be interpreted as the increase of *SWP* reduced the stretch ability as well as the compression effect of spandex on loops, as shown in figures (5.2-f) and (5.2-g), and reduced the stitch density as well, as shown in table 5.1. The increase of loop length increased the loop's overlapping; therefore, the fabric thickness increased consequently. The thickness of *fp* samples was higher than *hp* samples, and this may be due to the spandex plaiting in all courses and alternative courses. The fabric thickness of 100% cotton knitted fabric decreased with the increase of stitch length due to the reduction of stitch density, and there is no stitch overlapping, as shown in figure (5.2-b).



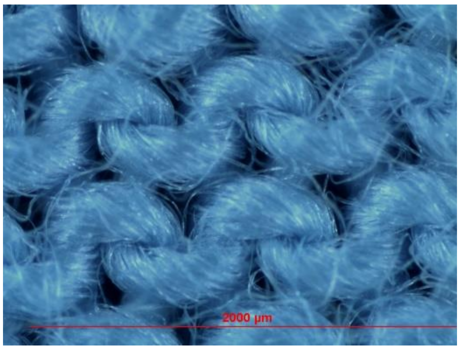
(a) Theoretical geometry of open structure



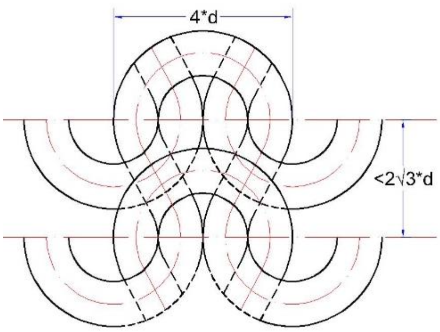
(b) Microscopic image of open structure at 35 Ne



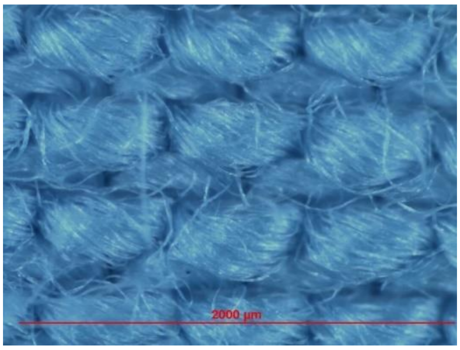
(c)Theoretical geometry of normal structure



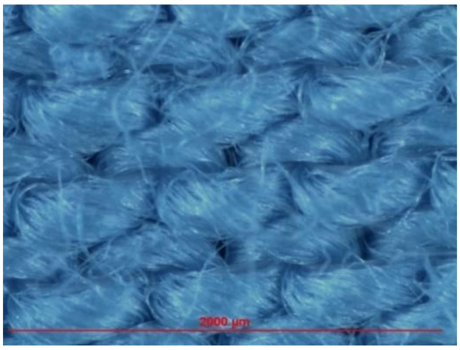
(d) Microscopic image of normal structure at 25 Ne



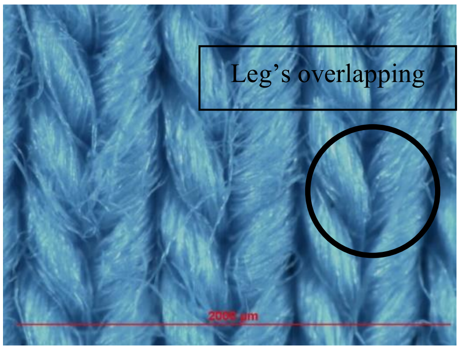
(e) Theoretical geometry of stitch overlapping



(f) Microscopic image of stitch overlapping at *SWP* 4% and 35 Ne

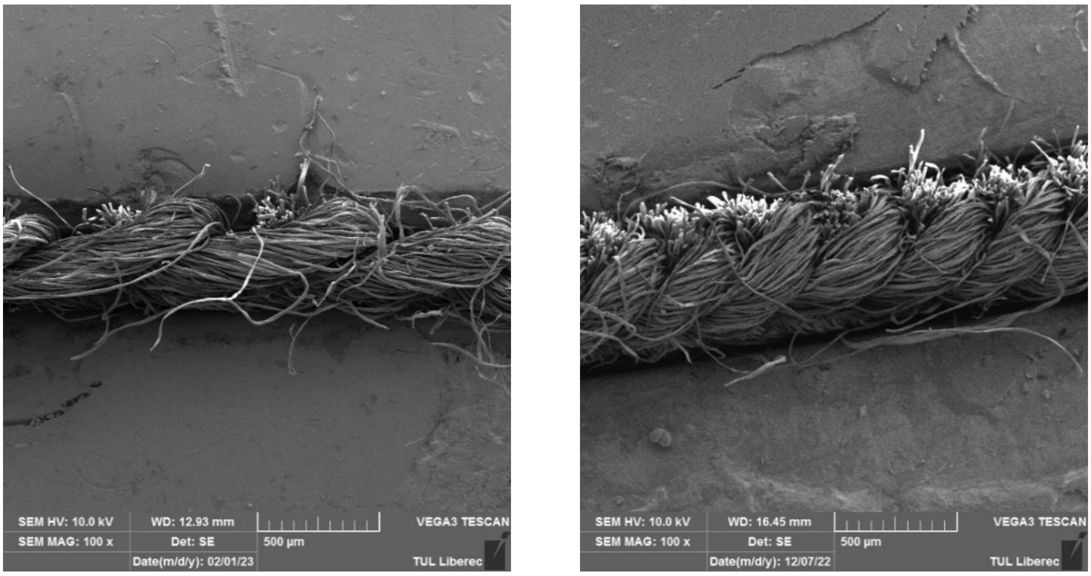


(g) Microscopic image of overlapping at *SWP* 8% and at 35 Ne



(h) Microscopic image of legs overlapping at *SWP* 4% and 35 Ne

Figure 5.2. Single jersey loop structure, all microscopic images at loop length 2.9 mm.



a- 100% cotton

b- Elastic knitted fabric at *SWP* 4%

Figure 5.3. SEM of images *SJKF* by SEM at loop length 2.7 mm and yarn count 35 Ne

All trends for *SJKF* produced from yarn count 25 Ne were the same of *SJKF* produced from yarn count 35 Ne. The thickness of fp produced from yarn count 25 Ne was higher than 100% cotton samples by 37 % at loop length 3.4 mm and *SWP* 8%.

Fabric thickness of samples produced from yarn count 25 Ne was higher than 35 Ne because yarn count 25 Ne had higher diameter than yarn count 35 Ne, and also bending rigidity of yarn 25 Ne was higher than yarn 35 Ne. The statistical analysis showed that *SWP*, loop length, plaiting technique and yarn count had a significant effect on the fabric thickness, see table 5.2. Therefore, the increase of fabric thickness may lead to an increase in the thermal resistance of the tested samples.

Table 5.1. Stitch density (cm^{-2}) of *SJKF*

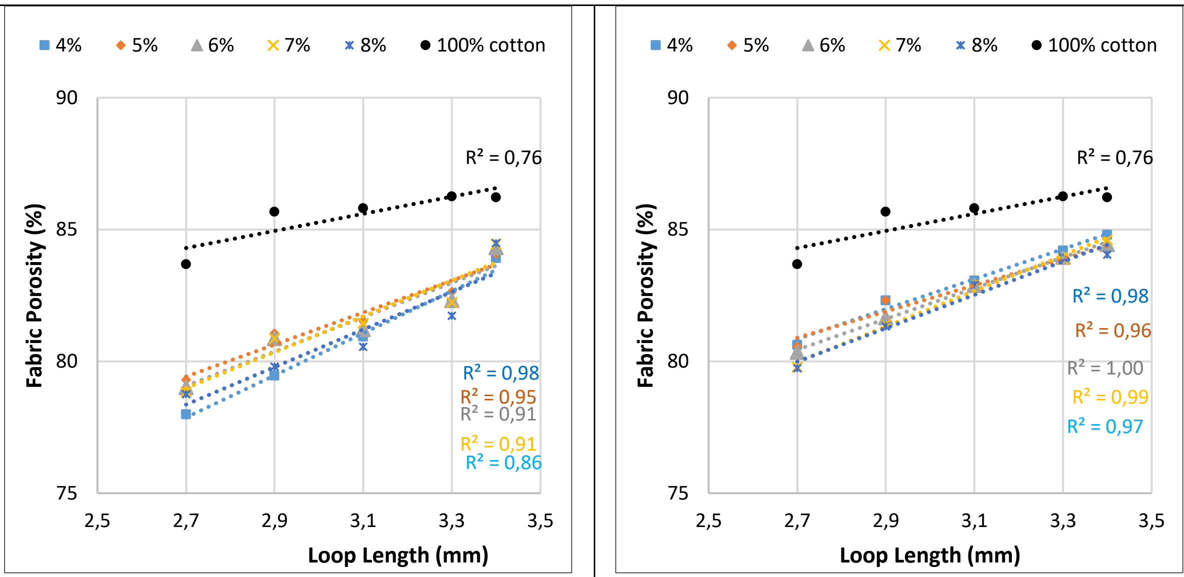
Yarn count			100% cotton	Full plaited					Half plaited				
	SWP (%)		0	4	5	6	7	8	4	5	6	7	8
35 Ne	Loop length (mm)	2.7	272	486	448	411	391	371	414	395	383	367	358
		2.9	230	437	403	379	366	356	371	362	340	323	315
		3.1	190	371	353	334	328	315	343	332	312	310	302
		3.3	177	353	340	321	309	293	319	310	301	287	281
		3.4	169	323	327	312	301	297	312	293	282	281	272

Table 5.2. The results of variance analysis (P value at significant level 95 %)

Dependent property	P value, Independent variables			
	Loop length (mm)	SWP (%)	Plaiting technique	Yarn count (Ne)
Fabric thickness (mm)	< 0.001	< 0.001	0.047	< 0.001
Thermal conductivity ($W. m^{-1}. K^{-1}$)	< 0.001	< 0.001	< 0.001	< 0.001
Thermal resistance ($m^2. K. W^{-1}$)	< 0.001	< 0.001	< 0.001	< 0.001
Thermal absorptivity ($W.m^{-2}. s^{1/2}. K^{-1}$)	< 0.001	< 0.001	< 0.001	< 0.001
WVR ($Pa.m^2. W^{-1}$)	< 0.001	< 0.001	< 0.001	< 0.001
Air permeability ($mm.s^{-1}$)	< 0.001	< 0.001	< 0.001	< 0.001

5.1.2 *Fabric porosity*

The fabric porosity of *fp* was lower than 100% cotton samples by just 7 and 2% at loop length 2.7 and 3.4 mm, respectively, and *SWP* 4%, as shown in figure (5.4-a). Also, the fabric porosity of *hp* was lower than 100% cotton by 4 and 1% at loop length 2.7 and 3.4 mm respectively and *SWP* 4%, as shown in figure (5.4-b).



a- Full plaited (35 Ne)   b- Half plaited (35 Ne)

Figure 5.4. Effect of loop length on the fabric porosity

The fabric porosity of *fp* and *hp* produced from yarn count 25 Ne were lower than 100% cotton by 6 and 4% respectively at loop length 2.7 mm and *SWP* 4%. The stitch density of elastic *SJKF* was higher than 100% cotton samples, and there was no a big difference between the porosity of 100% cotton and elastic *SJKF*, the pores size and distribution inside the structure plays an important role in thermo-physiological properties. The fabric porosity of *hp* was slightly high than *fp* due to the ridges formed on the hp fabric surface. The fabric porosity of *SJKF* went up with the increasing of the loop length due to the stitch density decreasing.

5.2 *Thermo-physiological properties*

5.2.1 *Thermal conductivity*

The thermal conductivity coefficient (λ) presents the amount of heat which passes from 1m^2 area of material through the distance 1m within 1s and the temperature difference 1K [6]. It is the fabric ability to transfer heat from body to environment and vice versa depending on the temperature difference between the body and environment[14]. The thermal conductivity can be expressed by the following equation.

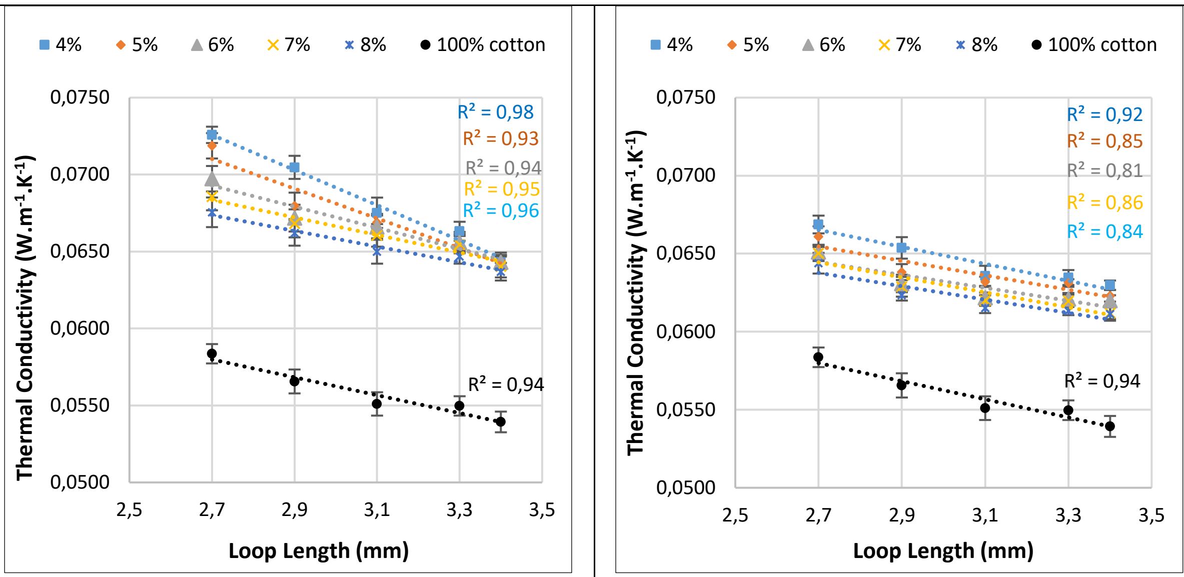
$$\lambda = \frac{Q * h}{A * \Delta T * 1000} \qquad \dots \dots . \dots \qquad (5.1)$$

Where λ is the thermal conductivity coefficient ($W.m^{-1}.K^{-1}$), Q is the amount of heat (W), h is the fabric thickness (mm), A is the fabric tested area (m^2), and ΔT is the temperature difference (K).

In general, the thermal conductivity of elastic knitted fabric decreased with increasing of *SWP* for both *fp* and *hp*, as illustrated in Figures (5.5-a) and (5.5-b) respectively. It could be interpreted that the stitch overlapping decreases with increasing of *SWP* and the stitch density decreases, as shown in table 5.1. So, the number of fibres per unit area decreased; therefore, the number of paths which the heat transferred through the fibres by conduction decreased. Increase *SWP* means to increase in the number of spandex fibres and a reduction in the number of cotton fibres. The thermal conductivity of spandex and cotton fibres is 0.15 and 0.5 W. m^{-1}. K^{-1}, respectively [42], so the average thermal conductivity of fibres decreased according to the following equation.

$$\lambda_f = \frac{SWP}{100}\,\lambda_s + \left(1 - \frac{SWP}{100}\right)\lambda_c \qquad \ldots\ \ldots\ \ldots\ \ (5.2)$$

Where λ_f is the thermal conductivity of fibres (W.m^{-1}.K^{-1}), λ_s is the thermal conductivity of spandex (0.15 W.m^{-1}.K^{-1}), and λ_c is the thermal conductivity of cotton fibres (0.5 W.m^{-1}.K^{-1})



a- Full plaited (35 Ne)

b- Half plaited (35 Ne)

Figure 5.5. Effect of loop length on the thermal conductivity (35 Ne)

The thermal conductivity of *SJKF* went down with the increase of loop length [43] it may be due to the increase of loop length leads to decrease the stitch density, as shown in table 5.1. So, the number of fibres per unit area decreases and the number of paths which the heat is transferred through the fibres by conduction decreases.

The thermal conductivity of elastic *SJKF* samples was higher than the 100% cotton samples by 24 and 15% at loop length 2.7 mm and *SWP* 4% for *fp* and *hp*, respectively, due to stitch density increase. The thermal conductivity of *fp* was higher than *hp* due to decrease in stitch density of *hp* because of the plaiting technique.

For knitted samples produced from yarn count 25 Ne, the same trends were found as knitted samples produced from yarn count 35 Ne. The thermal conductivity of fp was higher than 100% cotton samples by 23 % at loop length 2.7 mm and *SWP* 4%. The thermal conductivity of knitted samples produced from yarn count 25 Ne was higher than 35 Ne [43] due to the increase of number of fibres in the yarn cross-section. The statistical analysis showed that *SWP*, loop length, plaiting technique and yarn count had a significant effect on the thermal conductivity, as shown in table 5.2.

5.2.2 Thermal resistance

Figure 5.6 illustrates the effect of loop length on the thermal resistance of SJKF produced from yarn count 35 Ne. Generally, the thermal resistance of elastic SJKF went up with the increase of loop length because the fabric thickness increased and thermal conductivity decreased when the loop length went up, as shown in figures 5.1 and 5.5, which matches with the heat transfer through conduction theory, as in Eq. (5.3). Also, the fabric porosity increased with the increase of loop length, as shown in figure 5.4 and the stitch density decreased with the loop length increasing. The stitch density and loop length had a significant effect on the thermal resistance of weft structures [44].

$$R = \left(\frac{h}{\lambda * 1000}\right) \qquad \text{.......................} \qquad (5.3)$$

where R is thermal resistance (K.m^2.W^{-1}), λ is thermal conductivity (W.m^{-1}.K^{-1}), and h is the fabric thickness (mm). Also, the thermal resistance of elastic *SJKF* went down when *SWP* went up because the fabric thickness decreased with increase of *SWP*.

The thermal resistance of 100% cotton samples decreased with the increase of loop length due to the decrease of fabric thickness when the loop length increased. The thermal resistance of elastic *SJKF* was higher than 100% cotton fabric by 60 and 52% for both *fp* and *hp*, respectively, at loop length 3.4 mm and *SWP* 4%.

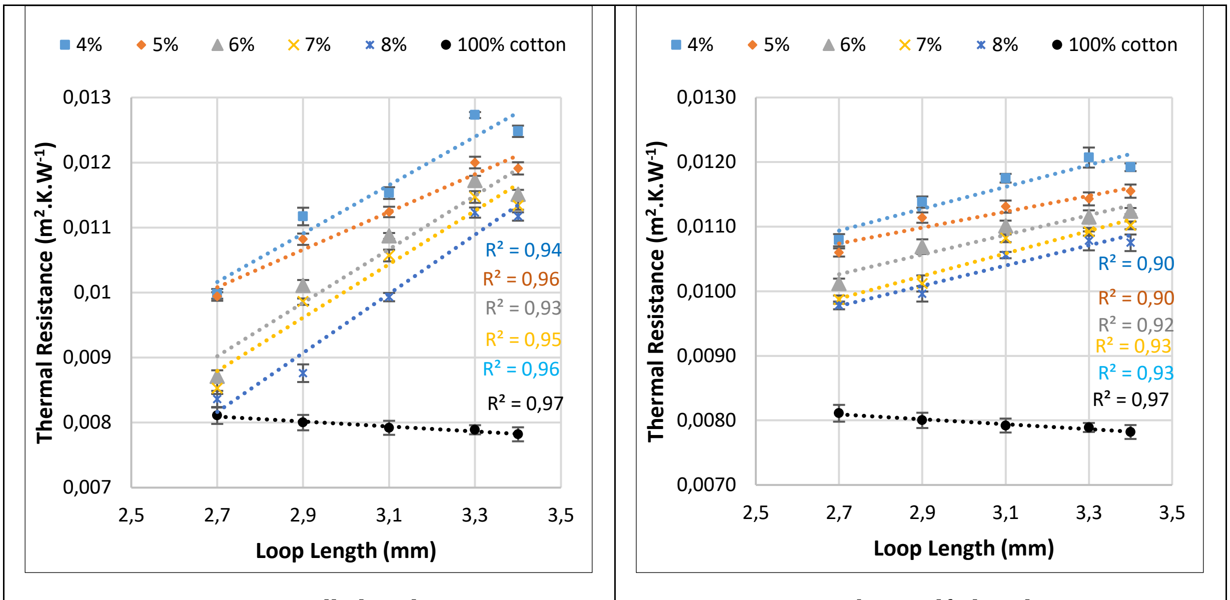


Figure 5.6. Effect of loop length on the thermal resistance (35 Ne)

5.2.3 Thermal absorptivity

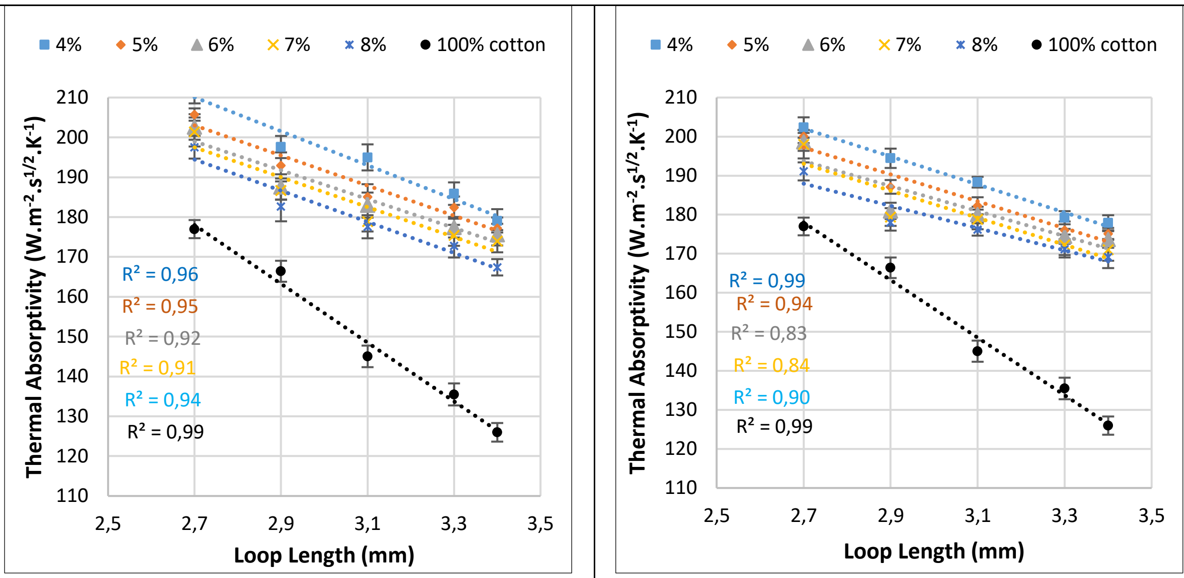
Thermal absorptivity is the objective measurement of the warm cool feeling of a fabric. Fabrics with a lower thermal absorptivity value have a warm feeling and vice versa [45]. The thermal absorptivity increases with the thermal conductivity increasing and fabric density according to the following equation [46].

$$b = (\lambda_{fab}\ \rho_{fabric}\ C)^{1/2} \qquad \text{...............} \qquad (5.4)$$

Where b: thermal absorptivity (W. s$^{1/2}$ m^{-2}. K^{-1}), λ: thermal conductivity (W.m^{-1}. K^{-1}), ρ: fabric density (kg.m^{-3}), C: specific heat capacity (J.kg^{-1}.K^{-1}).

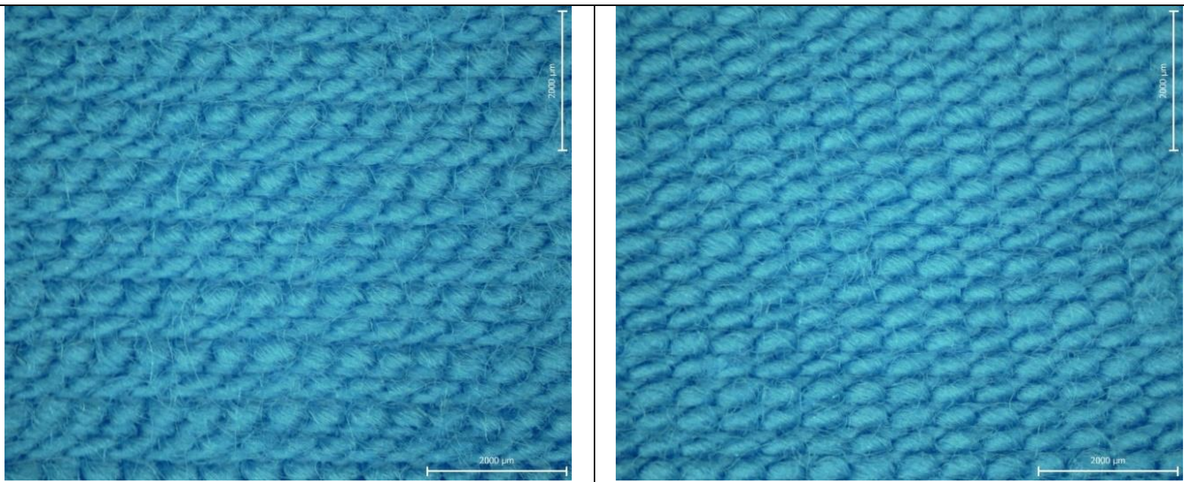
The thermal absorptivity has a strong correlation with fabric structure, fibre type, surface roughness and contact points [47][48], and the contact area is perpendicular to the normal line of heat flow.

The thermal absorptivity of both *fp* and *hp* went down with the increase of *SWP* and loop length, as shown in figure 5.7; this may be due to the reduction of contact points at a very short time and a decrease in thermal conductivity because of the decrease in stitch density with the increase of *SWP*, as shown in table 5.1. The thermal absorptivity of *fp* was higher than *hp*, it may be due to the ridges formed on the *hp* fabric surface due to the spandex plating technique in alternative courses, as shown in figure 5.8. So, the number of contact point in *hp* is less than *fp*, and the effective contact heat flow will be lower, and the thermal conductivity of *fp* was higher than *hp* as shown in figure 5.5. The thermal absorptivity of 100% cotton samples decreased with the loop length increasing, it was lower than *fp* and *hp* by up to 42 and 41%, respectively, at loop length 3.4 mm and *SWP* 4%, so 100% cotton samples give a warmer feeling compared to *fp* samples.



a- Full plaited b- Half plaited

Figure 5.7. Effect of *SWP* on the thermal absorptivity (35 Ne)



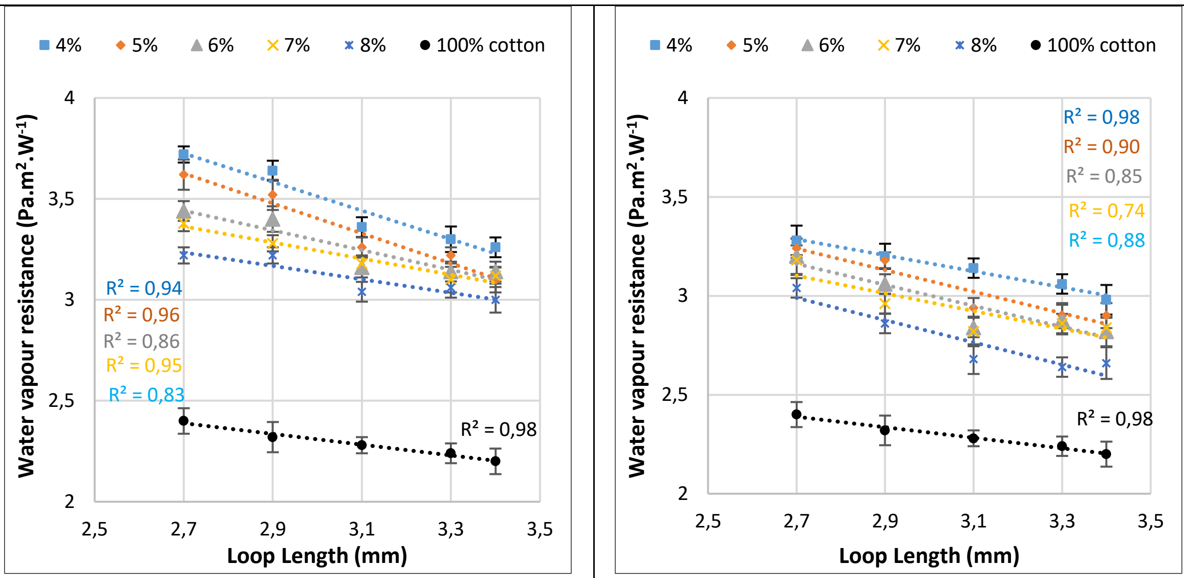
a- Half plaited b- Full plaited

Figure 5.8. Microscopic back images of elastic knitted fabrics at 2.7 mm loop length and 5% *SWP*

The thermal absorptivity of the samples produced from yarn count 25 Ne had the same trends as the samples produced from yarn count 35 Ne, as shown in figure 5.15. The thermal absorptivity of *SJKF* produced from yarn count 25 Ne was higher than samples produced from yarn count 35 Ne because the produced samples from yarn count 25 Ne had higher thermal conductivity than produced samples from yarn count 25 Ne, as shown in figures 5.10 and 5.11. *SWP*, loop length, plaiting technique, and yarn count had a significant effect on the thermal absorptivity, as shown in table 5.1.

5.2.4 Water vapour resistance

Figure 5.9 shows the water vapour resistance (*WVR*) of *fp* and *hp SJKF* at different levels of *SWP* and loop length.



a- Full plaited b- Half plaited

Figure 5.9. Effect of loop length on the water vapour resistance (35 Ne)

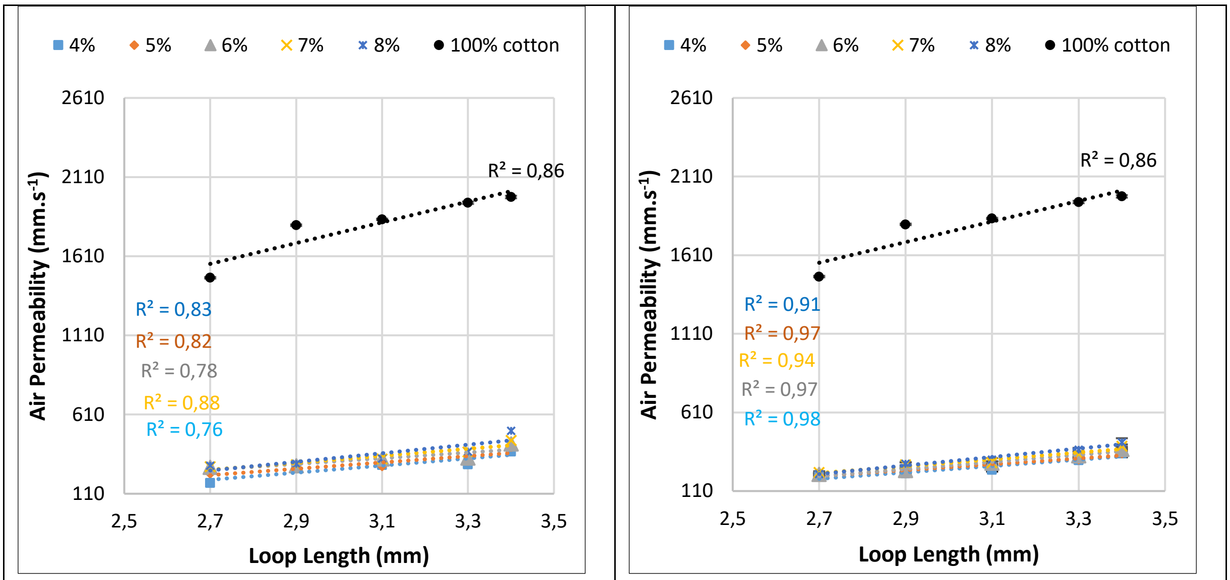
The *WVR* decreased with the increase of *SWP* and loop length for both *fp* and *hp* due to the decrease of stitch density as shown in table 5.1, which leads to an increase in air pore's size and water vapour transfer by diffusion through air gaps. The *WVR* of *fp* was relatively higher than *hp*. The *WVR* values of both *fp* and *hp* were less than 5 so the *WVR* was within an excellent level of water vapour transfer [49]. It could be interpreted that all samples were produced from hydrophilic fibres and absorbed water by capillary phenomena. The *WVR* of elastic *SJKF* samples was higher than 100% cotton samples by 55 and 37% for *fp* and *hp*, respectively, at loop length 2.7 mm and *SWP* 4%.

Also, the *WVR* of elastic *SJKF* produced from yarn count 25 Ne decreased when the loop length and *SWP* increased for both *fp* and *hp*. The *WVR* of samples produced from yarn count 25 Ne was higher than the samples produced from yarn count 35 Ne it may be due to the samples produced from yarn count 25 Ne had lower porosity, therefore; lower pore size. Statistical analysis showed that *SWP*, loop length, yarn count and plaiting technique had a significant effect on *WVR* as shown in table 5.2.

5.2.5 Air permeability

Air permeability is the rate of airflow through the fabric when subjected to a pressure difference on either surface of the fabric, and it is mostly affected by the fabric porosity in addition to the thickness[6][50].

Air flow passes through three paths, the first one is through the pores between yarns, and this is the easiest way. The second path of air flow is through pores of single yarns. The third path is through yarn crossing, and it is considered the hardest path of air flow. Generally, air permeability of both *fp* and *hp* elastic knitted fabrics went up with the increase of loop length and *SWP*, as shown in figure 5.10, because of the decrease in the stitch density. Therefore, the pores size increased, and the rate of airflow through the fabric went up. The air permeability of *fp* samples was less than 100% cotton samples by 82% at 3.1 mm loop length and 5% *SWP*. For the elastic *SJKF*, the stitch density was higher than 100% cotton samples and there was stitch overlapping, therefore; the pores volume of elastic samples was lower than 100% cotton samples. The statistical analysis showed that *SWP* and loop length had a significant effect on the air permeability, as shown in table 5.2.



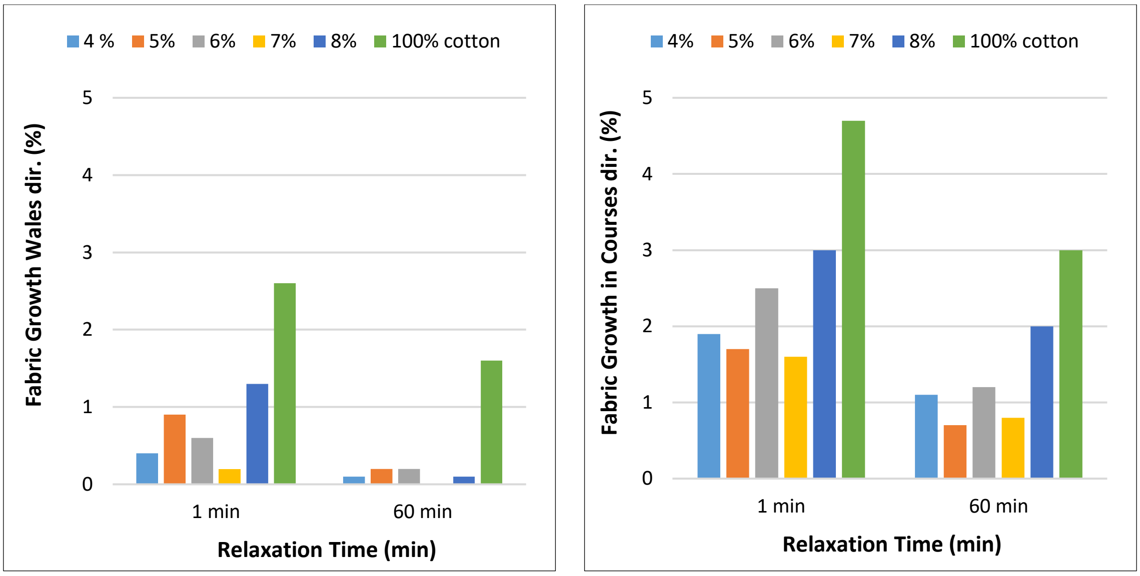
a- Full plaited b- Half plaited

Figure 5.10. Effect of loop length on the air permeability

5.3 Fabric growth and fabric stretch

Stretch fabrics improve comfort through freedom of body movement by providing the necessary elasticity for a garment to respond to every movement of the body and return to its original size and shape[51][22]. Therefore, it was necessary to investigate the fabric stretch and fabric growth.

5.3.1 Fabric growth



a- Wales direction b- Courses direction

Figure 5.11. Effect of *SWP* on fabric growth

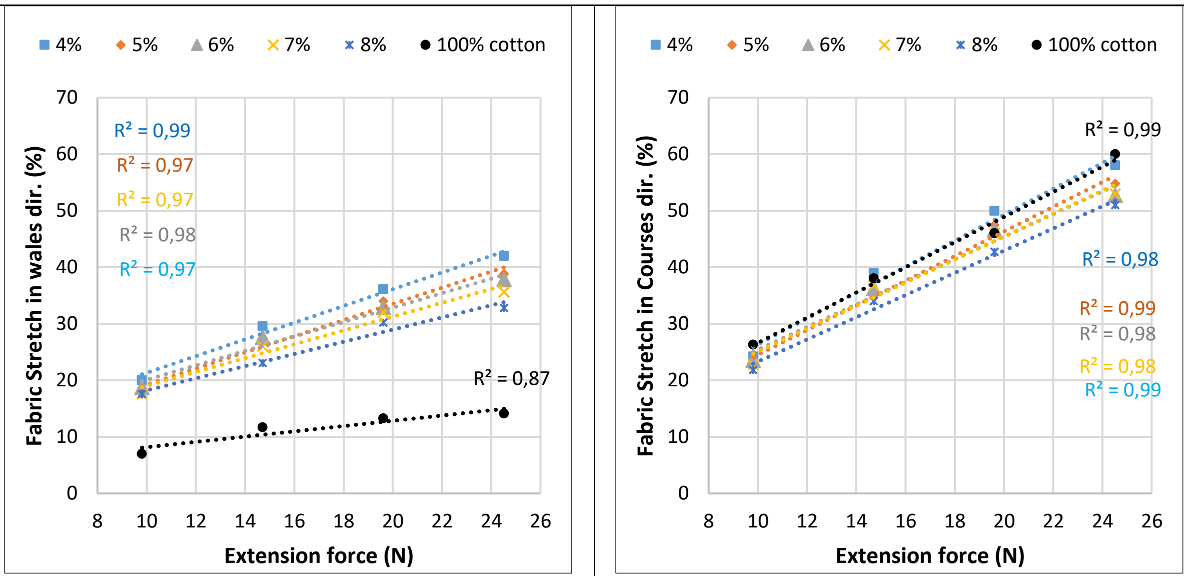
Figure 5.11 shows the fabric growth after 1 and 60 min of relaxation time in wales (*FGW*) and courses (*FGC*) directions at loop length 2.9 mm for both 100% cotton fabric and elastic fabrics produced from yarn count 35 Ne with 5 levels of *SWP*. In both directions, the 100% cotton fabric growth was higher than elastic fabric because of the presence of spandex. *FGW* was lower than *FGC*. 95% and 99% of extension in wales direction recovered after 1 and 60 min, respectively, while in 100% cotton 79 and 89 % of extension recovered after 1 and 60 min, respectively. The *FGW* and *FGC* of samples produced from yarn count 35 Ne were less than samples produced from yarn count 25 Ne. The effect of yarn count and *SWP* were significant on the growth of elastic fabric see table 5.3.

Table 5.3. The significant levels of yarn count and *SWP* on fabric growth and stretch

Dependent property	P value, (Independent variable)			
	SWP		Yarn count	
	Wales direction	Courses direction	Wales direction	Courses direction
Fabric growth	<0.001	<0.001	<0.001	<0.001
Fabric stretch	<0.001	<0.001	<0.001	<0.001

5.3.2 *Fabric stretch*

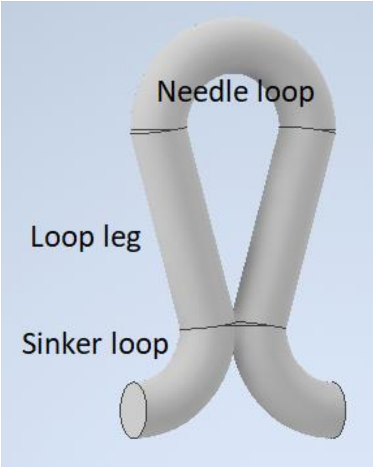
Figures (5.12-a) and (5.12-b) illustrate the fabric stretch in wales (*FSW*) and courses (*FSC*) directions at different extension forces. *FSW* is lower than *FSC*. When tension is applied in the course's direction, the needle loop, sinker loop, and loop legs straighten, as shown in figure (5.13-c), and wale density increases. When the applied tension is in the wale's direction, there is no opportunity to straighten the needle loop, sinker loop and loop leg, but it started to change the overlap structure to the normal structure as shown in figure (5.13- d). The fabric stretch went up with decreasing in *SWP* because of stitch overlapping and stitch density increasing. *FSW* of elastic fabric was higher than 100% cotton.



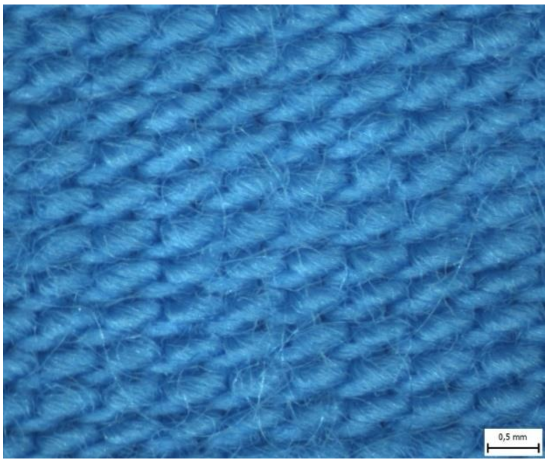
a- Wales direction

b- Courses direction

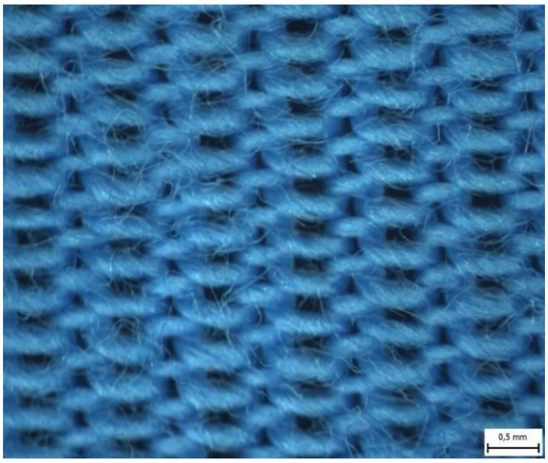
Figure 5.12. Effect of *SWP* on the fabric stretch



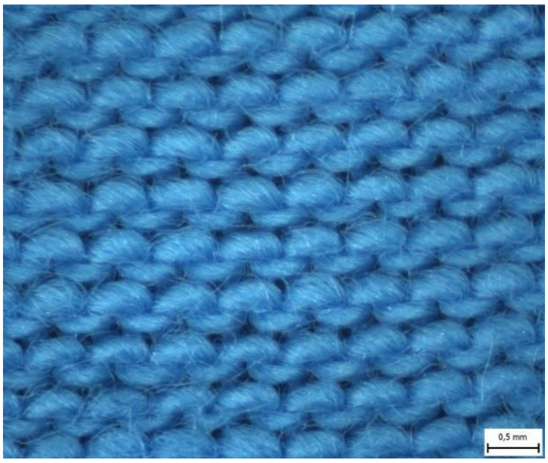
a- 3D loop



b- Sample image at *SWP* 4% without extension



c- Sample image at 30% extension in course direction



d- Sample image at 15% extension in warp direction

Figure 5.13. Sample images at different extensions in wales and course direction

FSW and *FSC* of samples produced from yarn count 35 Ne were higher than *FSW* and *FSC* of samples produced from yarn count 25 Ne. The yarn count and *SWP* had a significant effect on the growth of elastic fabric see table 5.3.

5.4 Fabric thickness and thermal properties under extension

Thermal properties were measured at two levels of extensions 15, and 30% in both warp and weft directions which were applied on elastic *SJKF* which were produced from yarn count 35 Ne at 2.9 mm loop length and five levels of *SWP*. Due to applied extension, the fabric thickness decreased by 5 and 15% for 15 and 30% extension, respectively, at *SWP* 4%, as shown in figure 5.14. When the extension was applied, the stitch overlapping disappeared gradually, as shown in figure 5.15, therefore; the fabric thickness decreased.

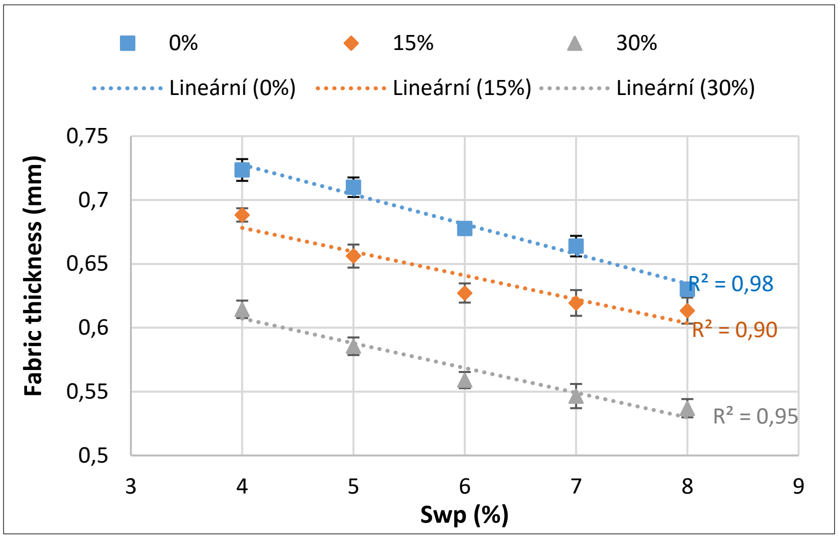
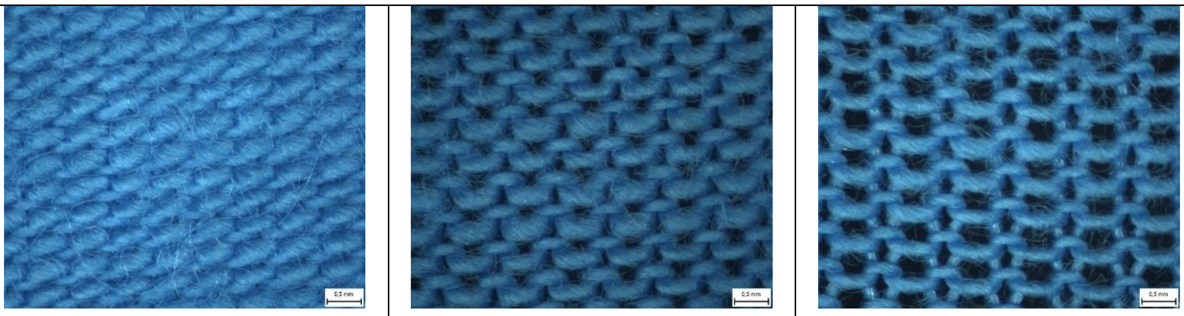


Figure 5.14. Fabric thickness after extension



a- Without extension	b- With 15% extension	c- With 30% extension

Figure 5.15. Sample images with and without an extension at loop length 2.9 mm and SWP 4%

The thermal conductivity increased due to the increase of extension from 0 to 15% at *SWP* 4, 5 and 6% and decreased at *SWP* 7 and 8% as shown in figure 5.16. When the extension reached to 15 % at *SWP* 4, 5, and 6%, the amount of heat flow increased due to the radiation because of the porosity increasing, as shown in figure (5.15-b). At extension 30%, the thermal conductivity went down due to a reduction in the number of fibres, as shown in figure (5.15-c).

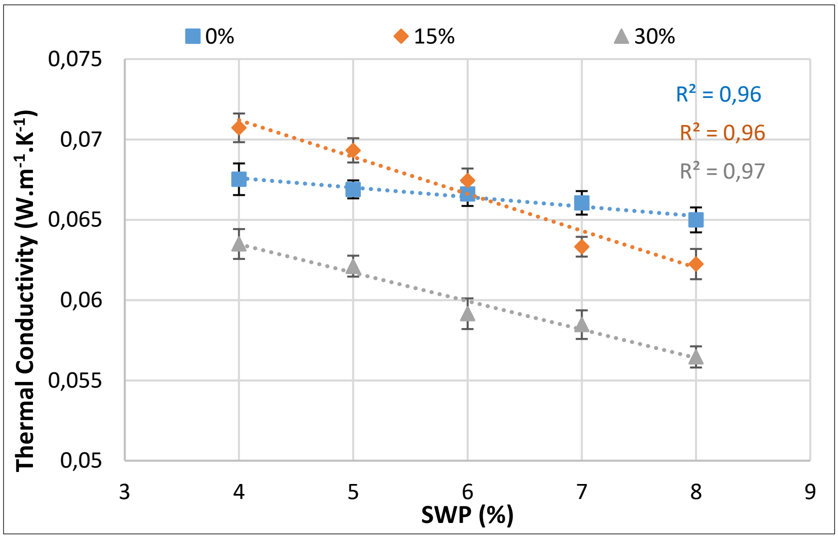


Figure 5.16. Thermal conductivity after extension

Figure 5.17 shows that the thermal resistance went down after applied extension 15 and 30% by

14 and 16 %, respectively, due to the fabric porosity and pore's size increased, as shown in figure 5.15, therefore, the amount of entrapped air increased, and the thermal conductivity decreased. Figure 5.18 shows that thermal absorptivity decreased with extension increasing due to a decrease in the thermal conductivity, the number of contact points per unit area and stitch density, as shown in figure 5.15.

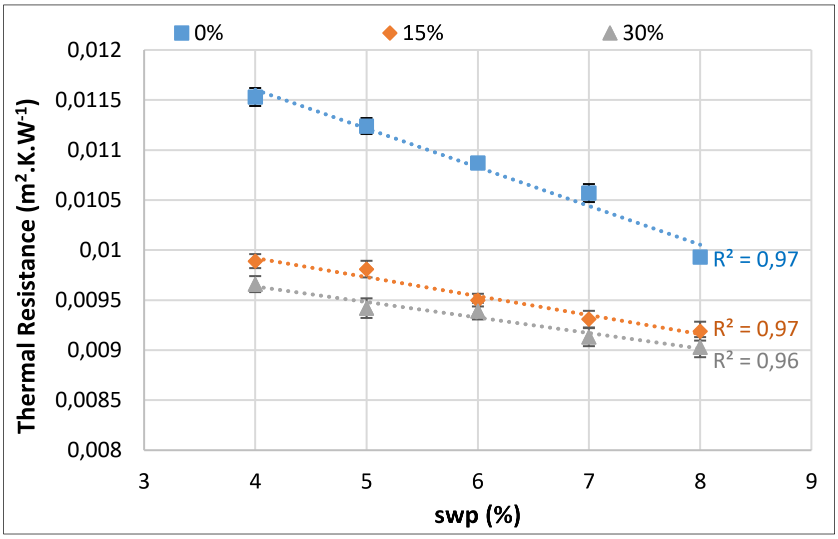


Figure 5.17. Thermal resistance after extension

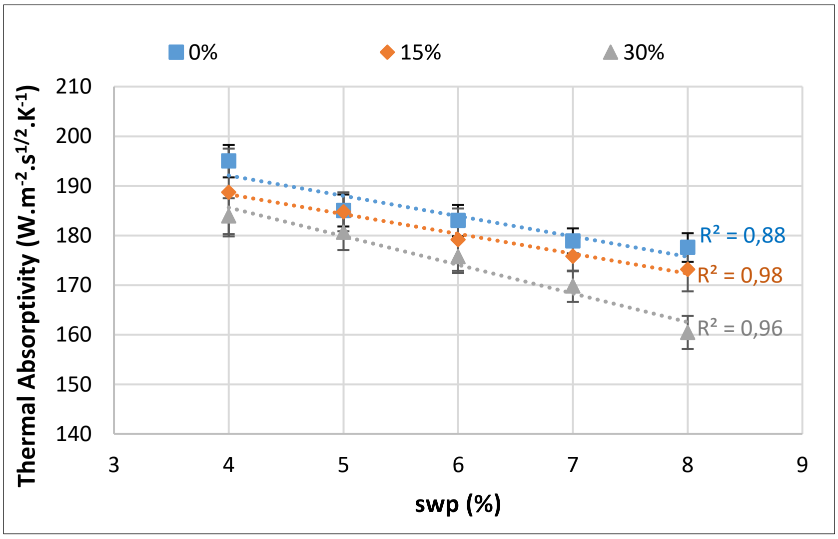


Figure 5.18. Thermal absorptivity after extension

CHAPTER 6: 3D GEOMETRICAL MODEL OF STITCH OVERLAPPING

The stitch overlapping phenomena of the elastic *SJKF* with high stitch density changes the conventional dimensions of *SJKF*; therefore, the physical properties in terms of the heat and moisture transfer. Hence the need to study the change occurring within the fabric structure and the distribution of pores size within the structure in the hope that this study could contribute to the interpretation of the relationships between structural parameters and physical properties.

The fabric porosity of elastic *SJKF* was relatively lower than 100% cotton by 7% as shown in figure 5.4. The stitch density, fabric thickness and thermal resistance of elastic *SJKF* were higher than 100% cotton samples by up to 80, 47 and 23% respectively at loop length 2.7 mm and *SWP* 4%. Also, air permeability of elastic *SJKF* was lower than 100% cotton samples by up to 85% at loop length 2.7 mm and *SWP* 4%, as the pores size and distribution inside the structure played an important role in heat and air flow. There were problems to analyse the pores size, distribution and porosity of elastic *SJKF* by Micro CT. Therefore, loop geometry model of *SJKF* was needed to investigate the pores size, distribution and porosity inside the structure.

In this chapter, 3D geometrical model based on different *SJKF* structures (open, max set, and stitch overlapping) was established to describe the pore's size, pores' distribution, and the fabric porosity through the different structures based on the actual geometrical parameters of the loop by using AutoCAD software. Then, the fabric thickness was divided into several sections, and the theoretical pore's size at each section of fabric thickness was analysed and calculated.

It is known that the fabric porosity influences the physical and thermal properties and hence, the fabric end-use. Fabric porosity can give a clue about thermal resistance, air permeability, and water vapour resistance. The heat, liquid sweat generation, and water vapour must also be transferred and dissipated from the body to the environment [52]. The water vapour moves primarily through fabric pores by a diffusion process in the air from one fabric side to the other [53]. The fabric porosity depends on pore size, volume, and pore distribution. These factors in turn, are influenced by fabric construction parameters such as yarn count, fabric structure, machine setting, and finishing process. According to Guidoin [54], [55] porosity is '*the ratio of void space within the boundaries of a solid material to the total volume occupied by this material, including void spaces*'.

Mostly, the fabric porosity is investigated using three methods, image processing, air permeability, and geometrical modelling [56]. A lot of research investigated the pore size and its distribution for woven and knitted fabric by using image processing techniques and based on yarn and fibre parameters from fabric cross-section images [52], [56]–[58]. The surface porosity of single jersey knitted fabrics was investigated by many researchers using image analysis techniques with and without yarn hairiness consideration. Inter pores between yarns were measured by computing the equivalent pores diameter, while intra pores inside yarns were calculated from Neckar's theoretical equation [59].

Since air permeability has a direct relationship to pore size [52], some research linked air permeability and knitted fabric porosity based on geometrical parameters such as fibre density, yarn count, stitch length, courses density, wales density, and fabric thickness [53], [56], [60], [61].

Furthermore, geometrical modelling was conducted using the geometry of the unit cell of a single loop. Fabric porosity was estimated from a 2D knitted fabric model by calculating the area covered by yarn and the total area of one repeat [62], [63]. Few models for 3D porosity are available that investigated weft knitted fabric, such as the Benltoufa and Karaguzel theoretical models and the Guidoin empirical model [64]. Benltoufa calculated the knitted fabric porosity from the geometrical representation of the elementary loop geometry, assuming a circular yarn cross-section [56]. In addition to this method, Benltoufa used the air permeability and image processing method and concluded that geometrical modelling is the most appropriate and easiest way to evaluate porosity.

Karaguzel's model predicted pore volume in addition to inter yarn pore size for simple weft knitted fabric structures, from fabric parameters, such as courses and wales density, yarn linear density, and fabric thickness, which characterize the structure [65]. A plug-in was developed using Python script to predict the plain knitted fabric porosity by using the actual parameters of the fabric. 3D solid and multifilament models of knitted fabric were generated automatically with two alternatives of models (Peirce and parametric). It was assumed that the yarn cross-section was circular that is swept around the yarn's central axis [54]. Adam K. et al. Modelled the air permeability of knitted fabric by using three-dimensional models of knitted fabrics and mapping the geometry in the microscale [66].

It is known that spandex yarns are incorporated with yarns in knitting machines to enhance the dimensional stability of knitted fabric during usage and after repeated stresses, which is considered the main defect of knitted fabrics, particularly single jersey knitted fabric [67]. Adding Spandex turns the knitted structure from an open and normal structure into a very compact structure, and causes stitch overlapping where the courses spacing becomes less than $2\sqrt{3}d$, wales spacing becomes less than $4d$, and fabric thickness becomes higher than $3d$, where d is yarn diameter [62], [68], [69]. Since the stitch overlapping effect was not studied earlier using the above-mentioned geometrical modelling method, this research presents a 3D modelling of the stitch overlap geometry to calculate the fabric porosity. The research developed a novel method of calculating porosity by making several sections of fabric thickness and calculating the accumulative volume of fibres in a unit cell of single jersey knitted fabric. The results are compared to porosity calculated by using the Guidoin model.

6.1 Basis of the presented model

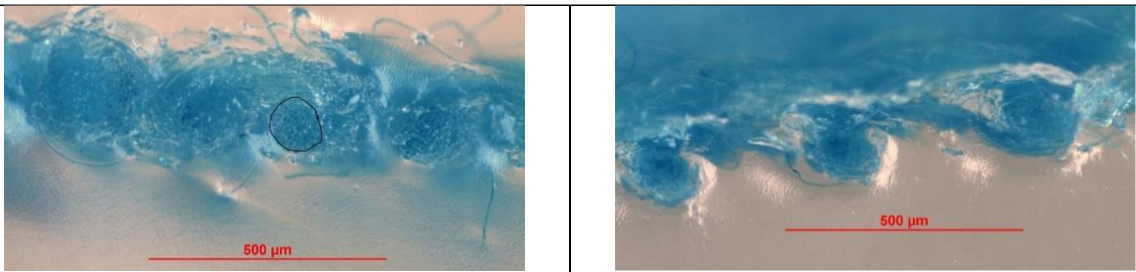
This model was based on the actual fabric parameters (yarn diameter and loop length) and theoretical assumptions.

6.1.1 Actual parameters

To obtain the overlapping structure, the produced full plaited *SJKF* sample from yarn count 35 Ne (d = 0.1662 mm) at the loop length 2.9 mm and *SWP* 8% was chosen. To obtain an open structure, 100% cotton *SJKF* (without spandex) was chosen at the same yarn count and loop length. Moreover, one more fabric structure called "maximum set" or normal structure was not produced, but instead, it was drawn since the maximum set is the transitional case between open and overlapping structures.

6.1.2 Mathematical model design

A 3-dimensional multi-fibre model (rather than a solid cylindrical model) was developed taking into consideration the following parameters: loop length (2.9 mm), yarn diameter (0.1662 mm) as actual and experimental parameters. Yarn cross-section inside the fabric was closed to circular as shown in figure 6.1, fibre length in a single loop, fibre diameter, fibre cross-section shape, the total number of fibres in yarn cross-section, and yarn twist. The model was constructed to simulate fabric structures.



a- Image of yarn cross section in courses direction | b- Image of yarn cross section in wales direction

Figure 6.1. Cross-section images of 100% cotton sample

6.1.2.1 *Assumptions*

1. The following assumptions were used to describe the fabric structure:
2. Fibres have kidney shape and their cross-section areas are equal.
3. The yarn cross-section is circular based on Peirce model [70].
4. Fibres are evenly distributed along the yarn cross-section.
5. Yarns forming the loops were fully flexible, touched, but not compressed [71].
6. Yarn hairiness is neglected.
7. Individual fibres are continuous.
8. Theoretical fabric thickness for open structure $2d$, for maximum set $2d$, and for overlapping $3d$.
9. Wales spacing is constant and equal to $4d$.

6.1.2.2 *Yarn structure*

The total number of fibres in the yarn cross-section, N was calculated according to equation (6.1):

$$N = \frac{T}{t} \qquad \ldots\ldots\ldots\ldots \qquad (6.1)$$

Where T is yarn count (tex), t is cotton fibre fineness (tex). Cotton fibre diameter, D (mm) was obtained according to equation (6.2) [72]:

$$D = \sqrt{\frac{4\,t}{\pi\,\rho_{\mathrm{f}}}} \qquad \ldots\ldots\ldots\ldots \qquad (6.2)$$

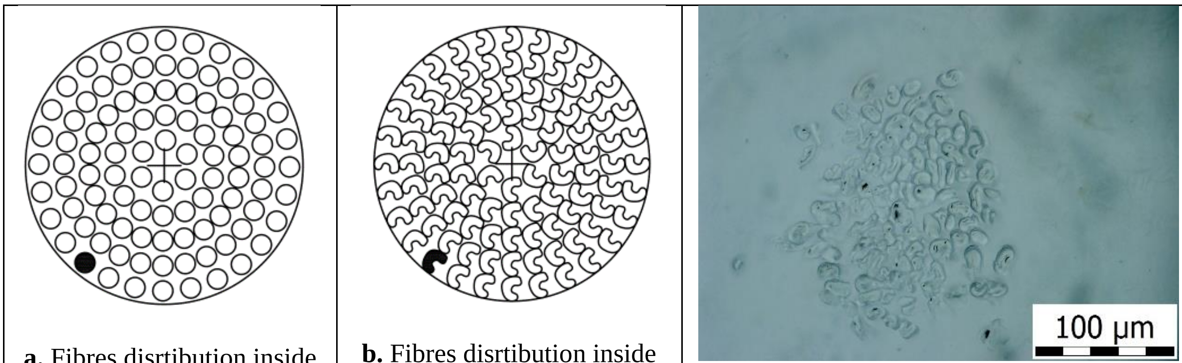
Where ρ_f is fibre density (kg/m^3). The cotton fibre cross-section area, A was obtained according to equation (6.3).

$$A = \frac{\pi D^2}{4} \qquad \ldots\ldots\ldots\ldots \qquad (6.3)$$

The circular cross-section that had an area A shown in Figure (6.2-a) was converted into a kidney shape with the same area to imitate the cotton fibre as shown in Figure (6.2-b). The number of twists per inch of that yarn, TPI was calculated according to equation (6.4).

$$TPI = \alpha_e \sqrt{Ne} \qquad \ldots\ldots\ldots\ldots \qquad (6.4)$$

Based on loop length, the number of twists in one loop of fabric was calculated. Spandex yarn diameter was calculated according to equation (6.2).



a. Fibres disrtibution inside yarn with circle cross section

b. Fibres disrtibution inside yarn with kidney cross section

c. Real yarn cross-section

Figure 6.2. Yarn cross-section.

6.1.2.3 *Fabric geometry*

To present the *SJKF* 3D model using AutoCAD software, a two-dimensional sketch of a single loop was carried out based on the Peirce model (the yarn axis follows a path composed of circular arcs and straight lines) [70], as shown in figure 6.3 and actual yarn diameter, wales, and courses density as shown in Figure 6.3. The actual loop parameters are shown in Table 6.1.

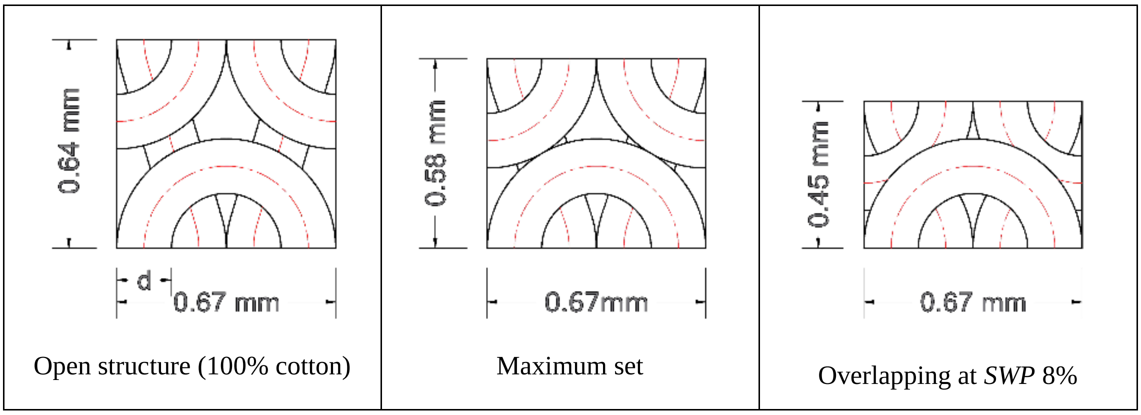


Figure 6.3. 2D Scheme of the knitted fabric structure.

Table 6.1. Actual loop geometrical parameters

Parameters	Single jersey knitted fabrics	
	Open Structure (100% Cotton)	Overlapping (elastic sample)
Wales/cm	14.63	15.92
Courses/cm	15.75	22.37
Stitch density/cm^2	230.4	356.1
Yarn diameter (mm)	0.16642	0.16642

As the inclusion of inter-fibre spacing is one of the important factors that determine the utility of the model for theoretical predictions of the porosity of textiles, a cross-sectional sketch of the yarn based on individual fibres was drawn, as shown in figure (6.2- b). Then, a sketch describing the profile of the loop in a 3D view was created consisting of a continuous spline as shown in Figure 6.4 [73]. For spandex yarn, it follows a shorter trajectory than in the case of 100% cotton yarn since more tension is applied while feeding, as shown in Figure 6.4. Therefore, the loop length in the 3D model varied slightly from the actual loop length, where the loop length of open, maximum set, and overlapping structures were 3.07 mm, 2.9 mm, and 2.85 mm, respectively. Finally, the 3D loop was obtained using the sweep operation of the fibre cross-sections.

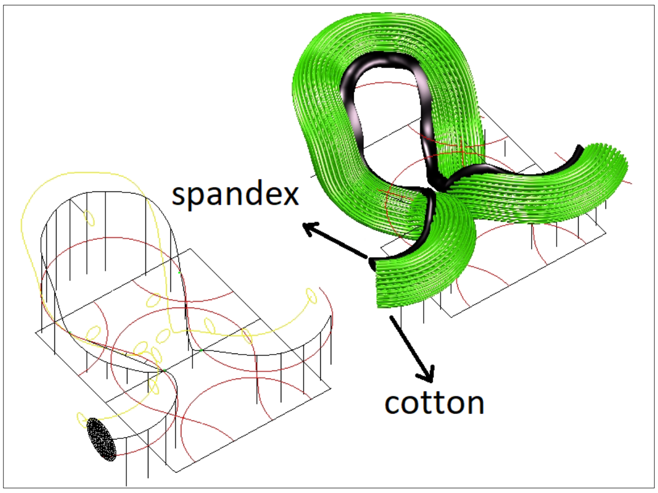


Figure 6.4. Stages of designing the 3D geometrical model of stitch overlapping.

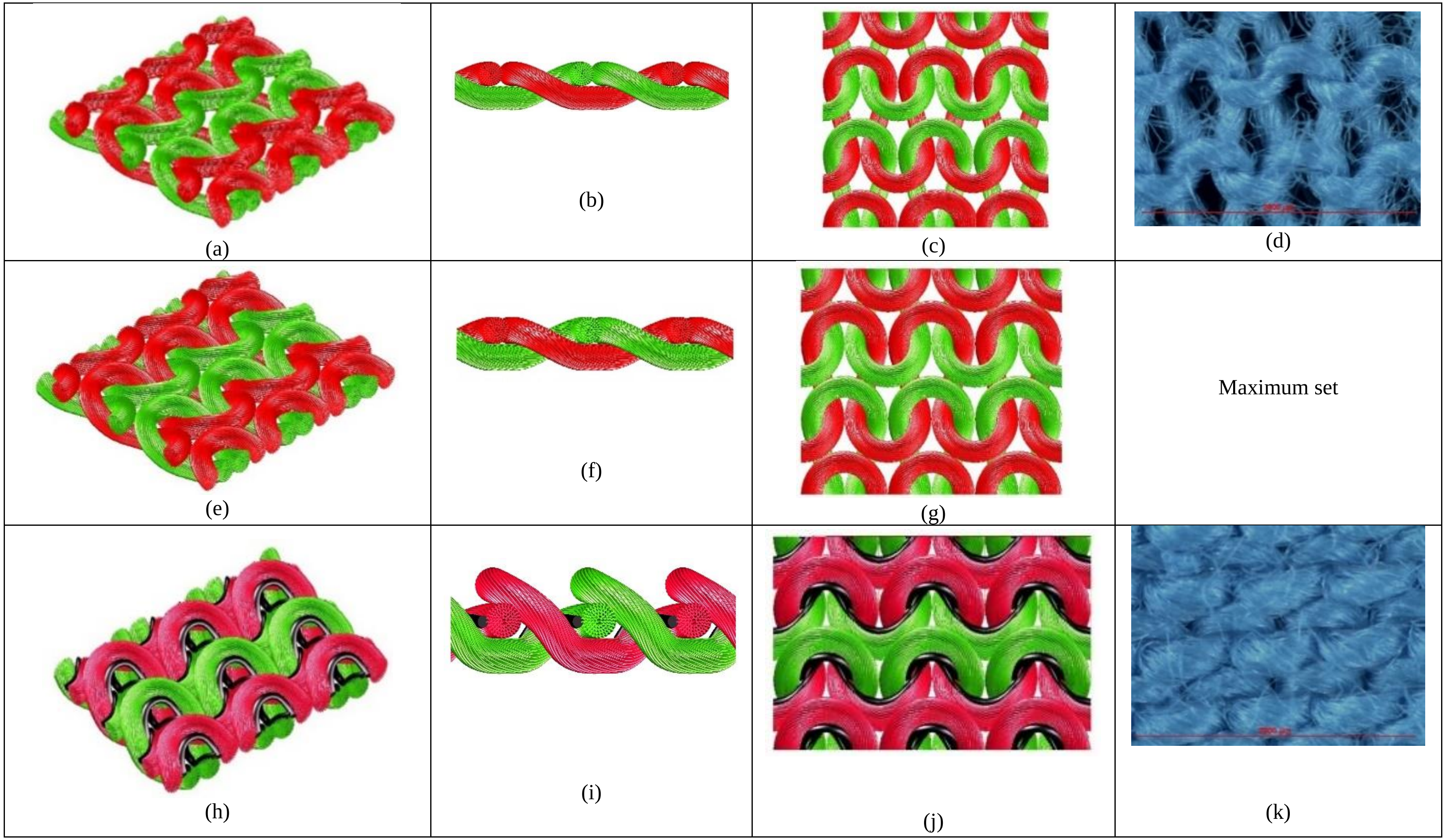


Figure 6.5. Optical microscopic images of fabric along with its corresponding 3D model

Afterwards, the loop was repeated to demonstrate the final fabric appearance. Figure 6.5 shows the different views for each structure. Figures (6.5-a), (6.5-e), and (6.5- h) show the 3D isometric projection of open *SJKF*, maximum set, and overlapping structures, respectively. Figures (6.5-b), (6.5-f), and (6.5-i) show the side view, and figures (6.5-c), (6.5-g), and (6.5-j) show the front views. Finally, figures (6.5-d) and (6.5-k) show the optical microscopic images of the produced open and overlapping *SJKF* structures, respectively.

6.2 Determining pore's size, volume, and distributions

An enclosure was drawn around the repeat of the knitted fabric structure to simulate the surrounding air, as shown in figure 6.6. The pore's volume was obtained by calculating the fibre's volume and total enclosure volume of progressive growing sections of the fabric (top to bottom), using a 0.033 mm increment value, as shown in Figure 6.7. The open structure and maximum set fabrics were divided into 10 sections, while overlapping was divided into 15 sections because its thickness was greater.

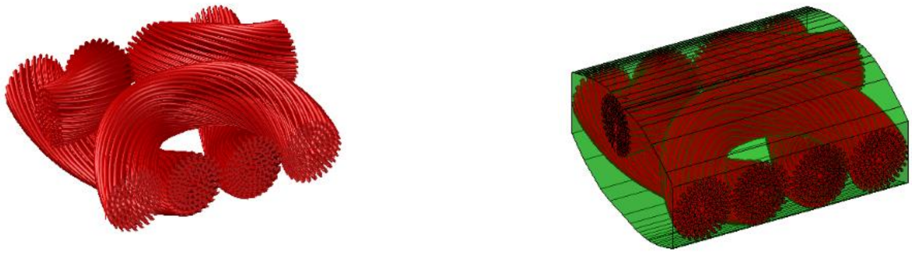


Figure 6.6. A volume enclosing the repeat of the knitted fabric structure.

The pores volume at ith section, V_{pi} can be calculated according to equation (6.5), as shown in table 6.2 for deferent structures.

$$V_{pi} = V_{xi} - V_{fi} \qquad \dots \dots \dots \dots \qquad (6.5)$$

Where V_{xi} is enclosure volume of the i^{th} section, and V_{fi} is fibre volume of the i^{th} section. The theoretical porosity in the i^{th} section, ε_i can be calculated according to equation (6.6).

$$\varepsilon_i = \frac{100V_{pi}}{V_{xi}} * 100 \qquad \dots \dots \dots \dots \qquad (6.6)$$

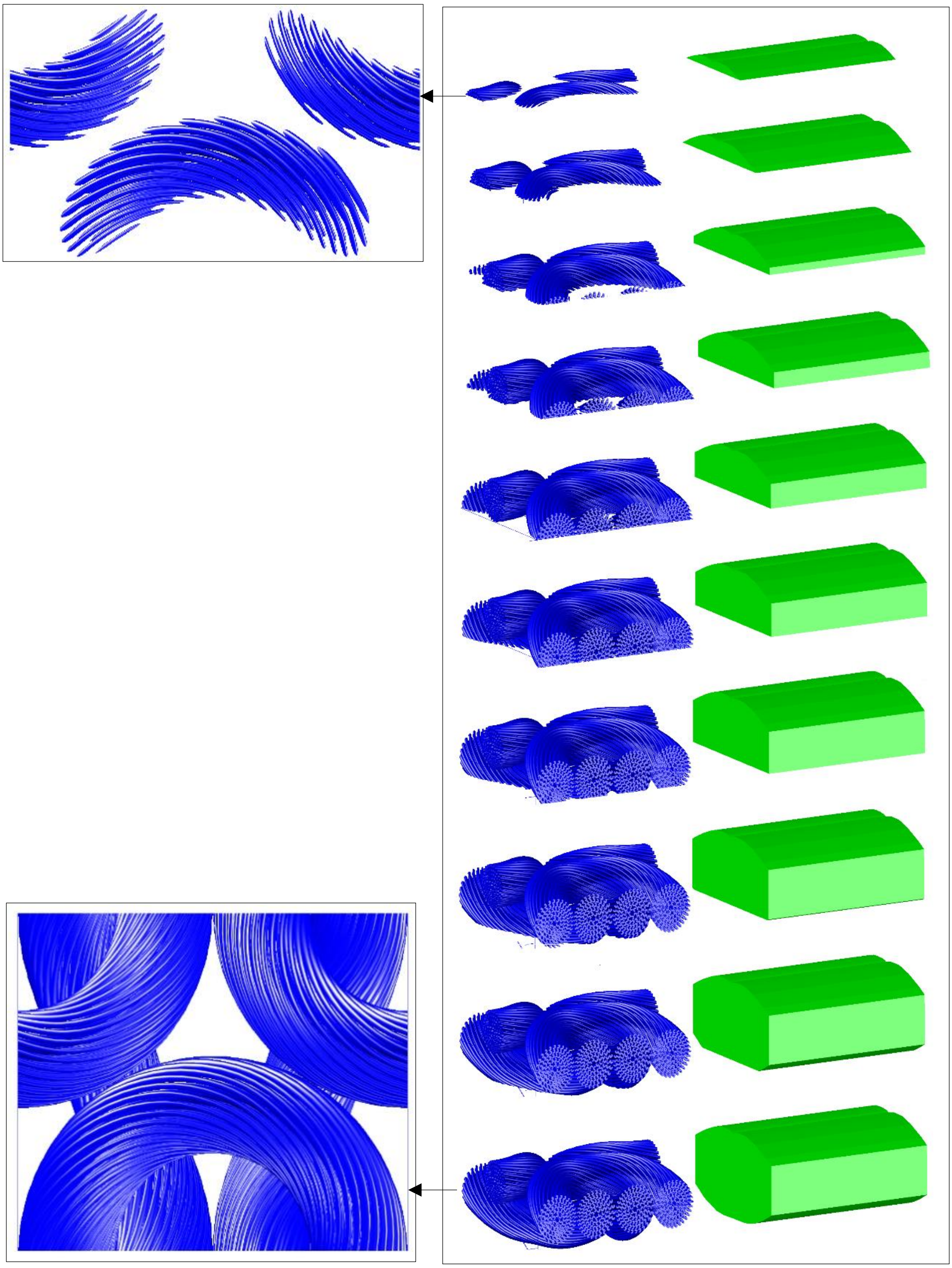


Figure 6.7. Progressive enclosure volume used to calculate fabric porosity (maximum set).

The total pores volume at each section of fabric thickness is shown in figure 6.8. It is obvious that the open structure has the highest pore volume at all sections followed by the maximum set followed by the overlapping structure. At the fabric thickness is equal to d, the total pores volume of overlapping structure is less than open and the maximum set, structures by 72 and 68%, respectively. Also, when fabric thickness is equal to 2d, the total pores volume of the overlapping structure is less than open and maximum set structures by 74 and 70%, respectively. So, adding spandex has a great effect in pore size and distribution of *SJKF*

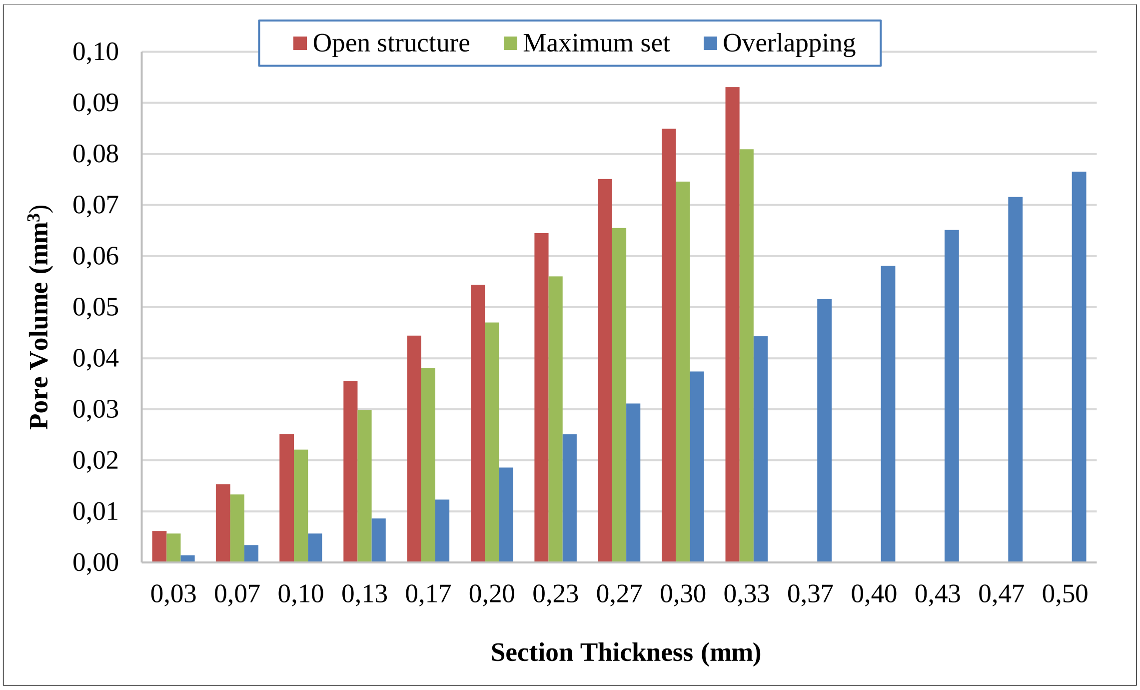


Figure 6.8. Total pore volume at ith fabric section

Figure 6.9 shows the theoretical values of fabric porosity at the ith fabric section (top to bottom) for different fabric structures. The porosity at the first section (top) is maximum and it significantly decreases with the increase in fabric thickness until the fabric centre line, then it increases again until the final section (bottom). This trend was almost the same for all structures. Based on the results of the 3D model, in all fabric sections, the fabric porosity of 100% cotton is the highest, followed by the maximum set, followed by overlapping.

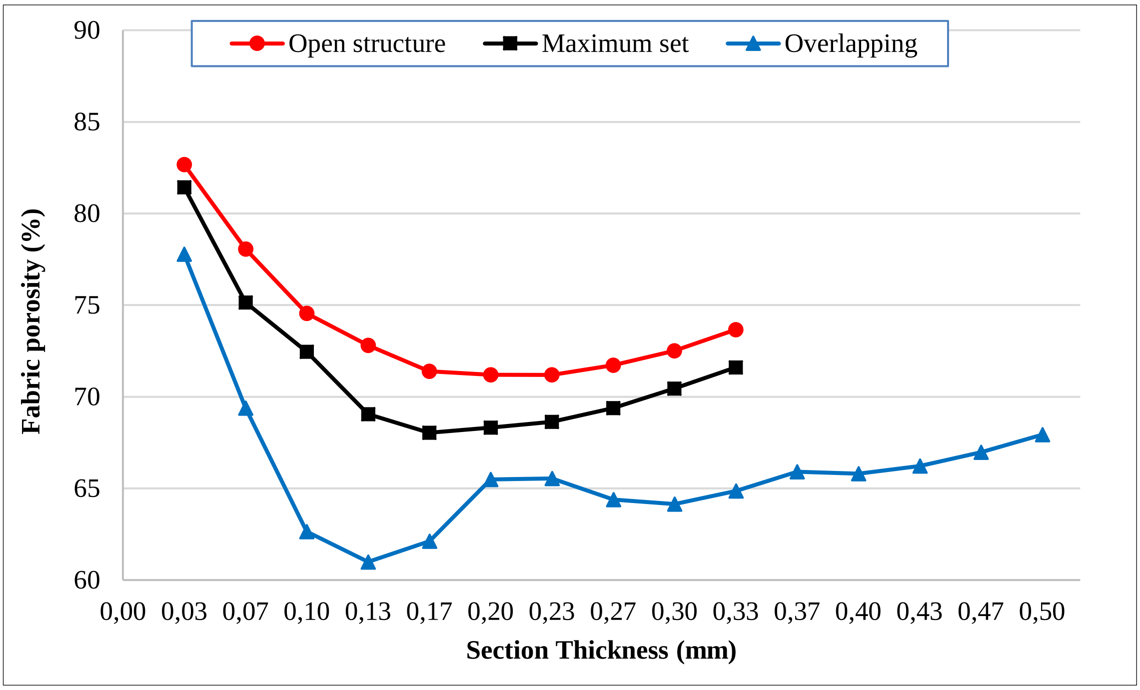


Figure 6.9. Fabric porosity at ith fabric section (top to bottom)

CHAPTER 7: PREDICTION OF THERMAL CONDUCTIVITY OF ELASTIC SJKF

Generally, the mathematical models are needed to interpret experimental relations, estimate the expected properties, and to assist in designing and developing of a new fabric to achieve a certain property. As there are several theoretical models to predict the thermal conductivity and resistance of textile fabrics by mathematical equations, empirical equations, neural network, finite element method, and multiple regression models. Still, there is a need to investigate if some of these models can be valid to elastic *SJKF* and is it possible to derive a new model that can predict the thermal conductivity of elastic *SJKF*.

The thermal resistance and conductivity of the fabrics can be predicted by means of experimental (empirical), analytical and numerical methods [74]. The preference of selection depends on the requisite precision and nature of the solution. Thermal conductivity and resistance were also predicted by using an Artificial Neural Network (ANN) [75]–[78]. The thermal conductivity of knitted fabrics made from cotton, viscose and spandex fibres was investigated by using an Artificial Neural Network [76], where the fabric structure and weight, yarn count and composition, gauge, spandex percent and count, fabric thickness, and loop length were used as input parameters. There are research that predicted thermal resistance by regression model [79]–[81]. The thermal resistance of fabric and socks was predicted by modelling in the wet state [74], [82]–[84].

Some researchers have predicted the thermal resistance and conductivity of fabrics with mathematical approaches. Several research presented a mathematical models of thermal conductivity and resistance of woven fabric based on actual construction parameters of repeat by using finite element method [85] and theoretical unit cell geometry [86][87].

Schuhmeister summarized the relationship between the thermal conductivity of a fabric and fabric structural parameters and assumed that one-third of fibres are parallel and two-third are in series with a homogeneous distribution in all directions as shown in figure 7.1 by the empirical equation as following [88]:

$$\lambda_{fab} = 0.33\,(F_f\lambda_f + F_a\lambda_a) \quad + 0.67\,\frac{\lambda_f \times \lambda_a}{\lambda_f\,F_a + \lambda_a\,F_f} \qquad \ldots\ldots\ldots(7.1)$$

Where λ_{fab} , λ_f , λ_a are thermal conductivity coefficients of fabric, fibres, and air respectively, and F_f, F_a are the volume fractions of fibres and air respectively.

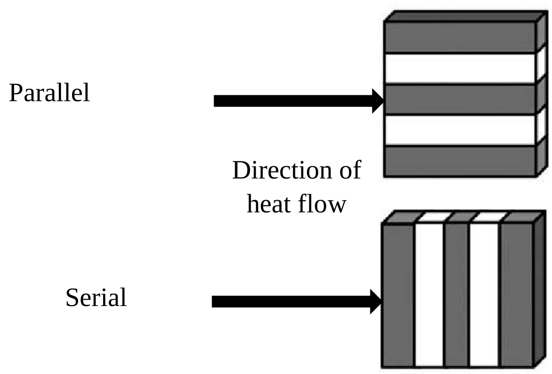


Figure 7.1. The direction of fibres compared to heat flow direction

Other researchers [89][90] have confirmed the equation and interpreted the first term as an ideal model for a fabric construction that fibres are parallel to the heat flow. The second term has been treated as an ideal model for a fabric construction where fibres lie in series to the heat flow.

Bogaty [91] found that the percent of fibres in series and parallel is 21% and 79%, respectively, for wool fabric. Militky [32] considered that 50% fibres in series and 50% in parallel to the heat flow, as shown in the following equation:

$$\lambda_{fab} = 0.5 * \left[((F_f\lambda_f + F_a\lambda_a) + \frac{\lambda_f \times \lambda_a}{\lambda_f F_a + \lambda_a F_f}\right] \quad \ldots\ldots\ldots(7.2)$$

Maxwell introduced the two-phase concept (continuous and dispersed phase) for the determination of electrical conductivity. Later on, Eucken used the same concept for thermal conductivity evaluation [92]. Maxwell–Eucken (ME) model can be used to describe the thermal conductivity of a two-component material with simple physical structures. The phase that is present in form of droplets is the dispersed phase, and the phase in which droplets are suspended is called the continuous phase. Thermal conductivity models require the naming of a continues and dispersed phase. The materials with exterior porosity, individual solid particles are surrounded by a gaseous matrix, and hence the gaseous component (air) forms the continuous phase, and the solid component (fibres) forms the dispersed phase (ME2) [93][94]. The Maxwell–Eucken 2 (ME2) model equation is as follows:

$$\lambda_{fab} = \frac{\lambda_a F_a + \lambda_f \; F_f \frac{3\lambda_a}{2\lambda_a + \lambda_f}}{F_a + F_f \frac{3\lambda_a}{2\lambda_a + \lambda_f}} \quad \ldots\ldots\ldots \quad (7.3)$$

7.1 Applying three simple mathematical models (Maxwell–Eucken 2, Schuhmeister, Militky)

Schuhmeister, Militky, and Maxwell–Eucken 2 were applied on elastic *SJKF* to calculate predicted values of the thermal conductivity and then compared to experimental values and see if one of them is valid to the elastic *SJKF*. The predicted values from ME2 was very low compared to the experimental values as shown in figure 7.2. The predicted values from Schuhmeister model (one-third of fibres are parallel and two-third are in series) was lower than experimental values. When the percent of fibres in parallel increased to fifty percent, the predicted values from Militky model were higher than experimental values as shown in figure 7.2. Therefore, the predicted thermal conductivity increased when the parallel component increased. So, a new model is needed to be valid for the elastic *SJKF* and this the aim is of this chapter.

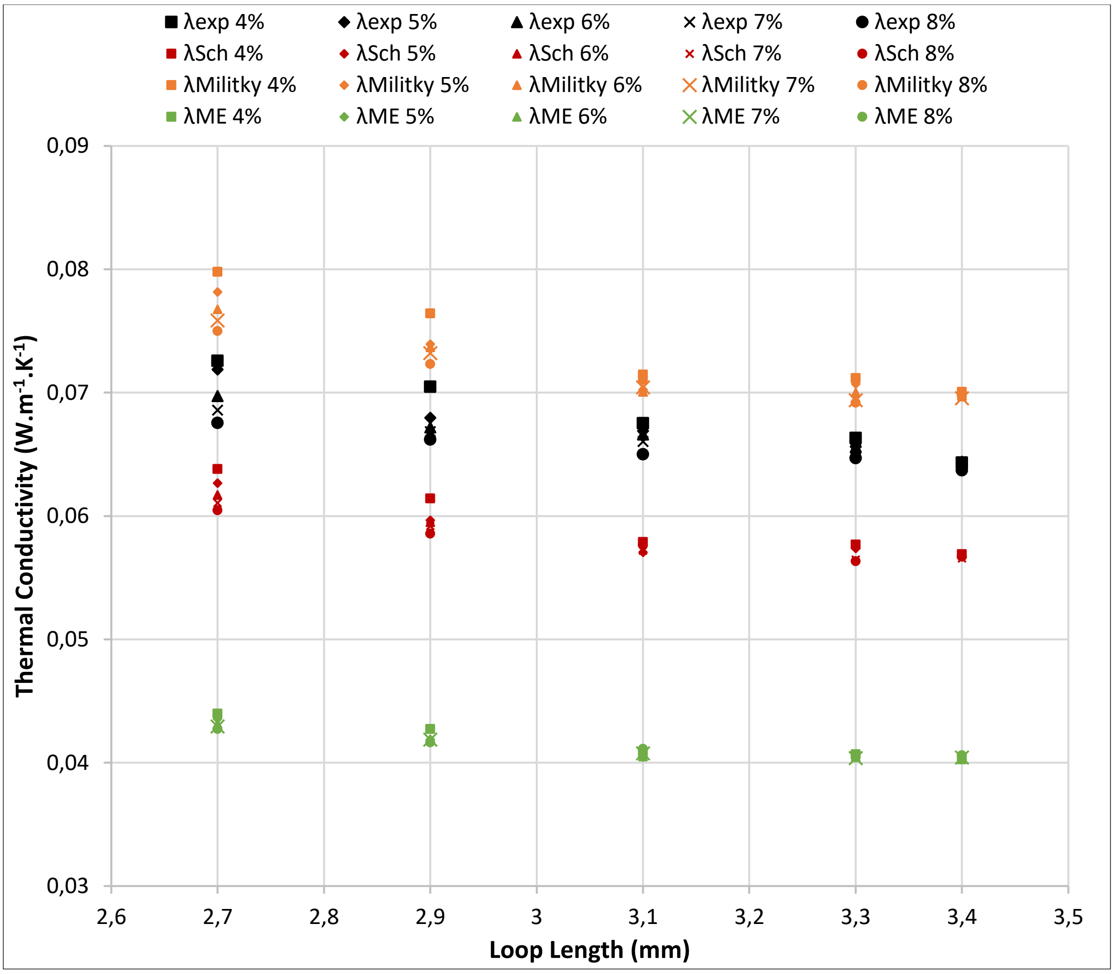


Figure 7.2. Experimental and predicted values from Schuhmeister, Militky, and ME 2 of thermal conductivity of elastic knitted fabric produced from yarn count 35 Ne

7.2 Assumptions and equations of a new model

7.2.1 Assumptions

A new model was derived based on the loop geometry and fabric construction parameters, namely wales and courses spacing, yarn diameter, fibres density, fabric thickness. It was assumed that:

- Yarn in one repeat was a cylinder with diameter d and its length equal to loop length (l).
- Fibres was divided to equal three components
- One third of fibres was in the same direction of heat flow (parallel to heat flow)
- Two third of fibres were in series with heat flow direction as shown.

7.2.2 Equations

7.2.2.1 ***Thermal conductivity of fibres in one repeat***

$$Total\ volume\ of\ one\ repeat,\ mm^3 = w * c * h$$

Where w is wales spacing (mm) = (1/wales density), c is courses spacing (mm) = (1/courses density), h is fabric thickness (mm) as shown in figure 7.3.

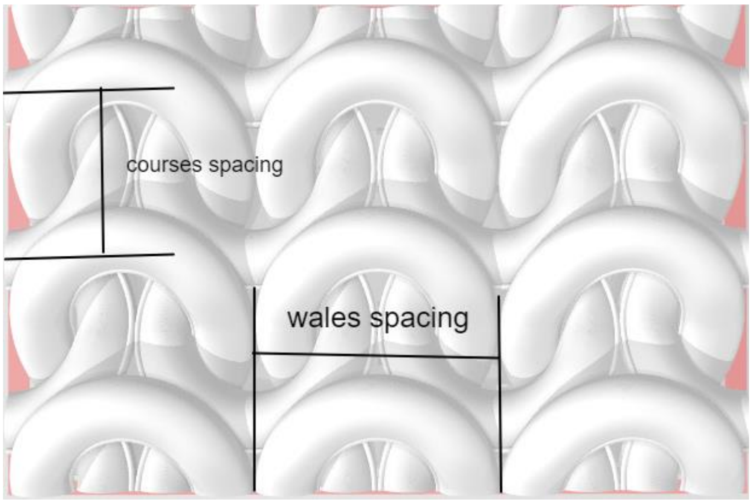


Figure 7.3. Theoretical image of elastic knitted fabric with the overlapping

$$Cotton\ yarn\ volume\ in\ one\ repeat\ (mm^3) = \frac{\pi}{4} * d^2 * l$$

$$Cotton\ fibres\ weight\ in\ one\ repeat\ (gm) = \frac{l}{1000 * Nm}$$

Where Nm is yarn metric count, l is the loop length (mm), and d is yarn diameter (mm).

$$Cotton\ fibres\ \ volume\ in\ one\ repeat(\ mm^3) = \frac{1000 * l}{\mathrm{Nm} * \rho_c}$$

$$Cotton\ fibres\ volume\ fraction, F_c = \frac{1000 * l}{\mathrm{Nm} * \mathrm{w} * \mathrm{c} * \mathrm{h} * \rho_c}$$

$$Thermal\ conductivity\ of\ cotton\ fibres\ in\ one\ repeat, \lambda_{cotton} = F_c * \lambda_c$$

Where λ_c is the thermal conductivity coefficient of cotton fibres (0.5 $W.m^{-1}.K^{-1}$) [42].

$$\lambda_{cotton} = \frac{1000*l}{Nm*w*c*h*\rho_c} * \lambda_c \qquad \dots\ \dots\ \dots \qquad (7.4)$$

$$Spandex\ \ weight\ in\ one\ repeat, gm = \ Cotton\ fibre\ weight\ in\ one\ repeat * \frac{SWP}{100}$$

$$Spandex\ \ weight\ in\ one\ repeat, gm = \frac{l * SWP}{10^5 * Nm}$$

$$Spandex\ \ volume\ in\ one\ repeat,\ mm^3 = \frac{Spandex\ \ weight\ in\ one\ repeat}{\rho_s}$$

$$Spandex\ \ volume\ in\ one\ repeat,\ mm^3 = \frac{10 * l * SWP}{Nm * \ \rho_s}$$

$$Spandex\ \ volume\ fraction, F_s = \frac{10 * l * SWP}{w * c * h * Nm * \ \rho_s}$$

$$Thermal\ conductivity\ of\ spandex\ in\ one\ repeat, \lambda_{spandex} = F_s * \lambda_s$$

Where λ_s is the thermal conductivity coefficient of spandex fibres (0.15 $W.m^{-1}.K^{-1}$) [42].

$$\lambda_{spandex} = \frac{10*l*SWP}{w*c*h*Nm*\rho_s} * \lambda_s \qquad \dots\ \dots\ \dots \qquad (7.5)$$

$$Total\ thermal\ conductivity\ of\ fibres, \lambda_f = \lambda_{cotton} + \lambda_{spandex} \qquad \dots\ \dots \qquad (7.6)$$

By substituting with the equation 7.4 and 7.5 on equation 7.6, λ_f can be calculated as follow:

$$\lambda_f = \frac{1000 * l}{Nm * w * c * h * \rho_c} * \lambda_c + \frac{10 * l * SWP}{w * c * h * Nm * \rho_s} * \lambda_s$$

$$\lambda_f = \left[\frac{l}{Nm * w * c * h}\right]\left[\frac{1000 * \lambda_c}{\rho_c} + \frac{10 * SWP * \lambda_s}{\rho_s}\right] \quad \dots \dots\dots \quad (7.7)$$

7.2.2.2 *Thermal conductivity of air in one repeat*

$$Inter\ air\ volume\ between\ yarns = Total\ volume\ of\ one\ repeat - (Cotton\ yarn\ volume\ in\ one\ repeat + Spandex\ volume\ in\ one\ repeat)$$

$$Inter\ air\ volume\ between\ yarns = w * c * h - \left(\frac{\pi}{4} * d^2 * l + \frac{10 * l * SWP}{Nm * \rho_s}\right)$$

$$Intra\ air\ volume\ inside\ cotton\ yarn = Cotton\ yarn\ volume\ in\ one\ repeat - Cotton\ fibres\ volume\ in\ one\ repeat$$

$$Intra\ air\ volume\ inside\ cotton\ yarn = \frac{\pi}{4} * d^2 * l - \frac{1000 * l}{Nm * \rho_c}$$

$$Total\ air\ volume\ inside\ one\ repeat = Inter\ air\ volume\ between\ yarns + Intra\ air\ volume\ inside\ cotton\ yarn$$

$$Total\ air\ volume\ inside\ one\ repeat = \left(w * c * h - \left(\frac{1000 * l}{Nm * \rho_c} + \frac{10 * l * SWP}{Nm * \rho_s}\right)\right) + \left(\frac{\pi}{4} * d^2 * l - \frac{1000 * l}{Nm * \rho_c}\right)$$

$$Total\ air\ volume\ fraction, F_a = \frac{\left(w * c * h - \left(\frac{\pi}{4} * d^2 * l + \frac{10 * l * SWP}{Nm * \rho_s}\right)\right) + \left(\frac{\pi}{4} * d^2 * l - \frac{1000 * l}{Nm * \rho_c}\right)}{w * c * h}$$

$$Thermal\ conductivity\ of\ air\ in\ one\ repeat, \lambda_{air} = F_a * \lambda_a$$

Where λ_a is the thermal conductivity coefficient of air (0.026 $W.m^{-1}.K^{-1}$)

$$\lambda_a = \frac{\left(w * c * h - \left(\frac{\pi}{4} * d^2 * l + \frac{10 * l * SWP}{Nm * \rho_s}\right)\right) + \left(\frac{\pi}{4} * d^2 * l - \frac{1000 * l}{Nm * \rho_c}\right)}{w * c * h} * \lambda_a \quad \dots \dots \dots \quad (7.8)$$

7.2.2.3 *Thermal conductivity of fabric*

In this model, λ_f was divided to equal three components, one-third was in the same direction of heat flow (parallel to heat flow), and two third were in series with the heat flow direction, as shown in figure 7.4.

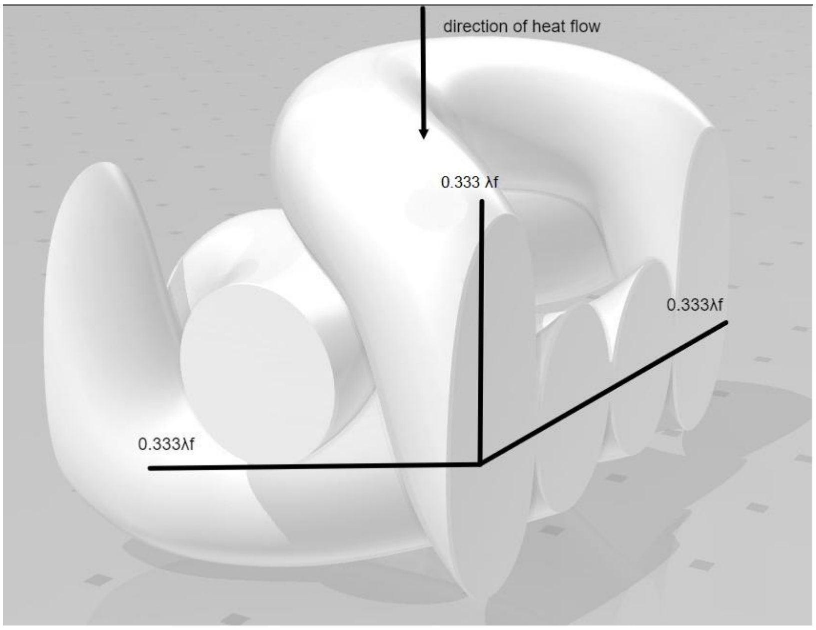


Figure 7.4. Fibres thermal conductivity components to heat flow direction

$$Thermal\ conductivity\ of\ fibres\ in\ series, \lambda_{ser} = \frac{0.333\lambda_f \times 0.333\lambda_f}{0.333\lambda_f + 0.333\lambda_f}$$

$$\lambda_{ser} = \frac{0.333\lambda_f}{2} \quad \ldots\ldots\ldots \quad (7.9)$$

$$Thermal\ conductivity\ of\ fibres\ in\ parallel, \lambda_p = 0.333\lambda_f \quad \ldots\ldots\ldots \quad (7.10)$$

$$Total\ thermal\ conductivity\ of\ fabric, \lambda_{fab} = \lambda_{\mathrm{ser}} + \lambda_p + \lambda_a \quad \ldots\ldots \quad (7.11)$$

7.3 Validation of the new model

A new model, Schuhmeister, Militky, and ME 2 were applied on elastic *SJKF* to compare between predicted values from a new model, Schuhmeister, Militky, ME 2 and experimental values and see if a new model can express the thermal conductivity of elastic *SJKF*.

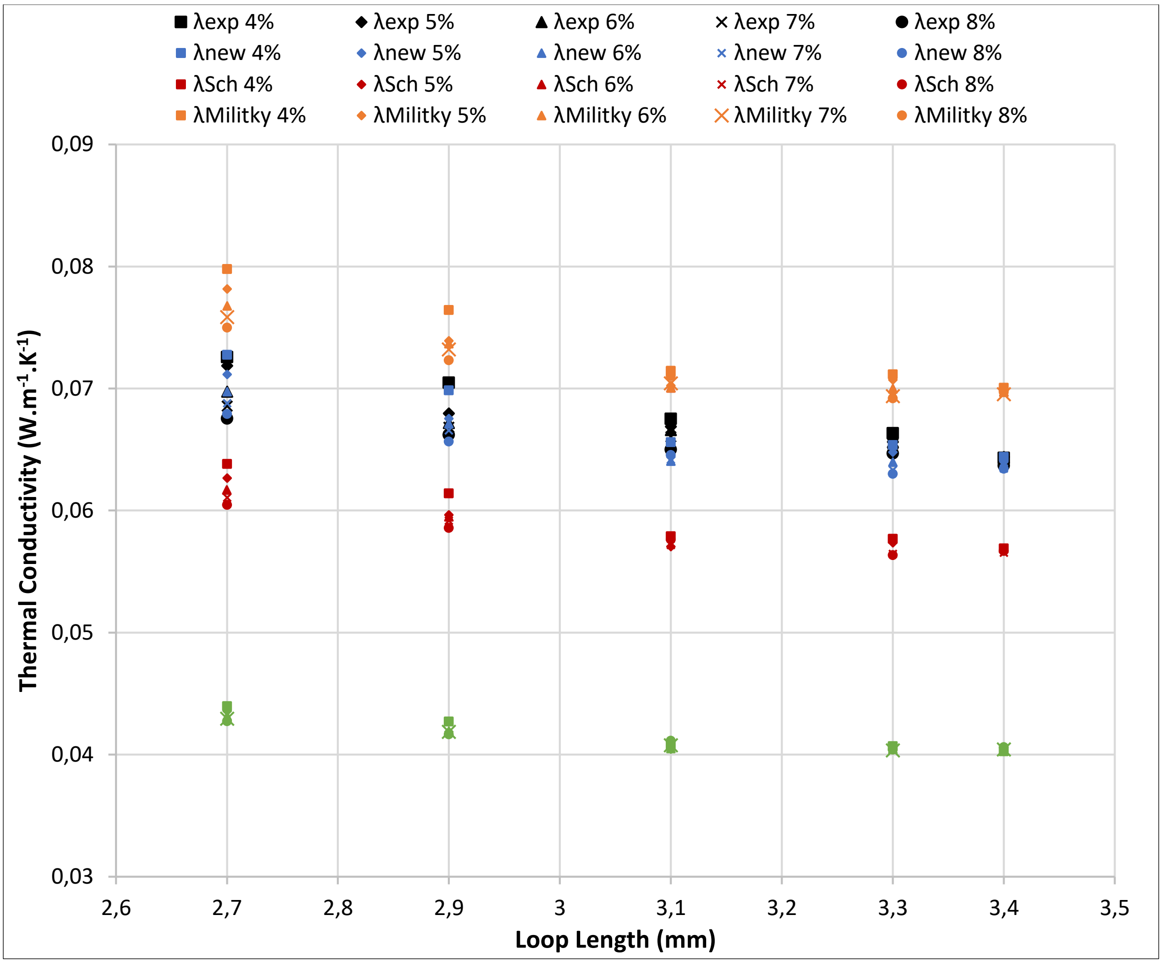


Figure 7.5. Experimental and predicted values of thermal conductivity of elastic knitted fabric produced from yarn count 35 Ne

Figure 7.5 shows the experimental and predicted values of thermal conductivity of elastic knitted fabric produced from yarn count 35 Ne. the predicted values from a new model were very closed to the experimental values of thermal conductivity at most points compared to the predicted values from Schuhmeister, Militky, and Maxwell–Eucken 2 models. For the elastic *SJKF* samples produced from yarn count 25 Ne, the predicted values of thermal conductivity from a new model were also closed to the experimental values, as shown in figure 7.6.

For more clear presentation, the predicted values from the new model of elastic *SJKF* produced from yarn count 25 and 35 Ne vs experimental values were represented as shown in figure 7.7. Therefore, it can be said that the new model can be used to predict the thermal conductivity of the elastic *SJKF* compared to Schuhmeister, Militky, and ME 2 models.

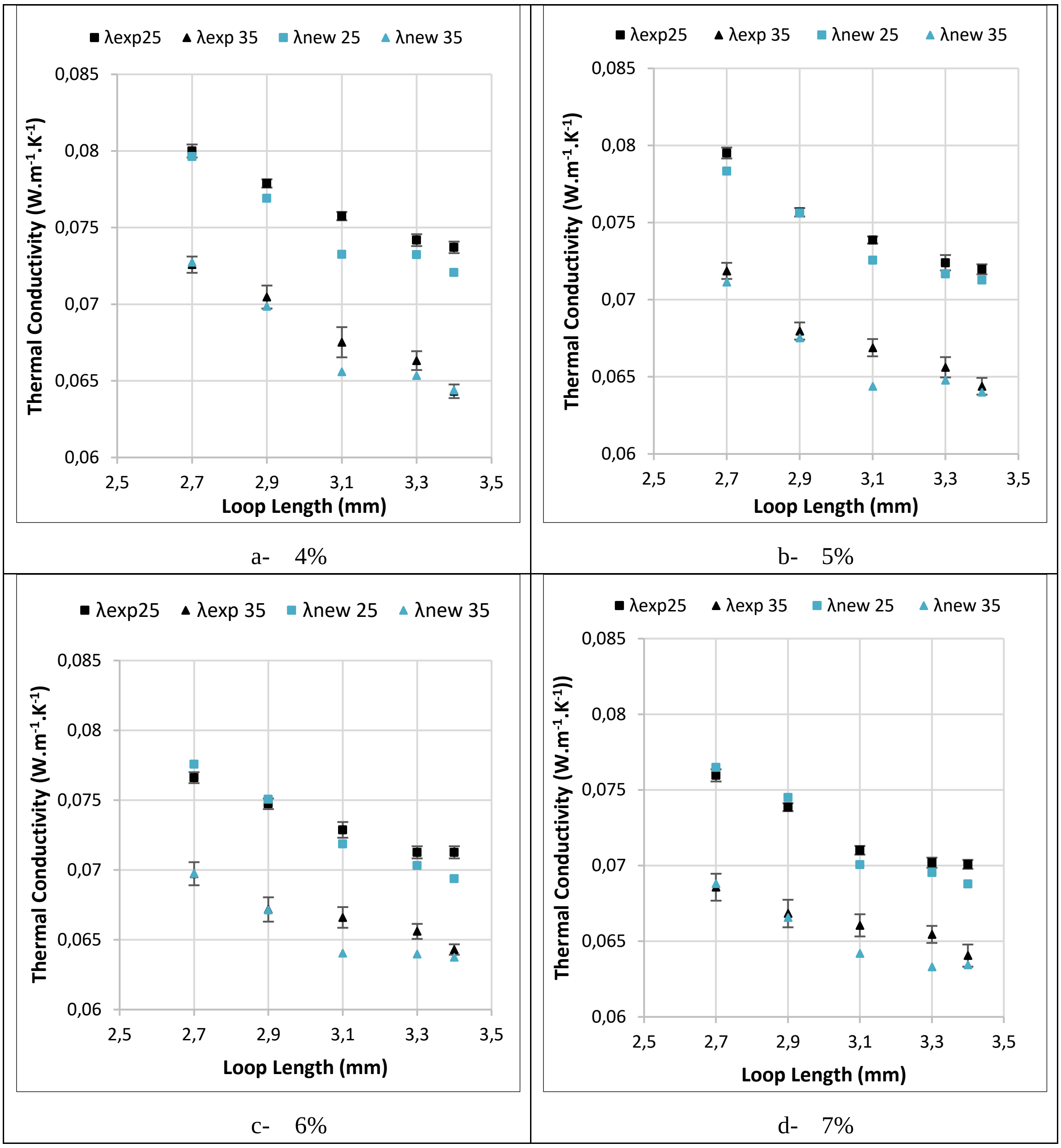


Figure 7.7. Predicted thermal conductivity values from the new model vs experimental values at different levels of *SWP* and yarn count.

Figure 7.8 shows the coefficient of determination (R^2) 0.95 between the predicted values from a new model and experimental values of the thermal conductivity of elastic *SJKF* samples produced from yarn count 25 and 35 Ne. the slope of trend line was 0.93 and the intercept was 0.0049.

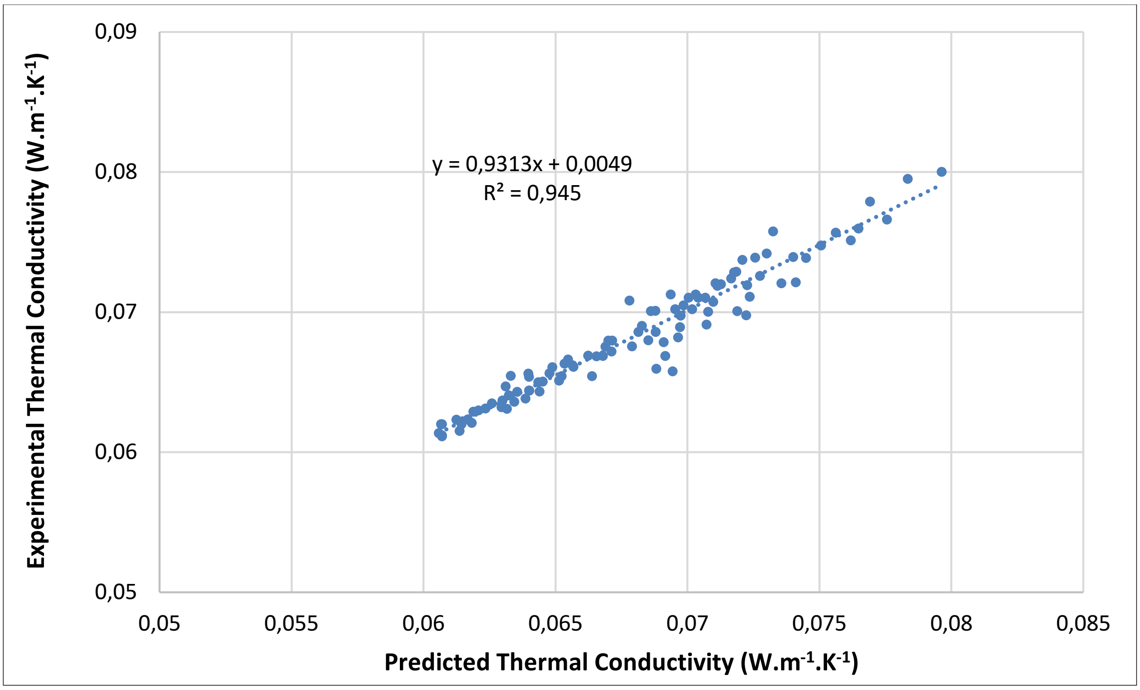


Figure 7.8. Experimental thermal conductivity vs predicted thermal conductivity from a new model

7.4 An attempt to determine structural parameters to obtain a desired thermal conductivity

At designing textiles, construction parameters are chosen in order to reach the appropriate physical properties for the specific end-use. Practically, these parameters are chosen based on previous experience in this field with the required adjustment within the competitive cost limitation. In this field, there are few mathematical models and equations that start with the desired property and end with the selection of the appropriate construction parameters, especially with the interference of the required properties.

In this part, an attempt to determine one property, which is thermal conductivity by selecting the appropriate structural parameters, namely yarn count, *SWP*, and the loop length as independent structural parameters is proposed, and vice versa. So that, the designers of elastic knitted fabric can choose the construction parameters for these fabrics based on knowing their thermal conductivity value.

To achieve this purpose, the equations 7.11, 7.10, 7.9, 7.8, and 7.7 were used to obtain the predicted value of thermal conductivity, which is the dependent variable, considering that the yarn count, *SWP*, and the loop length are independent variables, and the wales spacing, courses spacing, and the fabric thickness are considered as dependent variables. The predicted values of thermal conductivity of elastic *SJKF* produced from yarn count 25 and 35 Ne versus loop length are illustrated in figure 7.9. The relation between thermal conductivity (y) and loop length (x) was presented by using polynomial equations as listed in table 7.1 at different levels of *SWP* and yarn count. This figure could be used to determine the structural parameters of elastic *SJKF* by knowing the desired value of the thermal conductivity.

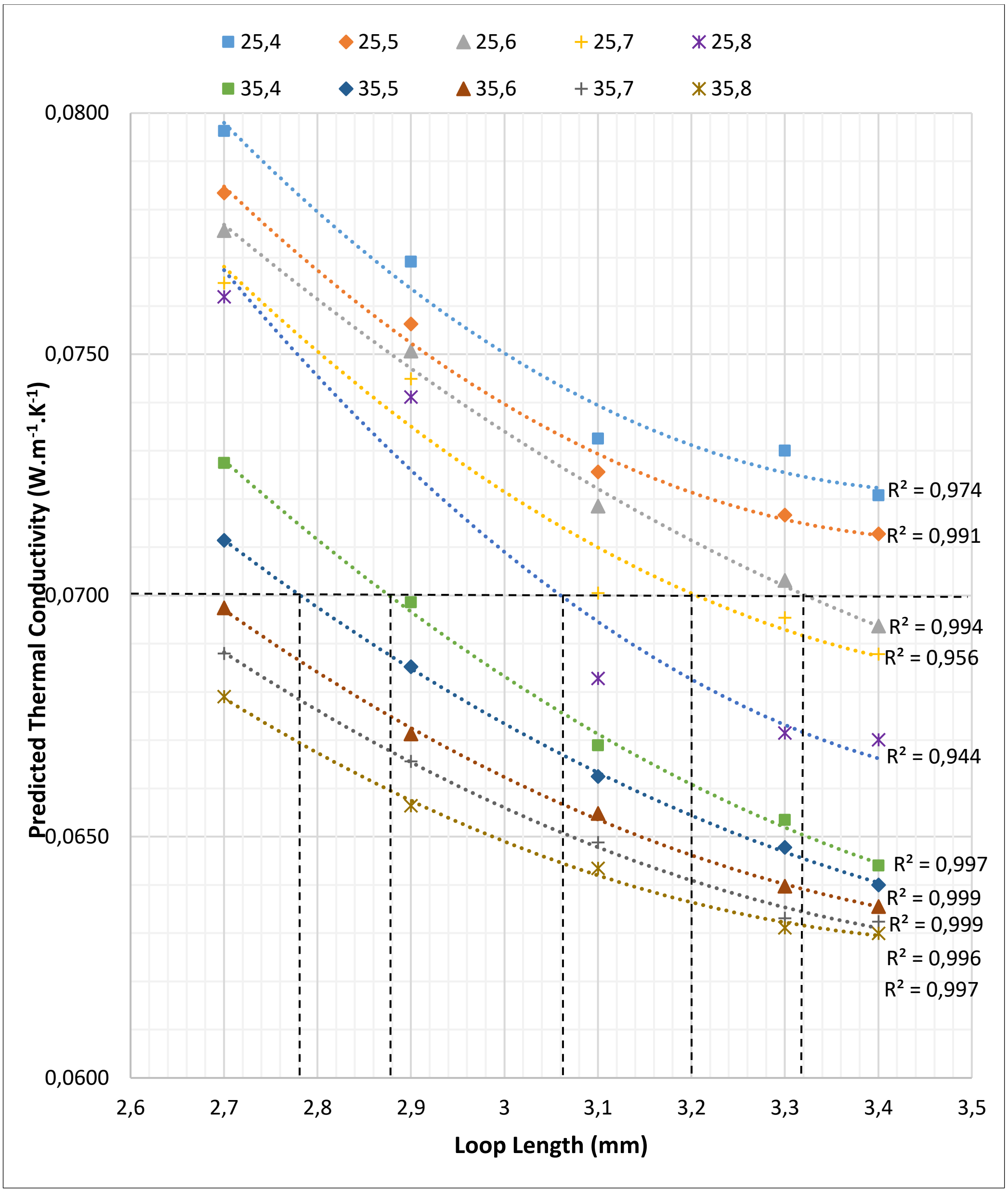


Figure 7.9. The predicted values of thermal conductivity of elastic *SJKF* versus loop length

Table 7.1. Curve fitting equations for the relation between thermal conductivity and loop length

Yarn count (Ne)	SWP (%)	Coefficient of determination (R^2)	Curve equation
25	4	0.974	$y = 0.013x^2 - 0.089x + 0.226$
	5	0.991	$y = 0.012x^2 - 0.082x + 0.215$
	6	0.994	$y = 0.006x^2 - 0.048x + 0.165$
	7	0.956	$y = 0.010x^2 - 0.073x + 0.200$
	8	0.944	$y = 0.013x^2 - 0.091x + 0.231$
35	4	0.997	$y = 0.008x^2 - 0.058x + 0.174$
	5	0.999	$y = 0.006x^2 - 0.049x + 0.157$
	6	0.999	$y = 0.007x^2 - 0.051x + 0.157$
	7	0.996	$y = 0.006x^2 - 0.047x + 0.150$
	8	0.997	$y = 0.007x^2 - 0.051x + 0.153$

For example, if the desired value of thermal conductivity of elastic *SJKF* is 0.07 $W.m^{-1}.K^{-1}$, this value could be achieved in case of:

Yarn count 35 Ne, loop length 2.78 mm, and *SWP* 5%.

Yarn count 35 Ne, loop length 2.88 mm, and *SWP* 4%.

Yarn count 25 Ne, loop length 3.06 mm, and *SWP* 8%.

Yarn count 25 Ne, loop length 3.2 mm, and *SWP* 7%.

Yarn count 25 Ne, loop length 3.32 mm, and *SWP* 6%.

These results are related to the used material (cotton), yarn count range 25- 35 Ne, and *SWP* 4 - 8 %, however, this attempt can be generalized and achieved practically and industrially by expanding the range of the yarn count, *SWP* and the type of raw material.

CHAPTER 8: EVALUATION OF RESULTS AND NEW FINDINGS

8.1 Conclusion

First, the effect of construction parameters, namely yarn count, loop length, spandex weight percent, and plaiting technique on the geometrical and thermo-physiological comfort properties of full and half plaited *SJKF* was investigated. Elastic *fp* and *hp* samples were produced at five levels of loop length five level of *SWP*, and two levels yarn count (25 and 35 Ne). For comparison. 100% cotton samples were produced at the same levels of loop length and yarn count. The geometrical properties (thickness, weight, stitch density, fabric bulk density), thermal conductivity and absorptivity, water vapour resistance, air permeability were measured. By using flexi frame, the fabric growth and stretch of *fp* knitted samples were measured, and the thermal properties were measured under two levels of extension 15 and 30%.

The results showed that:

- The *fp* thickness was higher than 100% cotton samples by up to 69% at 3.4 mm loop length and 8% *SWP*.
- **The elastic *SJKF* thickness was ranged between 3.6** d **to 4.4** d where d is the yarn diameter **because of stitch overlapping**. The elastic fabric thickness decreased with increasing of *SWP* and increased with loop length increase for both *fp* and *hp*.
- The thermal conductivity and *WVR* were higher than 100% cotton samples by 24 and 55%, respectively, at 2.7 mm loop length and 4% *SWP*.
- The thermal resistance and absorptivity were higher than 100% cotton samples by 60 and 42%, respectively, at 3.4 mm loop length and 4% *SWP*.
- The thermal conductivity, thermal absorptivity, and water vapour resistance of both *fp* and *hp* decreased with increasing of *SWP*, **so the elastic *SJKF* could be used in summer and winter with comfort feeling.**
- For all elastic *SJKF* samples, the *WVR* values were less than 5 and it is within excellent level of *WVR* transfer ability which gives comfort during wearing.
- Yarn count had a significant effect on the geometrical and thermo-physiological properties. The thickness of elastic fabric decreased with increased yarn count from 25 to 35 Ne. The fabric weight went down with increasing of yarn count. **Thermal conductivity and absorptivity of elastic *SJKF* went down with yarn count increase**.
- The thermal conductivity and absorptivity, and water vapour resistance values of elastic single jersey samples indicated to comfort, so adding spandex to *SJKF* had a good impact to geometrical and thermo-physiological properties.
- Adding spandex enhanced the elastic recovery of *SJKF*. Fabric growth of elastic samples were less than 100% cotton samples and *FGW* was less than *FGC*.
- Fabric stretch of elastic samples decreased when *SWP* increased and *FSW* of elastic samples was higher than 100% samples.
- Thermal conductivity, resistance and absorptivity and fabric thickness of elastic fabrics decreased when the extension was up to 30%.
- Adding spandex from 4 to 8% to *SJKF* samples had a great effect on the geometrical and thermo-physiological properties compared to 100% cotton samples.
- Adding spandex leads to stitch overlapping therefore, the open structure converts to maximum set (normal structure) and overlapping (compact structure)

Second, AutoCAD software was used to present **an innovated 3D modelling of stitch overlapping, maximum set, and open structures** to **investigate the pore size and distribution** for different *SJKF* structures. The fabric thickness was divided to several sections to calculate the pore size at each section. It was marked that the open structure had the highest pore volume at all sections, followed by maximum set, followed by overlapping structure.

Third, a new geometrical model to predict thermal conductivity of elastic *SJKF* was derived based on geometrical parameters of loop and the fibres direction to the direction of heat flow. Then the predicted values from a new model and three theoretical model and experimental values were compared. **The predicted values from the new model was very closed to experimental values. Therefore, the new model can be used to investigate the thermal conductivity of elastic *SJKF*** and vice versa**, where an attempt to determine structural parameters to obtain a desired thermal conductivity** was proposed.

8.2 Recommendations for continuing work

Based on this thesis, it was recommended that:

1. The effect of construction parameters on the thermo-physiological properties on the elastic knitted fabric can be investigated with changing the raw material, fabric structure and increase the range of yarn count.
2. Tabulated information can be prepared to help the knitted fabric manufacturers to predict thermal conductivity from the construction parameters and vice versa
3. The thermal conductivity can be predicted by using the finite element method and 3 D geometrical model by using AutoCAD software.

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CHAPTER 10: LIST OF PAPERS PUBLISHED BY THE AUTHOR

10.1 List of journal papers

1) **Khalil, A**., Fouda, A., Těšinová, P., & Eldeeb, A. S. (2021). Comprehensive assessment of the properties of cotton single Jersey knitted fabrics produced from different Lycra States. *AUTEX Research Journal*, *21*(1), 71-78.
2) **Khalil, A**., Aboalasaad, A. R., & Těšinová, P. (2021). Thermal comfort properties of cotton/spandex single jersey knitted fabric. Industria Textila, 72(3), 244-249. 21.
3) **Khalil, A**., Těšinová, P. & Aboalasaad, A. (2021). Effect of Lycra Weight Percent and Loop Length on Thermo-physiological Properties of Elastic Single Jersey Knitted Fabric. Autex Research Journal, 22(4) 419-426.
4) **Khalil, A**., Eldeeb, M., Těšinová, P., & Fouda, A. (2023). Theoretical Porosity of Elastic Single Jersey Knitted Fabric Based on 3D Geometrical Model of Stitch Overlapping. Journal of Natural Fibers, 20(1). https://doi.org/10.1080/15440478.2023.2181274
5) Aboalasaad, A., Sirková, B., Mansoor, T., Skenderi, Z. & **Khalil, A**. (2020). Theoretical and Experimental Evaluation of Thermal Resistance for Compression Bandages. Autex Research Journal, 22(1) 18-25.
6) Mansoor, T., Hes, L., **Khalil, A.**, Militky, J., Tunak, M., Bajzik, V., Kyosev, Y. (2021). Conductive Heat Transfer Prediction of Plain Socks in Wet State. Autex Research Journal, 22(4) 391- 403.
7) Aboalasaad, A., Skenderi, Z., Brigita Kacavas's. & **Khalil, A**. (2020). Analysis of Factors Affecting Thermal Comfort Properties of Woven Compression Bandages. Autex Research Journal,20(2) 178-185.
8) Fouda, A., Těšinová, P., **Khalil, A.**, & Eldeeb, M. (2022). Thermo-physiological properties of polyester chenille single Jersey knitted fabrics. Alexandria Engineering Journal, 61(9), 7029-7036

10.2 List of Conferences Participation

1) **Khalil, A**., El-Shahat, I.M., Těšinová, P., Eldeeb, A.S. "Estimate Thermal Comfort Properties of Bed Cover Produced from Double Honeycomb", the 9th Central European Conference, Liberec, PhD student day, September 14th, 2017.
2) **Khalil, A**., Tešinová, P., & Aboalasaad, A. R. "Geometrical and Thermal Properties of Stretched Single Jersey Knitted Fabric". Workshop for PhD student, Liberec, November 2019.
3) **Khalil, A**., Tešinová, P., & Aboalasaad, A. R. "Effect of Some Knitted Fabric Structures on Thermal Comfort Properties". Workshop for PhD student, Liberec, January 2021.
4) **Khalil, A**., Tešinová, P., & Aboalasaad, A. R. (2019). Thermal comfort properties of single jersey knitted fabric produced at different Lycra states. *ICNF 2019-4th International Conference on Natural Fibres*. Porto, Portugal.
5) **Khalil, A**., Tešinová, P., & Aboalasaad, A. R., "Geometrical and Thermal Properties of Elastic Single Jersey Knitted Fabric", ICNF 5th International Conference on Natural Fibres conference, Portugal, 17-19 May 2021.
6) **Khalil, A**., Tešinová, P., & Aboalasaad, A. R. "Correlation between Geometrical and Thermo-physiological Properties of Elastic Knitted Fabric". Autex 2021 - 20th World Textile Conference, Portugal, 100% online.
7) **Khalil, A**., & Tešinová, P. "Elastic Recovery of Full Plaited Knitted Fabric". Autex 2022 - 21 World Textile Conference, Lodz, Portugal.

CHAPTER 11: CURRICULUM VITAE

Personal Data

Name: Amany Ahmed Salama Khalil.

Sex: Female

Nationality: Egyptian

Date of birth: 02.07.1985, Dakahlia, Egypt.

Permanent Address: 6 Amr Ibn Elaas Street, Mansoura, Egypt.

Mobile number: +420776690508.

Marital status: Married, has three kids.

Email: engamanysalama@gmail.com & amany,khalil@tul.cz

Education

- M.Sc. degree in textile engineering "Comparative Study between Double Honeycomb and Weft Backed Fabric", 2015.
- Bachelor science in textile engineering, Mansoura University, June 2007, **"Very good with honour degree", Ranked 1st of class**.
- Undergraduate project: "Quality control of knitted fabric properties", with grade "Excellent".

Employment Experience

1) **PhD scholar** in Technical University of Liberec, Department of Textile Evaluation (15.12.2016) till now.
2) **Lecturer assistant,** from (12-2015) till now, Faculty of Engineering, Textile Department, Mansoura University, Egypt.
3) **Demonstrator,** from (12-2007) until (11-2015), Faculty of Engineering, Textile Department, Mansoura University, Egypt.
4) **Production engineer** in EL GAZZAR CO. for knitwear**,** from (7-2007) till (11-2007), 80 Abdel Salam Aref St. El Mansoura, El Dakahleya, Egypt.

Internship

1) Internship no I in Mansoura University, Egypt (15.05.2017 to 14.06.2017)
2) Internship no II in Mansoura University, Egypt (11.02.2019 to 10.04.2019)
3) Internship III in El Nasr Clothing and Textiles Company (Kabo), Alexandria, Egypt (03.12.2019 to 18.02.2020).

Training

1- Training in "Masr Company for Spinning and Weaving", Mahala El Kobra, Egypt. From (6:9-2006).

2- Training in "Dakahlia (DTEX) Company for Spinning and Dying" in Mansoura, Egypt. (6:9-2005).

Personal Skills

- Computer:
  - Software:
  - Matlab
  - AutoCAD
  - Iventor
  - Internet (Browsing, Searching…).
  - Hardware:
  - Aware of common hardware problems.
- Languages:
  - First language: Arabic (Native)
  - Second language: English (Very good)

Recommendation of Supervisor

SUPERVISOR'S OPINION OF THE DISSERTATION THESIS

with the title

EFFECT OF ELASTIC KNITTED FABRIC CONSTRUCTION PARAMETERS ON THERMO-PHYSIOLOGICAL PROPERTIES

Student: Amany Ahmed Salama KHALIL

Study program: Doctoral, P3106 TTMEA

This is the recommendation and comments on the dissertation thesis and work habits of the student with whom I am the supervisor. I worked with Amany Khalil from the start of her study in 2016. Ms. Khalil successfully passed all exams, including her Comprehensive Doctoral Exam at 08. 06. 2022. The length of her study was affected by her family situation during that time, not by the lack of her effort at all. Her effort is exemplary.

The topic was chosen with the concern of her previous background and the fact, that she comes from the region where production of knitted cotton fabrics run in a number of factories. The relation between cotton and elastane interaction is still not fully theoretically described for the knitted materials and because the thesis gives the prediction outputs, the results of the student have got potential for optimization of the production in real. A set of tested fabrics was produced specially for her thesis in Egypt, where she fulfilled her compulsory training. Ms. Khalil looked after the process and defined fabrics throughout the whole production, including finishing. Fabrics are in the range of how it is effective for real production but still offer some variety to obtain significant trends where they are.

The thesis content was adapted through the process of research work as usual. Ms. Khalil listens to the recommendations of professors at FT and thinks critically about how to implement them in the process of her work. We both heard from more sides about the necessity of micro CT for the description of the porosity of tested fabrics. With concern that the faculty instrument is broken for a long time and other precise instruments can be hired for unaffordable prices only, Ms. Khalil constructed a structure at AutoCad to simulate it and offer a porosity overview. It was also used standard optical microscopy in soft sections (yarns, fabrics), hard sections and tested CT to obtain a real idea of the structure. Figure 1 shows how unsatisfactory it is possible to take a picture by available CT at the Faculty of Mechanical Engineering, so AutoCad simulation gives relevant information. It is just one example of how she works with details. When a student faces a problem, she finds another way to solve it and offers an alternative. She can think outside the box, which is one of the essential properties of an excellent researcher.

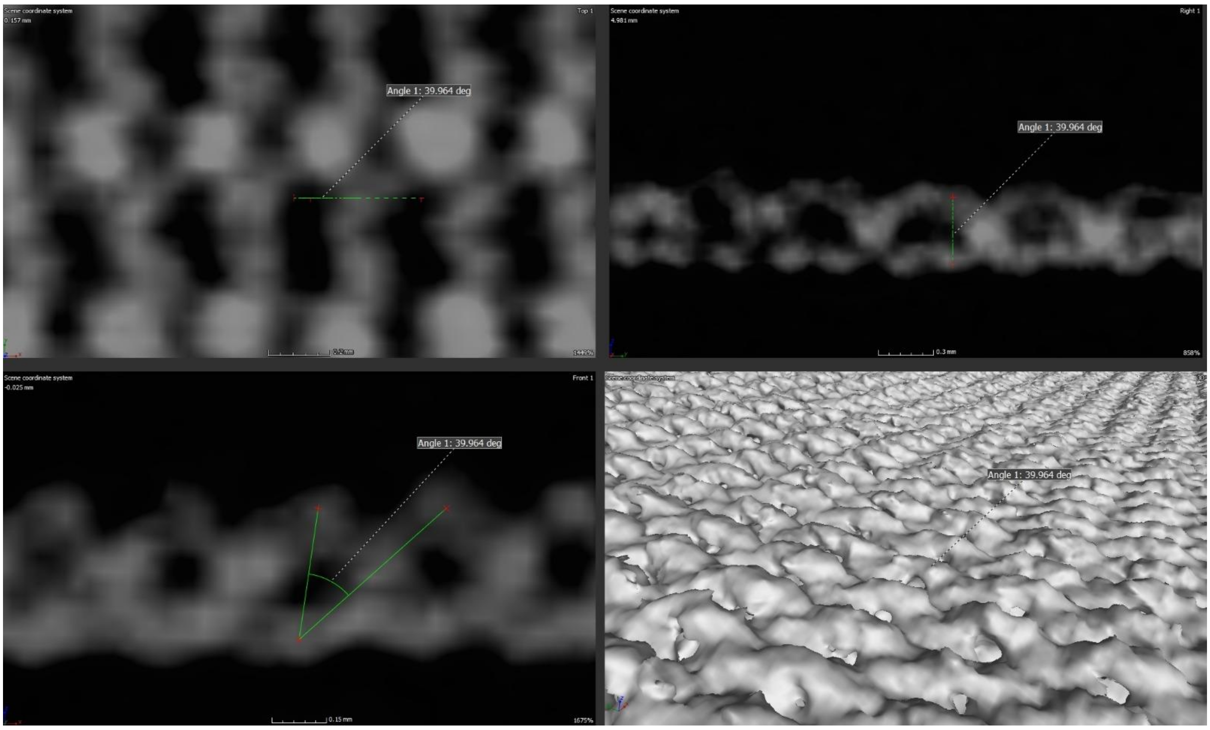

Figure 1. CT images were done at the Faculty of Mechanical Engineering TUL facility. Although we are thankful to the skilled operator, images cannot be in better resolution to show yarn contours or single fibers because of the instrument's limits.

The formal site of the work is good. Sources are cited in the relevant places. Literature research is up to date and related well to the content in the proper amount. Images and tables are readable, as close to the related text as possible.

It is necessary to comment on the plagiarism checking in theses.cz, which shows 22 similar documents and 10% similarity with one document. That document is related to another thesis with the topic concerned with the fabric's structure, the same as part of Khalil's thesis. Both works used some same sources, of course, which brings citing the same definitions. Part of the similarity is also because the formal first pages with the text need to be mentioned in the exact wording according to the TUL rules. Both effects give that high number of similarities. There is no similarity found in the parts belonging to her own findings or inventions, only in formal parts or theoretic definitions where no change is desired because of the change of the meaning. The similar reasons are related to the other similar findings.

The second document, similarity 9%, is partly of the formal first pages and topic related to the comfort of knitted socks so it is necessary to use the same definitions for the loop length, water vapor resistance, extension, etc. There is no match in the same sentence but study of the same properties on different materials and with different methods of extension. The third document is a journal paper properly cited in the thesis, with similarity defined at 8%. The effect of similarity is reasonable because it studies the plaited knitted fabrics too. The study is smaller than the thesis sample set and it is prepared in another way for testing. It did not obtain so deep results in the same properties and finished in discussion with the experimental description only.

The other similarity match is not higher than 5%. It is because of a similar topic or used testing device. Some works are cited where it is the same topic, and all text is paraphrased or uses the same definitions and manes of the properties. If the similarity is found by the system in the results part of the thesis, it is not because of taken from the source but because results are leading to similar trends which is not unpredictable. Some match is also because of same sources are used but not mentioned in the same way but adapted for the thesis topic. The literature summary for the thesis was made individually. **I did not find plagiarism in the thesis of Ms. Khalil.**

Ms. Khalil works systematically and with concern for details. She is enthusiastic about textiles with deep knowledge already and has the potential to move further in the research area she will work in the future. Ms. Khalil is already very well accepted at her home university and, after graduation, will strengthen her position as one of the key researchers who can also give an excellent background to her students. I wish her all the best in her life.

The overall structure, theoretical background, and scientific content are at the proper dissertation level. All aims were fulfilled, and the results were discussed. The outputs are relevant and can be beneficial for the producers of knitted fabrics or apparel designers.

The submitted dissertation fulfilled the requirements of the dissertation thesis. **I recommend a dissertation thesis for the defense** and, based on a successful defense, to give a Ph.D. degree to a student Amany Ahmed Salama KHALIL.

In Liberec 10. 05. 2023

Ing. Pavla Těšinová, Ph.D.

Reviews of the Opponents

Opponent's opinion of the doctoral dissertation

Doctoral student: **Amany Ahmed Salama Khalil, M.Eng.**

Name of dissertation thesis: **Effect of elastic knitted fabric construction parameters on thermo-physiological properties**

Opponent: **CAPT. Ing. Jana Švecová, Ph.D.**

Topicality and significance of the topic

Dissertation thesis addresses an important and very beneficial topic. Problematics of investigation of the effect of construction parameters of elastic single jersey knitted fabric on the geometrical and thermo-physiological propertiesis very topical for several reasons:

- The thermo-physiological properties of the fabric are one of the most important properties that affect on the comfort and psyche of human and it is very important for the wearing of clothing, whether for sports, professional soldiers or the other aplication.
- The spandex incorporating in the weft knitting machine had a good impact on the geometrical and thermo-physiological properties.
- This study presented an innovated 3D geometrical models and it was noticed that the overlapping structure had the smallest pore volume, followed by the maximum set, followed by the open structure.
- It was marked that new derive model is prepare to be used for prediction of thermal properties of SJKF.

Therefore, I believe that the chosen topic of the dissertation is beneficial and promising.

The aim of the dissertation

Based on the literature review, were identification aims of the thesis in chapters three:

1. To investigate the effect of construction parameters of elastic SJKF (yarn count, loop length, spandex weight percent and plaiting technique) on the geometrical and thermo-physiological properties.
2. To analyse the effect of spandex percent on fabric growth and fabric stretch of SJKF.

3. To present a theoretical 3D model of stitch overlapping, maximum set, and open structures by using AutoCAD software to investigate the pore size and distribution for different SJKF structures.
4. To apply three simple mathematical models (Maxwell–Eucken 2, Schuhmeister, Militky) of thermal conductivity to investigate if these models can be used to predict the thermal conductivity of elastic SJKF.
5. To derive a new equation that describes the thermal conductivity of the elastic SJKF based on the loop geometry and the yarn and fibres inclination on the direction of heat flow.
6. To assist the manufacturers and designers to predict the thermo-physiological properties of elastic SJKF produced from cotton yarns.

Selected methods and solution procedure

The solution procedure has a logical structure, the appropriate graphic and language level. The work can be divided into theoretical and practical part. From the review of literature followed to need investigation the effect of spandex weight percent on the thermo-physiological comfort properties of elastic SJKF. First, the influence of the design parameters of the elastic SJKF, namely yarn count, loop length and spandex weight percentage, on the geometric and thermophysiological comfort properties was estimated. Second, a mathematical model for predicting the thermal conductivity of elastic SJKF was presented. Third, a new approach was proposed to investigate the pore size and pore distribution inside the SJKF structure. The chosen solution methods are suitable for this area of scientific work.

Evaluation of achieved results

Two different numbers of worsted yarns were made from Giza 86 Egyptian cotton fibers. Full and half knit SJKFs were then produced with two yarn counts and five levels of spandex weight percent and five levels of loop length. The spandex yarns were incorporated using a braiding technique where the spandex yarns have a separate feed system, a braiding roller and a guide eye. The percent spandex treatment was obtained by adjusting and optimizing the speed of the spandex feed system. The results of investigating the effect of design parameters, namely yarn count, loop length, spandex weight percentage and knitting technique on the geometric and thermophysiological comfort properties of fully and half knitted SJKF, were found by measuring the thickness, weight, stitch density, bulk density of the fabric, thermal conductivity and absorbency, water vapor resistance and air permeability. Using a flexi frame, the growth and stretch fp of the knitted samples were measured and the thermal properties were measured at two stretch levels of 15 and 30%. The new model can be used to investigate the thermal conductivity of elastic SJKF and vice versa, where an attempt has been made to determine the structural parameters to obtain the desired thermal conductivity. These and other findings are important for designing and preparing different types of knitwear from elastic materials intended for the first layer of clothing and other applications.

Significance for the practice or development of a scientific field

The dissertation sought to present findings that could be useful in defining future direction and provide researchers with insider references. All of the above findings of research experiments should be taken into account with great importance in the design and preparation of knitted fabric production. The work opens up further space for continuing the investigation of the influence of design parameters on the thermophysiological properties of elastic knitwear with a change in raw material, fabric structure and an increase in the number of yarns. I see another benefit in the presented an innovated 3D modelling, the possibility of using a new geometric model to investigate the thermal conductivity of elastic SJKF and to propose an attempt to determine the structural parameters to obtain the desired thermal conductivity. The results can also be used for the patterning and innovation phase of functional clothing components of the armed and safety forces of the Czech Republic.

Publication aktivity

The publishing activity of the doctoral student is adequate and relates to the topic of the submitted dissertation. The doctoral student published 8 articles in professional Journals and 7 articles in professional Conferences.

Questions and comments on the dissertation:

In my opinion, the introduction to the thesis lacks the theoretical basis of selected thermophysiological and geometric properties in relation to clothing comfort, together with the introduction to the topic.

Other comments are more of a formal nature, resulting from the inconsistency of the structure of dissertations at various universities in the Czech Republic. ČSN ISO 7144 (010161) Documentation - Formal arrangement of dissertations and similar documents: states that the formal arrangement, style and arrangement of the bibliography of dissertations must be in accordance with the special rules of the university to which the dissertation is submitted. According to the extract from the TUL Study and Examination Regulations, Article 20, Point 3, the requirements for the content of the thesis are met. In Article 20 point 5) it is further stated that the indicative scope of the dissertation and other comments may be further modified by the relevant directive of the dean. I did not have this document. However, I would like to make a few comments, rather recommendations for a better overview and coherence of the text in the future:

- After each chapter, it would be appropriate to have another subchapter in the form of a partial conclusion, which summarizes the most important and key things that happened in the chapter, the most important findings.
- Unification of bullet points, sizes and placement of images, tables throughout the work.
- Cite the source for each figure and table, especially in the theoretical part, even if it is your own source.

My questions:

1. It is clear from your results that the addition of spandex to SJKF had a good effect on the geometric and physiological properties as well as on the elastic recovery. How much would the cost of the garment and its production differ by adding spandex to the fabric?
2. What next direction will you take in your research?

Final evaluation

The submitted dissertation fulfilled the subject and goals set in the introduction. It meets the requirements on dissertation thesis, including verification of authenticity, publication activities and therefore **I recommends work for defense.**

July 7, 2023 Brno

CAPT. Ing. Jana Švecová, Ph.D.
Faculty of Military Leadership
University of Defence

Prof. Dr. Alaa Arafa Badr, Professor
Alexandria University
Faculty of Engineering
Textile Engineering Department
Alexandria, Egypt

Review Report on Doctoral Dissertation

of Amany Ahmed Salama Khalil, M.Eng.

entitled: **"Effect of elastic knitted fabric construction parameters on the thermo-physiological properties"**

prepared based on invitation letter delivered on 6th June 2023

from Dean of Faculty of Textile Engineering doc. Ing. Vladimir Bajzik, Ph.D.

Supervisor:

Ing. Pavla Těšinová, Ph.D. Department of
Textile Evaluation Department
Faculty of Textile Engineering
Technical University of Liberec

General description

The review has been performed on the basis of the Doctoral Dissertation in English.

The doctoral dissertation consists of 10 chapters, including an introduction, an overview of the current state of the problem, description of experimental parts, evaluation of results and new findings, list of references, and appendices. Additionally, a list of papers published by the author and a short Curriculum Vitae are included.

The material of the doctoral dissertation contains 109 pages, including 54 figures and 34 tables.The content of the dissertation is presented and divided into ten individual chapters. In the beginning, the list of abbreviations and nomenclature used in the dissertation is presented.

The first chapter was an introduction and overview of the current state of the problem. The second chapter was a review of the scientific literature. The third chapter describes the aim of the thesis.

The fourth chapter is focused on the studied material and used method. In this chapter, the characterization of yarns used in the fabric production, the materials description, experimental techniques, and research methodology are included.

Chapter five is the longest chapter focused on summary of the achieved results and studied the effect of construction parameters on the geometrical and thermo-physiological properties of elastic knitted fabrics. Chapter six proposed a 3D geometrical model of stitch overlapping. Chapter seven presented a prediction of thermal conductivity of elastic *SJKF*.

The summary of research work, evaluation of results, new findings, and recommendations are presented in chapter eight. Chapter nine included 94 scientific references. Finally, in the last chapter of the dissertation, some of the appendices are included.

The topicality of the thesis

The main goals of the presented scientific work were:

- Firstly, to study the effect of construction parameters of elastic single Jersey knitted fabric (*SJKF*) on the thermo-physiological properties.
- Secondly, to propose a 3D geometrical model to investigate the pores volume through three different structures of knitted single jersey.
- Thirdly, to present a model of the thermal conductivity that could use to predict the thermal conductivity of elastic knitted fabric based on the fabric construction parameters and fibers inclination to the heat flow direction.

To achieve these goals, 120 *SJKF* samples were produced with different levels of construction parameters. The author tries to assist the manufacturers and designers of knitted fabric by her attempt to predict the construction parameters of elastic knitted single jersey fabric, when the requested thermal conductivity is known, as illustrated in chapter 7.

In accordance with the topic of research, the aim has been achieved. The aim of the dissertation is actual, very interesting and important from the practical point ofview in industry.

Taking the above into consideration, I can state that the dissertation topic is current and relevantin the context of up-to-date research in textile material engineering.

Methodology

PhD candidate has produced two combed yarn count, then produced full plaited and half plaited *SJKF* with five levels of loop length and spandex weight percent. Also, 100% cotton samples were produced at the same yarn counts and loop length. The geometrical and thermo-physiological properties were measured according to standard test methods, yarns diameter and its bending rigidity were also measured. The fabric growth and stretch were measured by designed flexi-frame.

AutoCAD software was used to draw the 3D model of stitch overlapping, maximum set, and open structures.

Chapters 5, 6, and 7 present many experiments and results with comments and analysis. All applied experimental methods have been described clearly and in detail. In my opinion, the methodology is adequate to the problem which the author undertook to solve.

Results and discussion

All experimental results have been presented clearly and in detail. The figures, schemes, and tables are correct and supported to analyze the findings. Results have been commented on deeply, but in some parts, they do not present why the results were observed.

Conclusions

In this chapter, evaluation of results and new findings were presented with conclusions of the work. Conclusions are based on results. The conclusions take into consideration all findings of performed experiments.

The dissertation showed some suggested and recommended solutions for the optimum selection of elastic *SJKF* based on the thermo-physiological properties.

Experiment and simulation confirmed that proposed theoretical model could represent the structure of elastic *SJKF* in different conditions.

Bibliography

The bibliography in the dissertation is wide and actual. The references include 94 items. They are mostly the scientific articles published in world-renowned scientific journals and conference papers. The selection of references is adequate to the topic of the thesis.

Referee remarks, questions, and conclusions

Remarks

The candidate thesis is interested in the thermo-physiological properties of knitted fabric and tried to find the optimum parameters that affect consumer comfort.

The author presented a theoretical 3D model of stitch overlapping, maximum set, and open structures using AutoCAD software to investigate the pore size and its distribution for different *SJKF* structures.

The author applied three simple mathematical models (Maxwell–Eucken 2, Schuhmeister, Militky) then derived a new equation that describes the thermal conductivity of the elastic *SJKF*.

Questions

Generally speaking, the whole work is interesting. However, there are few comments summarized below.

1- Finishing methods details applied on the fabrics before and after dyeing "mentioned in Chapter 4" need more elaboration.

2- The author is advised to cite some relevant references in CHAPTER 5: SUMMARY OF THE ACHIEVED RESULT everywhere. So, this part would be more objective.

Conclusions

The author of the dissertation has high scientific achievements. The results of the research have been presented in 8 scientific publications, at 7 conferences and workshops.

At the conclusion of my review, I would state that the presented dissertation fulfils all formal requirements and the thesis conforms to principles and requests to the structure of scientific research.

Therefore, I recommend the dissertation submitted by Amany Ahmed Salama Khalil, M. Eng, for the next procedure at the Faculty of Textile Engineering of the TUL. In case of positive results of the dissertation defense, I recommend awarding the title of Ph.D.

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