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Thermal Absorptivity and Other Thermal Comfort Parameters of Rib Knitted Fabrics

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List of Symbols and Description

Symbol	Description
Q	Heat flow per meter squared [Wm^{-2}]
λ	Thermal conductivity [$Wm^{-1}K^{-1}$]
α	Convective heat transfer coefficient [$Wm^{-2}K^{-1}$]
ρ	Density [$kg.m^{-3}$]
Nu	Nusselt dimensionless number
Re, Pr	Reynolds and Prandtl dimensionless numbers
v	Light frequency [Hz]
σ	Stephan-Boltzmann constant
	$5.670400*10^{-8}$ [$W\ m^{-2}\ K^{-4}$]
ε	Emissivity [dimensionless quantity]
b	Wien’s constant, approximately 2890 µm. K
c_k	Specific heat [$J\ kg^{-1}\ m^{-1}$]
λ_{df}	Thermal conductivity of ultra-dry fabric [$Wm^{-1}K^{-1}$]
λ_w	Thermal conductivity of water (0.60) [$Wm^{-1}K^{-1}$]
μ	Ratio of water in total wet fabric
P_v	Fabric porosity [dimensionless number ratio]
θ	Porosity of matter equal to water absorption
$\rho_w\ \rho_s$	Densities of water and substance [$kg\ m^{-3}$]
ρ_w	Density of fabric [$kg.m^{-3}$]
ρ_f	Density of fibres [$kg\ m^{-3}$]
ε	Fibre volume ratio in fabric
P_d	Porosity “density” of fabric [dimensionless number]
μ	Proportion of water in wet fabric
F_w	Weight of wet fabric [kg]
F_d	Weight of dry fabric without moisture [kg]
λ_{AB}	Weighted thermal conductivity of fibres [$Wm^{-1}K^{-1}$]
$\lambda_a\lambda_b$	Thermal conductivity of fibre an and fibre b [$Wm^{-1}K^{-1}$]

h	Average fabric thickness [m] measured with the help of Alambeta
λ_a	Thermal conductivity of air (0.026) [$Wm^{-1}K^{-1}$]
R_m	Thermal resistance of moisture in the fabric [m^2KW^{-1}]
λ_w	Thermal conductivity of water (0.60) [$Wm^{-1}K^{-1}$]
t	Temperature

ABSTRACT

The objective of this study is to investigate the impact of changing the profile of functional knitted ribs on thermal properties of fabric, including thermal conductivity, thermal absorptivity, and thermal resistance. This introduced a new model for the extrapolation of thermal absorptivity due to the variation in the interaction area between human skin and knitted rib fabric. Thermal absorptivity is an indicator of the warm-cool feeling. Polyester yarn was used to produce study samples. The study endorsed that variation in surface profile impacts the thermal parameters. Based on this discussion a new term “thermal contact absorptivity” was created and introduced for the first time. Thermal contact absorptivity indicates the modification in thermal absorptivity due to the contact points between two surfaces. The model was developed using a novel approach and had extensive agreement with measured values. It was further verified that with a higher interaction area between human skin and knitted rib the thermal absorptivity values escalated. This was predominantly due to the increase in contact points, which provided more area for heat transfer through conduction. The equally important thermal resistance and thermal conductivity values were measured, and a correlation was developed between thermal resistance, thermal conductivity, and contact area. A significant equivalence was found between the thermal parameters and surface profile. Subjective analysis was also conducted by involving a group of 30 people for the confirmation of objective values. Impact of parallel and vertical direction on water vapour permeability was measured and a significant impact from direction of air and water permeability was found. In conclusion, the knitted rib made using polyester with a discriminated surface profile provides a different thermal absorptivity. Higher contact points between human skin and knitted rib fabric give a cooling effect which was investigated on functional ribs produced on a flat knitting machine.

Keywords: Functional knitted ribs, Thermal conductivity, Thermal absorptivity, Thermal resistance, contact points

ABSTRAKT

Cílem této práce je zjistit vliv různých profilů funkčních žebrových pletenin na jejich tepelné vlastnosti jako je tepelná vodivost, tepelná absorpce a tepelný odpor. Práce zahrnuje představení nového modelu pro extrapolaci tepelné absorpce vzhledem k rozdílu v oblasti interakce mezi lidskou kůží a žebrovou pleteninou. Tepelná absorpce je indikátorem pocitu tepla a chladu. Vzorky byly vyrobeny z polyesterové příze. Studie potvrzuje, see změna profilu povrchu žebrové pleteniny má podstatný vliv na její tepelné vlastnosti. Na základě této skutečnosti byl poprvé uveden nový termín tepelná kontaktní absorpce. Tepelná kontaktní absorpce představuje modifikaci tepelné absorpce vzhledem ke kontaktním bodům mezi dvěma povrchy. Stejně tak nově vyvinutý model je v souladu s naměřenými hodnotami.

V další části práce je ověřeno, see oblast s vyšší interakcí mezi lidskou kůží a žebrovou pleteninou zvyšuje hodnoty tepelné absorpce. To je převážně způsobeno nárůstem kontaktních míst, která poskytují větší plochu pro přenos tepla kondukcí. Stejně důležité bylo také změřit hodnoty tepelného odporu a tepelné vodivosti. Byla zjištěna korelace mezi tepelným odporem, tepelnou vodivostí a kontaktní plochou. Bylo zjištěno, see existuje významná ekvivalence mezi tepelnými parametry a profilem povrchu.

Třicet respondentů dále provedlo subjektivní analýzu pro potvrzení hodnot z objektivního měření. Rovněž byl změřen vliv paralelního a svislého směru na propustnost vodních par. Bylo zjištěno, see směr má významný vliv na propustnost vzduchu a vody. Studie dospěla k závěru, see funkční žebrové pleteniny vyrobené z polyesteru mají u různého profilu povrchu různou tepelnou absorpci. Více kontaktních bodů mezi lidskou kůží a žebrovou pleteninou způsobuje chladivý účinek. To vše bylo studováno na funkčních žebrových pleteninách, které byly vyrobeny na plochém pletacím stroji.

Klíčová slova: funkční žebrové pleteniny, tepelná vodivost, tepelná absorpce, tepelný odpor, kontaktní body

1. INTRODUCTION

This study examines the influence of the surface profile of a knitted rib on thermal conductivity, thermal resistance, thermal absorptivity, water vapour resistance, and air permeability. It is also to develop an equation for the estimation of thermal absorptivity of knitted rib due to the variation in its surface profile, which maintains the contact area between human skin and the knitted rib. For this purpose, knitted rib samples were produced using polyester yarn on a flat knitting machine.

The objective of this study is to find out the impact of relative contact area on thermal absorptivity of the fabric for this reason to study the impact of fineness of yarn, type of finishes applied on fabric for this study has a less weightage. The samples used in this study are special, not standard ones, and they serve for the experimental confirmation of theory of thermal absorptivity only, the effect of geometrical porosity and contact area. To study all the properties of knit rib nit is not possible, however in this study only rib knits which differ in geometrical porosity and contact area. Cotton fibre was not used purposely because even small changes in the moisture regain can change the results of absorptivity. Polyester is principally dry; the moisture does not affect the results.

Knitted fabrics are produced by intermeshing the yarns which can be made from natural, synthetic, or regenerated fibres. The raw material types and structures give different properties for the yarns used in knitting. The variation in yarn properties results in variation of knitted fabrics properties such as dimensional, mechanical, comfort, and appearance. Mechanical properties, particularly strength and elongation, are the most important performance properties of knitted fabrics which governs the fabric performance in use by causing a change of dimensions of strained knitted fabrics [1].

Knitted rib fabric is typically raised from both sides of the fabric by vertical wales generally called ribs, knitted ribs is one of the four basic knit structure other than Interlock, plain knit and purl. Knitted rib fabrics can be knitted using any Fibre or yarn type and in all weights. The fabric is knitted on double-bed knitting machines with two sets of alternating single-headed needles. The vertical ribs on one side of the fabric are composed of face stitches that are knitted on one needle-bed.

Its weight ranges from 100 to 600 grams per square meter. Knit ribs are an important section of the knitwear field. Changing the knit and stitches creates a flexible fabric, which may be used in cuffs, hems, and innerwear. In most cases, it is used to make undergarments, sweater cuffs, waistbands, caps, etc. However, rib is also used to produce clothing like T-Shirts. Its surface profile is quite distinctive as compared to the surface profile of normal knitted fabrics.

Knitted rib samples were tested using the Alambeta, Permetest, Kawabata Evaluation System, and SDL Atlas Air Perm tester under standard conditions. Thermal conductivity, thermal resistance, thermal absorptivity, water vapour resistance, and air permeability were measured. Transformations in thermal parameters were scrutinized with reference to deviations in the surface profile of knitted rib. A significant connection was found between the different parameters selected for the study and the surface profile of knitted rib. Moreover, an equation using a modelling technique was developed for the prediction of thermal absorptivity of knitted rib. This unique technique proved to be the one for predicting the thermal absorptivity of knitted rib. Based on the results, it is likely that this technique will be equally good for other fabrics.

A subjective evaluation was carried out using a group of thirty people to confirm the testing using Alambeta. The subjective evaluation confirmed the results of Alambeta. In addition to that, Permetest was used to measure water vapour resistance. It was observed that there is a strong correlation between surface profile and water vapour resistance.

This study produced two major benefits. Firstly, it extends the knowledgebase by producing a model for the prediction of thermal absorptivity, and secondly provides a guideline for designers to develop fabrics that can provide higher thermal comfort based on the contact area between human skin and fabric.

This study has main four sections. The first section has a detailed discussion of the thermal parameters of fabric, knitted rib-manufacturing technique, measuring instruments, and the work already carried out in this field. The second section provides a complete description of the experiments. The third section discusses the results, and the last section provides the final conclusion.

1.1 Problem statement

There is an understandable significant correlation between surface profile, thermal absorptivity, thermal conductivity, and the thermal resistance of fabric. Changes in thermal parameters due to variation in a surface profile are not linear. This is due to many factors, which include the contact points between human skin and the fabric surface, physical parameters of the fabric, the compressibility of the fabric, and many other factors. This situation demands the development of a model that can predict the changes in thermal absorptivity based on contact points or the surface profile. Such a model is very useful for manufacturing undergarments which have direct contact with the skin.

It was observed during an initial survey of end users of undergarments that a cool feel is experienced for a very short time. This shows that the surface profile plays a crucial role in the warm-cool feeling. It's important to understand the role of the surface profile in the warm-cool feeling. This study provides a systematic observation using high tech instruments to discover the role of the surface profile in the warm-cool feeling. For testing purposes, 15 knitted rib samples with diverse surface profiles were produced. This study also suggests the best surface profile for a warmer feeling when wearing knitted rib. A recommended product is the second significant output from this study. For this purpose, there is the need for a functional knitted rib, which should have the lowest thermal absorptivity and lowest contact area.

1.2 Aims and objectives

1. Taking into account changes in the surface profile due to changes in knitting designs and change in contact points when placed close to the skin.
2. Evaluation of the model with experimental data and finding a considerable agreement between values obtained using the model and experimental values.
3. The model should be able to predict thermal absorptivity of knitted rib made using 100 polyester yarn with diverse surface profile parameters, and its confirmation by logical testing of knitted rib samples.

4. There was a complete study conducted on effect of enzyme on comfort properties of fabric.
5. Computation of the influence of change in surface profile on the thermal parameters of conventional knitted rib, and knitted rib produced using different knitting techniques to produce significant differences in surface profile.
6. Fair analysis of air and moisture permeability, geometrical roughness, and surface friction of conventional and functional knitted rib.
7. Subjective evaluation of conventional and functional knitted rib to establish the difference between people’s perception and objective results. Functional knitted rib only has a twelve percent contact area while conventional knitted ribs has more than a fifty percent contact area, and higher thermal absorptivity as compared to functional knitted rib.

1.3 Scope of the research

This Study is confined to knitted rib made of polyester yarn and processed with one type of dye, so that wet processing should not influence the thermal parameters of knitted rib and their objective and subjective evaluation to equate thermal parameters and the suggestion of a model for the forecast of thermal absorptivity of knitted rib having different surface profiles.

1.4 Type of research

This is an investigational research. However, a simulation process has been used to forecast thermal absorptivity. The results of the simulation were matched with the actual data.

1.5 Research methodology

Many published materials on thermal absorptivity and surface profile were surveyed, and the latest work in this field was obtained and considered. After considering the discussion of scholars, and the guidance provided in the the literature, a mathematical model was proposed for the prediction of thermal absorptivity of knitted rib under dry conditions. Additionally, 15 knitted rib samples were produced using polyester yarn on a flat knitting machine. The main variable was the change in surface profile of the knitted rib, which governs the contact area when knitted rib is in contact with human skin. In addition, thermal conductivity, thermal absorptivity thermal resistance, air permeability, vapour resistance, and surface friction were measured. A subjective evaluation was also carried out to confirm the objective evaluation of the warm-cool feeling.

1.6 Contribution of study

This study offers a model for the prediction of thermal absorptivity of knitted rib under dry conditions. The second outcome of the study is the testing of functional knitted rib. Various tests prove that functional knitted rib made using polyester provides a better warm-cool feeling when it is in contact with human skin compared to traditional knitted rib. The third contribution of the study is the introduction of the "**Thermal contact absorptivity**" term which describes the thermal absorptivity with reference to contact points between two surfaces.

2 REVIEW OF THE CURRENT STATE OF ISSUES

2.1 Thermal absorptivity

Thermal absorptivity is a vital characteristic of fabrics and is the subject of numerous studies. It relies on the thermal conductivity of fibres, density, and the specific heat of the material. Thermal absorptivity demonstrates the capacity of a material to give a warm-cool feeling when a material is touched for a short time, approximately for two seconds. Thermal conductivity is anisotropic in nature and relies on the structure and chemistry of the material. The density of the fabric is depicted as the mass per unit volume of a fabric [kgm^{-3}]. It indicates the ratio of solid and void area in the fabric. Fabric consists of polymers (filaments), air trapped inside the fabric, and dampness in voids in the case of a humid environment. Thermal absorptivity [$Ws^{0.5}m^{-2}K^{-1}$] is linked with thermal conductivity [$Wm^{-1}K^{-1}$] and the thermal capacity of a fabric [$Jm^{-3}\,K^{-1}$]. Thermal capacity is a product of density [kgm^{-3}] and specific heat [$Jkg^{-1}K^{-1}$][2-7].

The term thermal absorptivity was created many years ago and is used to characterise the contact temperature when two semi-infinite bodies come into mutual thermal contact (boundary condition of the fourth order - you will have studied all this before). Hes' contribution was the proposal to use this parameter for studying textile fabric in contact with human skin, and the experimental verification of this idea. However, in the original theory, excellent and ideal contact of smooth surfaces was anticipated.

Nevertheless, thermal absorptivity can also be considered, when the body is subject to the boundary condition of the third order, see below

$$\alpha\,(t_1 - t_2) = -\,\lambda.\,\frac{dt}{dx} \qquad (2.1)$$

This is where the free fabric surface is exposed to an airflow where convection heat transfer takes place. Here, the time course (dynamic behaviour) of the fabric surface temperature is affected by the thermal absorptivity of the fabric. To distinguish the above case from the simple case of contact between two smooth surfaces, the term “thermal contact absorptivity" was introduced. Here, the effective heat conduction area is considered, when a fabric with a rough (rib, textured) surface comes into contact with human skin. When two large mutual body collide together 4th order boundary condition is used because of the semi-infinite body central temperature suitable for the linear function of thermal absorptivity (b) [$Ws^{0.5}m^{-2}K^{-1}$].

2.2 Absorption - an ever-lasting concept

Many fields of science use the term “absorption”. In civil engineering, it is used to explain the absorption of heat and water. In radiation, it is used to explain radiation absorption. In the field of chemistry, it is used to describe the process where atoms, molecules or ions enter some bulk phase, like, gas, liquid or solid material. Thermal absorption of construction material is given much importance in the construction industry, as discussed by Yang et al. [8]. Yang et al. have discussed shock absorption, radiation absorption, and damp absorption of material. In medical sciences, it depicts the movement of a drug into the bloodstream. In the field of physics, absorption of electromagnetic radiation is used to explain the energy of a photon taken up by matter. This term was first used to explain the warm-cool feeling of fabric by Hes [9].

2.3 Thermal absorptivity - an indicator of warm-cool feeling

Thermal absorptivity was discussed in detail by Nield and Bejan [10]. They considered the effect of porosity in the solution of the partial differential equation for transient heat conduction in porous bodies. However, the author, with his supervisor, has used porosity for the calculation of thermal absorptivity. The work of Nield and Bejan [10]shows that thermal absorptivity is a subject which has been discussed by many researchers. However, the first time this was used for the warm-cool feeling of fabric was by Hes [9].

Hes and Dolezal [6] have given the analytical solution of thermal absorptivity in detail. Their work provides the basis for the theory behind the thermal absorptivity for the warm-cool feeling of fabric. Hes [9] presented the concept of thermal absorptivity in 1987 and used this parameter for the prediction of the warm-cool feeling during an initial contact, for a short time, between human skin and the textile material. For this resolution, Hes introduced the concept of thermal contact for a time of τ between human skin and the fabric. This time is shorter than a few seconds. Hes assumed the fabric was a semi-infinite homogeneous fabric with a thermal capacity of ρc [$Jm^{-3}K^{-1}$] and an initial temperature t_2. Hes further said that an unsteady temperature field exists between human skin and fabric and its temperature is denoted by t_1. According to Hes and Dolezal, many ways were introduced to measure the static properties of fabric, like thermal resistance, thermal conductivity, and others. However, no method was introduced to measure the dynamic thermal conditions of fabric. Nevertheless, Kawabata and Akagi already pointed out its importance in 1977 and described it as having a "warm-cool feeling" quality. Hes and Dolezal [11] presented a new approach, which improved on the original concept by Yoneda and Kawabata and gave a numerical value to the warm-cool feeling. They used heat flux [q_{max}] transferred from the skin to the fabric as a measure of the warm-cool feeling of fabric. Hes and Dolezal [11] presented a new approach, which was originally based on the idea of Yoneda and Kawabata. This approach was novel because it was not based on the environmental temperature. They called it thermal absorptivity and denoted it with a *b*. The new concept of warm-cool feeling was based on other thermal and non-thermal properties of the fabric. It was the square root of the product of thermal conductivity, density, and specific heat of the fabric.

$$b = \sqrt{\lambda \rho c} \tag{2.2}$$

Thermal absorptivity and was introduced by Hes in 1987 [9]. The value calculated can be used to express the thermal handle of textile. In this approach, two different bodies are considered ideal homogeneous semi-solids with different temperatures. Moreover, the contact area is perpendicular to the normal line of heat flow. Time course is calculated using a one-dimensional partial differential equation

$$\frac{\partial T}{\partial t} = a\ \frac{\partial^2 T}{\partial x^2} \tag{2.3}$$

Where a is the thermal diffusivity of the fabric [m^2s^{-1}], which is considered a pseudo-homogeneous solid. Thermal diffusivity is defined as the ratio between thermal conductivity (λ) [$Wm^{-1}K^{-1}$] and the volumetric heat capacity (c) [$Jkg^{-1}K^{-1}$] and density (ρ)
[kgm^{-3}].

$$a = \frac{\lambda}{c\rho} \tag{2.4}$$

Hes and Dolezal [11] assumed thermal absorptivity of body 1 (b_1) is much higher than body 2 (b_2). When these two bodies are put together, the second body will take temperature (t_1) of the first body and the second body, in the long run, will keep its original temperature (t_2). The Gaussian error integral is a useful method to solve the issue using initial boundary conditions.

$$\frac{\mathrm{t} - t(x,\tau)}{t_1 - t_2} = erfc \frac{x}{\sqrt{\pi a_2 \tau}} \tag{2.5}$$

Using Fourier's law for one-dimension, heat flow from one body to another during a time τ can be determined. Fourier law states A rate equation that allows determination of the conduction heat flux from knowledge of the temperature distribution in a medium [12]. Fourier developed his theory of heat conduction at the beginning of the nineteenth century. It states that the temperature profile of an isolated system will evolve the conservation of temperature measured by position at time specific heat per unit volume, the thermal conductivity of the object Fourier's law may be applied, in particular, to a system in contact with two heat reservoirs at different temperatures [13].

$$q(x = 0) = -\lambda \frac{d\theta}{dx} \tag{2.6}$$

$$q(x = 0) = \frac{b}{\sqrt{\pi\tau}}(t_1 - t_2) \tag{2.7}$$

It is obvious from the final equation that the coefficient of heat absorptivity b enables an unambiguous calculation of heat flow between two bodies through the contact area. In addition, there are better chances of accuracy since the bodies have a finite dimension and the time is too short. It was assumed that due to the short time the two bodies are semisolid. Considering the depth of penetration of heat is less than the thickness of the body, *h₁* and contact time is:

$$\tau > \frac{h^2}{12.96a} \tag{2.8}$$

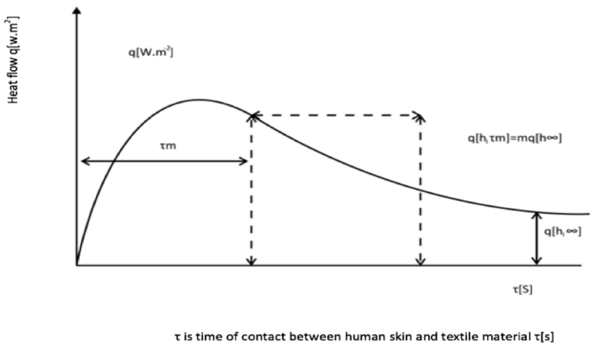


Figure 2-1 The process of heat flow in skin during thermal contact

The figure 2-1 is the process of heat flow when a body is in contact with some object with a fabric for a certain period of time and after 2 second the body comes in thermal equilibrium [11]. Boundary condition of first order is used in below equation

$$q = \frac{b(t_1 - t_2)}{\sqrt{\pi\tau}} \tag{2.9}$$

Where t is temperature, τ is time of contact between human skin and the textile material, and b is thermal absorptivity [$Ws^{0.5}m^{-2}K^{-1}$] and is calculated using the following equation. This was the final equation used by Hes [14] to measure the thermal absorptivity of any fabric

$$b = \sqrt{\lambda\rho c} \tag{2.10}$$

Where ρC is the thermal capacity of the material [$Jm^{-3}K^{-1}$] and λ is its thermal conductivity [$Wm^{-1}K^{-1}$]. Thermal absorptivity values range from 20 to 600 [15]. Higher values of thermal absorptivity indicate that there will be a cool feeling on touching the fabric for a very short period of time. Dry fabrics made up of cotton give the lowest value, and very wet fabrics give values above 600 [16]. Thermal capacity and thermal conductivity both properties have significant effect on thermal absorptivity, The effect of heat conduction and heat accumulation contrary to steady state heat transfer processes.

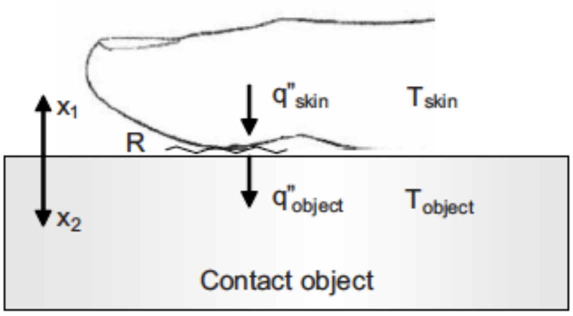


Figure 2-2 Schematic representation of the heat transfer during hand-object interactions

The above Figure 2-2 is the schematic representation of a contact object with human skin As long as the contact time is short enough for a semi-infinite body model to be valid both the skin and object can be modelled as semi-infinite bodies and the governing equations of the skin and object [17].

2.4 Surface profile and thermal absorptivity, Current state of issue

The literature provides many studies conducted to develop an equation for the prediction of the thermal conductivity of fabric. All such studies have ignored the role of fabric fibre alignment, which determines the surface profile. However, many researchers have pointed out that with a change in heat flow direction and material surface profile, there is a change in heat flux. Few examples are given here for the support of the idea that there is a change in thermal conductivity due to a change in material configuration, and this change leads towards the change in thermal absorptivity [9, 18-23].

Jiang et al. [24] have explained the effect of the directions of carbon fibres in detail. They conclude that the thermal conductivity of carbon fibres is influenced by the content and anisotropic nature of the fibre arrangements. They measured thermal conductivity of carbon fibres in a longitudinal direction that is 220-230 [$Wm^{-1}K^{-1}$] and the same material in the transverse direction has 110-120 [$Wm^{-1}K^{-1}$]. The difference is almost 100%. It shows that without considering the direction, the precise measurement of thermal conductivity is impossible. Anisotropy is the characteristic of a material that is directionally dependent. It is the opposite of isotropy, which implies similar properties in all directions.

Cheng et al. [18] studied thermal conductivity of 3-d braided fibre composites: experimental and numerical results. Their work shows that thermal conductivity depends upon the content and angle of braiding. Thermal conductivity of material with higher braiding angles will be higher. Their measurements showed that actual thermal conductivity is 21% higher than the calculated thermal conductivity. This shows that models developed by ignoring the direction of the fibres cannot predict thermal conductivity of a fabric because they have insufficient information about the alignment of the fibres.

Rengasamy and Kawabata [21] computed thermal conductivity of fibres from the thermal conductivity of twisted yarn. They compared thermal conductivity of fibres keeping all fibres aligned in a longitudinal form and by giving them a twist. They found that that there is a significant difference in thermal conductivity values of straight and twisted fibres at 60°**.** Longitudinal thermal conductivity is lower when the fibres are twisted. It shows the dependence of thermal conductivity on the fibre direction. Keeping this point in mind, the models developed to predict thermal conductivity must take into consideration the anisotropic nature of thermal conductivity. Any change in thermal conductivity will have a sure impact on the thermal resistance of the fabric. The discussion, above, shows that thermal resistance of the material can be increased by making it align more in a longitudinal form without changing the type and amount of the content.

Kawabata and Rengasamy [25] measured thermal conductivity of different yarns along their x-axis and in transverse directions. They concluded that thermal conductivity along their x-axis is much higher than thermal conductivity in the transverse direction. They concluded that Polyethylene filament yarn shows the highest anisotropy, followed by Vectrerbon, Kevlar, Technora, linen, high-tenacity polyester, and jute. Moreover, fibres with the same chemical structure and high-tenacity fibres have slightly higher longitudinal and lower transverse thermal conductivity values compared to apparel-grade fibres. In addition, high-strength polyester and nylons have high anisotropy in passing heat compared to ordinary fibres used in fabric manufacturing. Their final observation is that the effect of fibre chemistry on the thermal conductivity of fibres is more than the effect of the orientation of its molecules. It can be concluded from the findings of Kawabata and Rengasamy that when a fibre's thermal conductivity is measured, there is a significant role in the alignment of the fibres. Models developed without considering the configuration and alignment of the fibres cannot provide trusted values for their thermal conductivity and thermal resistance.

Militky [19] investigated the thermal conductivity of various knitted fabrics and developed a model using fabric porosity and fibre orientation. He used a value 1 when all fibres are perpendicular to the direction of heat flow, 2/3 for random fibre orientation and 5/6 for half of the fibres being random and the other half being normal to the direction of heat flow. Militky used the 5/6 value in his model. These were just assumed as no exact measurement was possible for the orientation of fibres. However, Mitra et al. [20] developed a model for the prediction of thermal resistance. They used artificial neural network models using four primary fabric constructions. Mitra et al. used ends per inch, picks per inch, warp count, and weft count as independent variables. They succeeded in predicting thermal resistance and achieved a correlation up to 0.90, which is quite significant. The question is about the suitability of any fabric made with the same content but with a small change in fibre orientation. For example, a small change in yarn twist per cm will significantly change the direction of fibres. Such a change will change the thermal conductivity, and ultimately the thermal resistance will be affected. Considering this factor, it can be said that models such as these are only fit for the fabric that was tested, and they cannot be used for any other fabric because of the anisotropic nature of thermal conductivity.

In the case of a woven fabric, the warp-weft intersections become compressed, while in a knit fabric the loops are stretched in one dimension while being compressed in the other. Because the loops are typically free to undergo much larger deformations than the compression of the intersections in a woven fabric, knits tend to be much stretcher than their woven counterparts [26]. Yu [27] measured the electrical conductivity of knitted fabric in the warp and weft directions. Yu concluded that the electrical conductivity of transverse knitted fabric is higher than the electrical conductivity in longitudinal knitted fabric. Yu has used this characteristic in the shielding effect.

Crow and Dewar [28] conducted a study to examine the vertical and horizontal wicking of water in fabrics and found a significant variation in the values. They concluded that it is not possible to develop an equation to predict the behaviour of wicking of water due to the significant influence of the fibre’s direction. Every fabric should be tested individually. When you consider this point, it can be seen that fibres have multiple directions in fabric. Particularly, after brushing, and there are lots of changes in direction. Even in yarn, fibres do not align in one direction. If 1 denotes horizontal alignment and 0 the transverse direction, there are many fibres with values between 0-1. Crow and Dewar proved that direction plays a significant role in wicking. Here one can use this observation for heat transfer. Wicking needs physical contact of the materials and water moves according to Fick’s law. The same rule is applied to heat flow through conduction, which needs physical contact between a hot and a cold area, and heat flow following Fourier’s law of heat transfer.

Taslim [29] conducted research to establish the fin effects on the overall heat transfer coefficient in a rib-roughened cooling channel. Taslim concluded that a rib structure is useful to protect the human body from heat loss because there is a layer of air present on the surface of the rib, which increases the thermal resistance of the fabric.

The surface profile plays an important role in thermal parameters; thermal conductivity, thermal resistance, and thermal absorptivity. Generally, in order to evaluate the handle of the fabric, fingers are slid on the surface of the fabric, compressed between the thumb and sign finger. The fingers containing more than 250 sensors per cm^2 are the crucial important organs determining the fabric quality. Tightening of the fabric between fingers gives idea about thickness, bulkiness, compressibility, thermal absorptivity and surface properties of the fabrics, whereas slipping of the fingers on the surface of the fabrics with a pressure renders about structure and elongation of the fabrics. Xu et al. [30] conducted a study to examine the impact of supercritical-pressure fluid flows and heat transfer of methane in ribbed cooling tubes. The work of Xu et al. tells that the height of rib wales helps increase heat transfer. However, at the same time, the air trapped on the surface of the rib cannot be ignored. Özdil et al. studied the impact of yarn properties on the thermal comfort of knitted fabrics [31]. Özdil et al. developed a 1x1 knitted rib and identified the thermal properties using various yarn varieties with distinct properties. They took yarn count, yarn twist, and combing process as independent variables and thermal resistance, thermal absorptivity, thermal conductivity, and water vapour permeability of samples as dependent variables.

Another aspect of knitted rib is the number of contact points between the human body and the surface of the fabric. Pac et al. [32] conducted a study on the process of a human hand touching the surface of a fabric with the skin at different temperatures compared to the fabric. During this process, heat transfers between the hand and the fabric. The first feeling is a warm-cool feeling. Pac et al. say that the significance of the warm-cool feeling depends on the contact points between the skin and the fabric. The fabric surface profile has a strong dependency on the structural parameters of the fabric, which include the physical and chemical properties of the fibre, the knitting or weaving pattern, fabric thickness, and porosity of the fabric. Usually, textile materials composed of fibres form complex networks of conducting parts that make multiple contacts. During deformation a number of mechanisms take place:

- The number of contact points changes;

- Fibres are extended;
- Fibre cross-section is decreased [33].

Clothing comfort can be induced by thermal, pressure-related, and tactile properties. Many studies have been conducted for various hypothetical examinations of heat transfer through fabrics [19, 34-39]. Their outcomes demonstrate that the procedure of high-temperature exchange through fabrics essentially happens through conduction. Thermal conductivity of dry fabrics needs to rely upon the structure and properties of the yarns or filaments. Crow [38] explains that two components that play a critical role in this context are the thickness of the fabric and the fibre arrangements. Parallel strands bring about three times higher thermal resistance in connection to the filaments, which are perpendicular to the fabric surface. Any change in thickness can change the thermal resistance of a fabric. The estimation of fabric thickness is very delicate, especially because of the compressibility of the fabric. A minor change in weight will change the thickness of the fabric. Such changes take place because of high porosity and jutting strands on the surface of the fabric. Similarly, thick fabric with a smooth surface essentially will not be influenced by pressure.

The above discussion shows a change in thermal conductivity of fabric is more likely to be due to a change in fibre alignment, surface profile, contact points, and surface roughness. It shows that when thermal conductivity changes thermal absorptivity will also change because thermal absorptivity is highly dependent on the thermal conductivity of the material. However, the literature does not provide any model that can predict thermal absorptivity due to change in contact points.

2.5 Thermal absorptivity and thermal contact absorptivity

Thermal absorptivity of any material is an indicator of a warm-cool feeling when the material is touched for a few seconds. Hes [14] used this term for the warm-cool feeling of fabric when it is put in touch with human skin. According to the equation proposed by Hes the thermal absorptivity depends upon the thermal conductivity and the heat capacity of the material.

This explanation shows that thermal absorptivity of any material correlates with the surface profile of the material. It is important to note that when thermal absorptivity is measured the surface of the material is totally covered with fluid. The fluid may be air, water or any liquid. In this case, a fluid covers the whole surface, and the surface profile plays no role in the thermal absorptivity of the fabric.

However, in this study, it was found that the surface profile played a significant role when measuring the values of thermal absorptivity of the fabric. It indicates that contact points are much more important when measuring the thermal absorptivity of any material. The role of contact points between two surfaces determines the thermal absorptivity of the fabric.

To describe this situation, we have coined the term “thermal contact absorptivity”. This is the first time this term has been used in the literature. According to this term, thermal contact absorptivity of any material depends upon thermal absorptivity and the contact points between two surfaces of the material. The problem of measuring the contact points between two surfaces was raised at this point. For this purpose, one needs the exact geometry of both surfaces and then has to apply probability rules to find the contact points. Precision is required to get the exact area of contact. We leave this topic for future studies. However, in this study, we used Alambeta which has a smooth surface. Therefore, there is no issue measuring the contact points of Alambeta plates. However, we still have to measure the contact points of the fabric. Three different techniques used to do this were geometrical calculation, image analysis, and paint techniques. It was observed there is no significant difference in values between the three methods. Any method could be used, depending upon the expertise and availability of the instrument.

Thermal contact absorptivity is a product of thermal absorptivity of any material in solid form, having no gaps and no fluid inside (air or moisture). Moreover, it has the maximum density. We can use the following equation to measure thermal contact absorptivity of any fabric. The following equation will be used to describe thermal contact absorptivity.

$$b_c = \mathrm{bA} \tag{2.11}$$

Where b_c indicates thermal contact absorptivity, b describes thermal absorptivity and A indicates the contact area in %. Using this equation, one can find the thermal contact absorptivity of any material. Material porosity is another factor, which plays a significant role in thermal absorptivity. As discussed by other authors, thermal absorptivity has a significant correlation with porosity.

Nield and Bejan [10] have worked on thermal absorptivity and porosity and provided in-depth knowledge about the role of thermal absorptivity and porosity.

For smooth fabrics (full contact area) b $_{Porous}$ = b $_{Full}$ PES 834. (1-P_{HW}) + b $_{air}$ This is valid for a smooth surface of 1m^2 area b rib = b full. (1-P_{HW}). In the case of rib, contact areas are lower as c<1 b rib = b full (1-P_{HW}). As the thermal conductivity of polyester is greater than air $\lambda_{PET} > \lambda_{air}$ the narrow contact layer of the heat absorptivity of mass is proportional to (1-P_2). The following equation has been developed to predict the thermal absorptivity of rib knit fabrics. This equation is based on simulation.

According to Nield and Bejan [10], one cannot ignore the role of porosity in thermal absorptivity. To adjust the porosity of any material, we made a significant change in our equation, and the modified equation is shown below.

$$b_c = \mathrm{bA}(1 - P_{HW}) \qquad (2.12)$$

Where b_c indicates thermal contact absorptivity [$Ws^{0.5}m^{-2}K^{-1}$] and A indicates the contact area in %. And P_{HW} is the ratio of density of the fabric and density of the material in solid form or in a cake form. In our case, it is the ratio of knitted rib made using polyester and thermal absorptivity of polyester in cake form [$Ws^{0.5}m^{-2}K^{-1}$] and using this equation, one can find the thermal contact absorptivity of any material.

Thermal comfort properties of textile materials have gained the attention of researchers in recent times. Although a plethora of researches have been conducted on the mechanical properties of textile fabrics, they have hardly played any role during the actual use of the fabrics. In contrast, comfort properties determine the way in which the heat, air and water vapour are transmitted across the fabric. During heavy activities, the body produces lots of heat energy and the body temperature rises. To reduce the temperature, the body perspires in liquid and vapour form. When this perspiration is evaporated to atmosphere, the body temperature reduces [40].

2.6 Bio polishing and thermal absorptivity

A soft and clean fabric surface, without any floating fibres, is one of the important factors for better marketing of clothing. The most common method for having such a clean fabric surface is the removal of protruding (floating) fibres from the surface of the fabric. Many studies have proved that enzymatic treatment, commonly called bio polishing, removes the floating fibres from the surface of fabric and gives a smooth surface to the fabric. Cellulose is highly effective in removing loose fibres from fabric surfaces, a process known as bio-polishing the concept of bio-polishing was first developed in Japan. The objectives were to create a smooth fabric and softening of the fibres without using traditional, topically applied chemicals. In cotton fabrics, the protruding fibres are removed by bio-polishing the fabric surface using celluloses. Celluloses are used to remove the fuzz or pills on the fibre or fabric surface, which will decrease the pilling propensity of the fabric [41].

There is a drastic change in the contact points after enzymatic treatment of fabric due to removal of protruding fibres from the fabric surface. A study was carried out to find out the correlation between thermal absorptivity and contact points. It was found that there is a significant correlation between thermal absorptivity and contact points. This was proven using objective and subjective evaluations methods. This experiment confirms the outcome of the study that surface profile plays a significant role in thermal absorptivity. Figure 2-3 [42] is a study in which it shows that enzyme treatment can remove the thick n thin impurities and make fabric surface smooth.

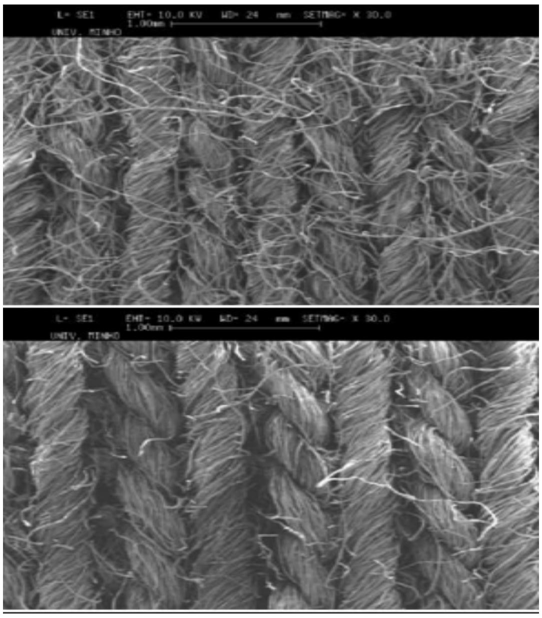


Figure 2-3 Effect of Bio-polishing on Fibres [42].

2.7 Thermal absorptivity and singeing

Singeing is the process in which fabric is passed through a flame to burn the protruding fibres from the fabric surface. It is very common for woven fabric made of cotton or cotton-polyester. It increases the contact points between human skin and the fabric surface. As we have discussed in depth there is a significant change in thermal absorptivity values due to a change in contact points. This experiment is further evidence that the surface profile plays a significant role in thermal absorptivity, which is called the thermal contact absorptivity. Singeing is essentially burning the free fibre ends that project from the fabric surface, using gas flame. It is typically used as an initial stage of fabric finishing the relatively harsh surface created by the singeing process can be made smoother through the heat and pressure of a calendaring process [43].

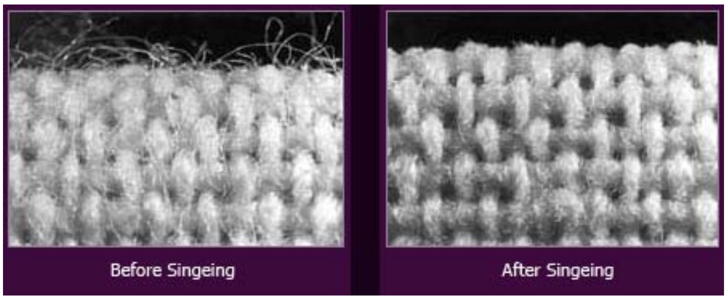


Figure 2-4 impact of singeing on fabric surface (osthoff-senge GmbH & Co. KG)

2.8 Thermal absorptivity of different fabrics

Figure 2-5 Alambeta Working machine for measuring thermal properties [44]

Hes [44] published the values of thermal absorptivity results for different fabrics using Alambeta. Results compiled by Hes [44] shows that thermal absorptivity of the fabrics is significantly affected by their structure and composition. Hes further stated that fibres and fibre polymers with higher moisture postulate a cooler feeling. It is obvious from the results that the warmest feelings can be found by using PVC, PP, PAN, whereas natural fibres like viscose, flax, cotton, and PAD show the coolest feeling. The selection of the material depends upon the wearer and the environment, e.g., cotton is better in a hot summer and polyester and wool are better in winter.

Table 2-1 Thermal absorptivity values of different fabrics [44]

AlambetaValues	Types of fabric
20 - 40	Micro-Fibre or fine PES fibre non-woven insulation webs
30 - 50	Low density raised PES knits, needled and thermally bonded PES light webs
40 - 90	Light knits from synthetic fibres (PAN) or textured filaments, raised tufted carpets
70 – 120	Light or rib cotton RS knits, raised wool/PES fabrics, brushed micro-fibre weaves
100 - 150	Light cotton or VS knits, rib cotton woven fabrics
130 - 180	Light finished cotton knits, raised light wool woven fabrics
150 - 200	Plain wool or PES/wool fabrics with rough surface
180 - 250	Permanent press treated cotton/VS rough weaves, dense micro-fibre knits
250 - 350	Dry cotton shirt fabrics with resin treatment, heavy smooth wool woven fabrics
300 - 400	Dry VS, Lyocell, silk weaves, smooth dry resin-free heavy cotton weaves (denims)
330 - 500	Close to skin surface of wetted (0,5 ml of water) cotton/PP (or spec. PES) knits
450 - 650	Heavy cotton weaves (denims) or wetted knits from spec. PES fibres (COOLMAX)
600 - 750	Rib knits from cotton or PES/cotton, knits from micro-fibres, if superficially wetted
> 750	Other woven and knitted fabrics in wet state
1600	Liquid water (evaporation effect not considered)

2.9 Instruments for the evaluation of thermal absorptivity of textile fabrics

Many instruments have been developed to measure thermal absorptivity. In 1983 Yoneda and Kawabata developed the first instrument. This instrument was able to measure the warm-cool feeling of fabrics precisely as described by Hes [44]. Yoneda and Kawabata used the maximum level of the contact heat flow q-max [$Wm^{-2}K^{-1}$] as a measure of momentary thermal characteristics. Kawabata published his measured values related to thermal-contact properties of the textile material. The name of their instrument was THERMO-LABO. It was the first attempt, and many people used this instrument. In 1986, the Technical University Liberec introduced its instrument for the objective evaluation of warm-cool feeling of textile material. It was based on a different concept. This computer-controlled semi-automatic non-destructive instrument was named Alambeta.

2.10 Heat transfer and airflow direction

One of the main characteristics of clothing is to provide protection from the environment and provide a balance between the human body and the environment. The textile industry is exploiting various techniques and methods to improve the functioning of clothing. One of those methods is to make changes in the structure of textile fabrics. One example is rib knit fabric, which has ribs on the surface. These ribs provide channels for airflow on the surface of the fabric The work of Vallabh [45] provides a detailed impact of tortuosity on the fluid mechanism. This study encompasses the concept of tortuosity, which had previously been considered only a function of porosity. Vallabh explains that tortuosity represents the structure of the pore volume in fibrous material. In this case, porosity size is not given priority, rather porosity direction is considered. Vallabh concludes that not only porosity, fibre size, fibre size distribution, pore size and pore size distribution, fibre orientation distribution, and pore channel tortuosity influence performance of the fluid.

The focus of this experiment was to find the impact of perpendicular and parallel flows of air on thermal resistance and water vapour permeability. Kast and Klan [46] have referred work of Churchill, W, Chu, HHS related to natural convection adjacent to perpendicular planes. Equation4 describes the role of vertical planes for both laminated turbulent flows.

The above discussion shows that there is a change in the heat transfer coefficient [HTC] due to a change in direction. Kast and Klan [46] have also discussed external flow and horizontal plates as discussed by W. H. McAdams has suggested the following equation to calculate the heat transfer coefficient in cases where the hot surface is facing up or down.

$$h = \frac{\lambda 0.54 Ra_L^{\frac{1}{4}}}{L}, 10^5 \leq Ra_L \leq 2 * 10^7 \tag{2.13}$$

$$h = \frac{\lambda 0.14 Ra_L^{\frac{1}{3}}}{L}, 2 * 10^7 \leq Ra_L \leq 3 * 10^{10} \quad (2.14)$$

In this experiment the heat transfer coefficient is not measured due to the change in directions of wales (Rib), rather we measure it's impact on thermal resistance and water vapour permeability. The case of natural convection with mass transfer has received considerably less attention. natural convection over vertical plates with variable normal mass transfer[47].

In this visualization, the laminar boundary layer and the wall layer in turbulent flow are both associated with the solution of order for flow with periodic disturbances of characteristic parameter ε [48]. The Reynolds number is important in analysing any type of flow when there is substantial velocity gradient (i.e. shear.) It indicates the relative significance of the viscous effect compared to the inertia effect. The Reynolds number is proportional to inertial force divided by viscous force [49].The flow is

- **laminar** when *Re < 2300*
- **transient** when *2300 < Re < 4000*
- **turbulent** when *4000 < Re*

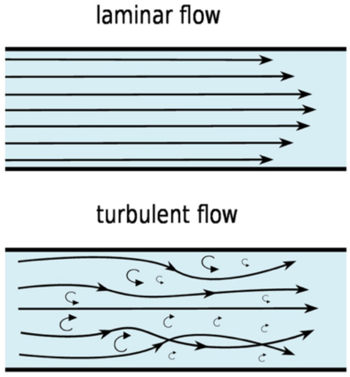


Figure 2-6: Pictorial working of Turbulent and Laminar flow

Source:http://www.cfdsupport.com/OpenFOAM-Training-by-CFD-Support/node263.htm

Due to the free convection principle, and due to the warm air's lower density it rises from the bottom to the top of the clothing of the wearer. This increases the vertical velocity of the air passing close to the outer surface of the fabric being worn and may increase heat and mass transfer between the environment and the wearer. Consequently, the effect of this free convection transfer may improve the thermo-physiological comfort of the wearer. A state of thermo-physiological comfort is reached when the body is relaxed and its sensors for “warmth and cold" are not activated i.e. the body is in thermal neutrality One of the interpretations of the IREQ index is to assess physiological strain in a cold environment, defined as the change in body temperature, skin wetness and the mean skin temperature [50].

It follows that the rib orientation in relation to the airflow direction should influence the resulting heat and mass transfer between the clothed body and the environment. This was confirmed in a far-reaching exploratory investigation of high-temperature exchange through woven and nonwoven fabrics, directed by Hes and Stanek, [22] in which, the Grasshoff number (Gr) depicts the impact of free convection, and it was found to be less than 1000. They further explained that the extent of high temperature exchanged by heat does not exceed 20% of the aggregate heat transfer. Heat transfer through radiation also depends upon the temperature. At low temperature, heat transfer through radiation is quite low because heat transfer through radiation depends upon the fourth power of temperature. Heat transfer in textiles by radiation is complicated, and the level of heat flow through a fabric is proportional to the difference between the fabric surface temperatures in Kelvins[51] .

2.11 Heat and mass transfer caused by forced convection

In the case that the wearer of the rib fabric is walking or running, the air direction will change. Its direction will be mostly horizontal (parallel to the ground), and its velocity v will exceed 1 m/s. Thus, the convection heat and mass transfer from the outer clothing is forced to be mostly laminar. For the calculation of the heat transfer coefficient, the experimental relationship for a plane with the length L can be used. Based on dimensionless numbers Nusselt Nu and Reynolds Re (Re = vL/v, where v means the kinematic viscosity of the fluid), the heat transfer coefficient between air and the solid object can be determined from the experimental relationship.

$$\alpha = 0.572 Re^{0.5} \tag{2.15}$$

All the samples were heated in the oven to 100°C to avoid the role of moisture in the fabric They were heated for almost 20 minutes, and the force convection phenomenon occurs here. Force

Convection is the mechanism of heat transfer through a fluid in the presence of a bulk fluid motion. Convection is classified as natural (or free) and forced convection depending on how the fluid motion is initiated. In natural convection, any fluid motion is caused by natural means such as the buoyancy effect, i.e., the rising of warmer fluid and falling of the cooler fluid. Whereas in forced convection, the fluid is forced to flow over a surface or in a tube by external means such as a pump or fan.

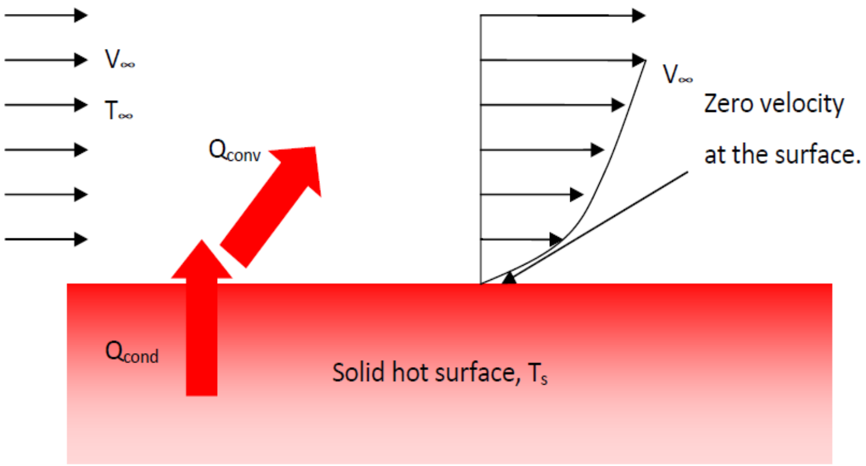


Figure 2-7: Forced convection

Source: http://www.sfu.ca/~mbahrami/ENSC%20388/Notes/F

The figure 2-7 shows how forced convection occurs. Heat transfer using movement of fluids is called convection. In natural convection, the flow is induced by the differences between fluid densities which is the result of temperature changes. Forced convection uses externally induced flows, such as wind. The heat transfer rate for convection is given by the following equation

$$q = -\lambda A\,(t_{surface} - t_{\infty}) \qquad (2.16)$$

Where λ is the convection coefficient, A is the surface area, and $t_{surface}$ and t_{∞} are the surface and ambient temperatures, respectively. The convection coefficient is a measure of how effective a fluid is at carrying heat to and away from the surface. It is dependent on factors such as the fluid density, velocity, and viscosity. Generally, fluids with higher velocity and/or higher density have greater λ.The calculated heat transfer coefficients then serve to calculate the total thermal resistance between the wearer´s clothing and the environment. This total thermal resistance consists of the thermal resistance of the fabric and the thermal resistance of the boundary layer. Here, the thermal resistance of the boundary layer R_{bl} is given by the inverted values of the previously determined heat transfer coefficients. A higher rate of heat transfer allows for a more efficient thermoregulatory mechanism. Should the rate of heat transfer decrease it is likely that core temperature would increase more rapidly [52].

2.12 Thermo-physiological comfort: function of heat and moisture transfer

Thermo-physiological comfort is the process that explains the changes occurring in a human body due to the alterations in temperature. It is a known fact that the human body is a thermal engine and produces heat and that it has a strong link with environmental temperature. Moreover, there is a constant change in the environment, and a human body has its own mechanism that takes necessary action when there is a change in skin temperature due to any variation in ambient temperature. During this activity, a thermal balance is required because our body tends to be at a steady state with the environment by keeping a thermal balance. Metabolism produces extra heat due to any activity transferred to the environment primarily through convection, radiation or a small proportion through conduction. If these mediums become insufficient, then evaporation is the last tactic to be called upon. The thermal engine of the human body functions on many factors, which are generally related to the physiology of a human body and its working conditions. The intensity of thermal generation is different in a child and an old man. The human body produces less heat when it is resting when compared to a running position. There are also many other factors, like, type and quantity of food, health conditions, age, etc. Knit fabric structures have microfilaments, such as superfine fibres on the external surface to reduce the porosity as much as possible so that the capillary phenomenon, in which moisture is discharged from the larger pores to the smaller pores, can be maximized [53].

The thermal comfort of a garment depends on several factors: heat and vapour transport, sweat absorption and drying ability. Total heat loss from skin results from the heat loss promoted by evaporation and the heat loss conveyed by conduction, convection and radiation. Under mild environmental conditions the loss of heat by evaporation takes place in the form of insensible perspiration which accounts for approximately 15% of the heat loss through the skin in the case of hard physical exercise or in tropical climates, the heat loss by evaporation is accompanied by sweating and the skin becomes covered with a film of water [54] .

Heat production is a regular function of the human body because it keeps the whole body active, as a constant function. How is the heat produced? It depends upon many factors, like level of activities, age, food eaten, etc. There is a need to dissipate the extra heat produced by the body. If this extra heat is not removed from the body, it would create discomfort for the human beings. There are two main ways to dissipate this extra heat, first through the skin, and then through the respiratory system. In respiration, we take moisture and heat from our lungs. The discussion about this process is out of the scope of this article. The second method where heat transfers through the skin is the domain where we need to argue in detail.

Our body has its own thermal regulation system. Heidorn [55] provides detailed information about it. This report reveals two sets of heat sensors that are present in the human body. The first sensor indicates the outflow of heat from a human body and lies close to the surface of the skin and is concentrated in the fingertips, the nose, and the bends of the elbow. The second sensor works in cases where the body temperature is low compared to the environment, and the body gains heat. It exists deeper in the skin and is concentrated in the chest, upper lip, chin, nose, and forehead. The core function of both sensors is to send signals to the brain, which takes action to respond to the effect of heat transformation from the body to the environment or vice versa. Thermal equilibrium can be established when parameters relating to ambience (air and radiant temperature, air velocity and humidity) and those concerning human physiology are balanced. Thermal energy is produced as a by-product of physical activities temperature to be stable heat losses need to balance heat production. This balance is given by the following equation:

$$Store = (Heat\ production - Heat\ loss) = (metabolic\ rate - external\ work) - (conduction + convection + radiation + evaporation + respiration)\ [56].$$

The thermal regulator of the human body is called the *hypothalamus*. It is a gland that lies at the base of the brain, just above the pituitary. It is set very close to 98.6^0 F (37^0 C) and keeps monitoring the body temperature through blood temperature because blood circulation is the main source of thermal distribution throughout the body. After sensing any change in blood temperature, the hypothalamus reacts accordingly and initiates a physiological response to increase or decrease the temperature of the body. During this entire movement, the body temperature goes very close to the set temperature of 98.6^0 F (37^0 C) and this is the most comfortable level for the human body. Any drastic change in blood temperature, low or high is uncomfortable because of the heat transfer phenomenon. In cold weather, the body loses its heat and to prevent this heat loss we use clothing. Whereas, in the hot summer, we wear lightweight and porous clothes so that our body heat may reduce and help in heat loss through convection, radiation, conduction, and evaporation. All such efforts are focused on satisfying the soft needs of a wearer and developing a thermal balance.

The human body generates heat that is removed from the body in many ways. Sweating and evaporation of sweat is one major phenomenon. Havenith et al.'s study proves that there is significant discrepancy between weight loss and the heat lost through evaporation. The error is more than 30%, which cannot be ignored [57].

Heidorn [55] further describes that in the case when there is a hot climate, the body starts sweating. These sweat starts evaporating and needs heat to convert this liquid into a gas. The human body surface provides this heat, and consequently, there is a cool feeling on the surface of the skin. [58].

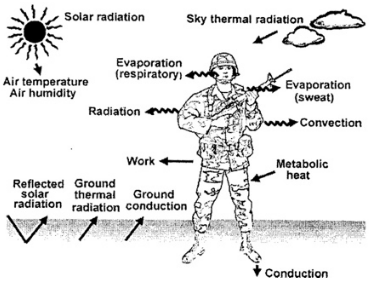


Figure 2-8: Heat exchange and the human body

Source : http://archive.cnx.org/contents/c6d531c8-2601-43f4-a58d-f7a9e2ca2750@1/module-1-situation-body-ambient-bondgraph-model-using-heat-flux-transducer

2.13 Influence of airflow direction on thermal resistance and water vapour permeability of rib knit fabrics

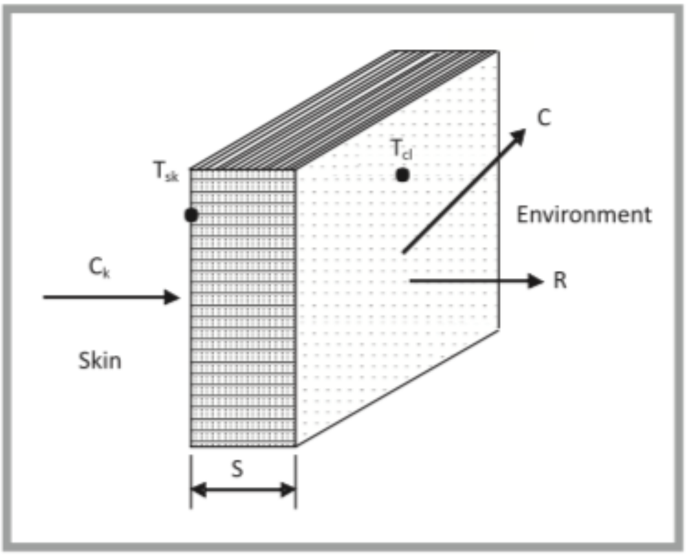


Figure 2-9: Heat energy flow through the clothing [59]

Figure 2-9 is demonstrating the heat energy flow from the clothing how heat is decreasing with the impact of convection. The heat energy ow through the clothing; R - heat loss by thermal radiation, W/m^2, C - heat loss by convection, W/m^2, C_k - heat loss by thermal conduction, W/m^2 (the heat steam from the body (skin) through the clothing), T_{sk} - skin temperature, ^{o}C, S - thickness[60]. The rate of heat loss by evaporation is the removal of heat from the body by the evaporation of perspiration from the skin. Evaporation always constitutes a rejection of heat from the body [59].

Ucar and Yilmaz [13] investigated the heat transfer coefficient α for natural and forced convection heat transfer for rib knit fabrics. Their experiment led to the conclusion that the tightness of rib knits has an influence on the heat transfer coefficient α for both situations. Both for natural and forced convection heat transfer and forced convection led to higher heat transfer coefficient α respectively to lowering of thermal resistance R. In this study, effort was focused on the investigation of the effect of the airflow direction (perpendicular or parallel) in relation to the orientation of the ribs on thermal resistance and water vapour permeability when forced convection heat transfer is used.

The measurements were carried out by using the small skin model tester called PERMETEST. This instrument is a product of SENSORA in the Czech Republic and is widely used for measuring water vapour permeability and thermal resistance [61-63]. The literature provides many studies related to the direction of fluid and its impact on the end results, but there is a lack of systemic measurement of the correlation between airflow direction and thermal resistance along with water vapour permeability.

$$R_{rat} = \frac{R_{par}}{R_{per}} \tag{2.17}$$

$$RWVP_{rat} = \frac{RWVP_{par}}{RWVP_{per}} \tag{2.18}$$

2.14 Subjective evaluation

Pan et al. [99] have talked about the issue appended with KES in measuring hand feel. They have proposed a subjective assessment of fabric for better understanding. Subjective assessment is one major part of this Study. Ozcelik et al. [13] have concentrated on the texture handle, and they inferred the conclusion that handle values rely on the mechanical properties of textures. It also relies on the individual who is doing the judging. Reeiners et al. [14] also confirm that subjective evaluation is as important as an objective evaluation. They directed a review to discover the distinction in human discernment and built up a huge contrast among various gatherings of individuals.

To enhance the target assessment of textures using instruments, many instruments were developed. However, the importance of subjective evaluation remained top. Therefore, the significance and importance of subjective assessment can't be dismissed [15-19].

Barker [18] concluded that objective and subjective estimations are both useful and are competent to fill certain needs. Nevertheless, none of these are completely competent to asses clothing comfort. An individual can give his or her perception about the skin sensation, warm or cool impact. However, they can't show overall comfort. There are many subjective evaluation studies, as discussed by Barker [18].

2.14.1 Kendall's concordance of conventional and functional knitted ribs

Kendall's coefficient of concordance [W] is applied to calculate the agreement among the group of subjective evaluators [64]. Kendall's coefficient of concordance [W] is calculated using the following equations:

$$W = \frac{12 * SSR}{K^2 n(n^2 - 1)} \tag{2.19}$$

$$SSR = \sum R^2 - \frac{\left(\sum R^2\right)}{n} \tag{2.20}$$

R is the total of the row and indicates the number of items and k is the number of sets of ranks. The Kendall Coefficient of concordance W shows the understanding of the subjective evaluator in assessing the specimens. If k (n-1) W is more critical value of chi-square, then one can dismiss the null hypothesis, which says that there is no normal ranking. The Kendall Coefficient of concordance W shows the understanding of the specialists when assessing the specimens. One should be careful when deriving the results because a significant value of W shows the significance, not the validity of the degree of association among different groups [64].

2.14.2 Median and 100 (1-α) confidence interval of conventional and functional knitted ribs

The established technique to calculate the middle of any data has numerous inadequacies when it is connected to a gathered or common data with classes. For better calculation, a couple of alterations are required to compute the middle of the data, which is made up of classifications and a request. Data that has an ordinal character has no metric. In such circumstance for Location estimator, the median XM can be utilized. The following methods have been proposed by Ott and Larson [64]:

$$XM = Me + 0.5 - \frac{F_{Me} - 0.5}{f_{Me}} \tag{2.21}$$

Where Me is the median category which is defined by inequalities:

$$F_{Me-1} \leq 0.5, F_{Me-1} \geq 0.5 \tag{2.22}$$

Where *FMe* is the cumulative relative frequency of the median category, *fMe* is the relative frequency of the median category. This characteristic can be used to explain the mean evaluation of hand or other characteristics whose evaluation is on an ordinal scale.

For some hands-on resolutions, the confidence interval of population median *Mp* is more useful than point estimation *XM*. Computation of a 100(1-α) confidence interval of *Mp* consists of the following steps. At first two cumulative frequencies *(*F^*_D*,* F^*_H*)*$\boldsymbol{F^*_D, F^*_H}$are calculated from the relation.

$$F^*_D, F^*_H = 0.5 \pm \frac{0.5\mu_{1-\alpha/2}}{\sqrt{n}} \tag{2.23}$$

The sign + is used for the calculation $F^*_H$$\boldsymbol{F^*_H}$and sign – for calculation $F^*_{D.}$ $\boldsymbol{F^*_D}$. These frequencies are used for determining categories D and H. The 100(1-α) confidence interval is then given by (D-0.5+d, H-0.5+h), where d and h are corrections.

Analogous to definition of category Me categories D and H are determined by inequalities:

$$d = \frac{F^*_D - F_{D-1}}{f_D} \text{ and } h\frac{F^*_H - F_{H-1}}{f_H} \; \boldsymbol{d = \frac{F^*_D - F_{D-1}}{f_D}} \; \boldsymbol{h = \frac{F^*_H - F_{H-1}}{f_H}} \tag{2.24}$$

2.15 Knitted fabric structure and porosity

In this study knitted rib has been used to measure the actual values of thermal parameters. It is imperative to have a short discussion about knitted rib and its structure to understand the whole work better.

The investigated area can be divided into three groups of problems or geometrics

1. The macro area consists of the wales and courses and spaces between wales and courses.
2. The micro area consists of the inner parts of the yarn, space between fibre to fibre, opening due to textured structure of yarn, space in the inner side of fibre (amorphous region of fibre).
3. Surfaces of fabric, which has direct interaction with the environment.

The volume of the fabric is filled with polymers, water, air, and any other foreign particles, such as textile auxiliaries, etc. The final value of thermal conductivity and thermal resistance of a fabric entirely depends upon the ratio and configuration of these substances.

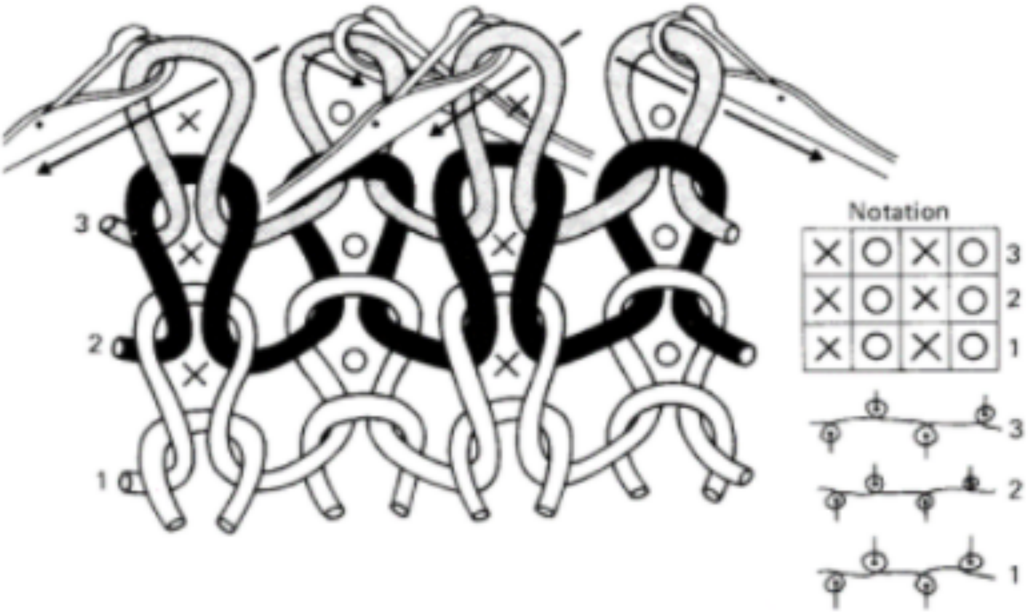


Figure 2-10: Schematic diagram of knitted rib(1x1) [65].

2.16 Knitted rib and its structure

Knitted rib is a fabric knitted on a double knit flat or circular knitting machine. In the rib structure, the face and back loop occurs along the course sequentially, and the loops of a wale are the same on both sites. The machine, which is used to produce the rib fabric, is known as a rib manufacturing machine. Interlock fabric is also knitted on a double-knit machine. Moreover, one of the significant differences between rib and interlock fabric is the occurrence of wales. In rib structure, wales are found alternatively on front and back sides. With interlock fabrics, the wales on both sides are present exactly behind one another. This arrangement makes rib more rigid and increases its grip as compared to interlock.

The knitted stitch is basic unit of intermeshing, with difference appearance on both sides i.e.; the face (front) and reverse (back) loop side. Fabrics using the rib stitch are also known as double jersey or double face fabrics. The rib stitch has excellent width wise elasticity, especially fabric knitted in a 2 x 2 rib structure. Because of this inherent elasticity, yarn having a relatively low elasticity can be used. Consequently, the rib stitch is widely used in sleeve trims, sweater waistbands and collars. With rib structures, extensions of up to 140% can be achieved. However, as the number of wales in each rib increases the elasticity decreases, as the number of changeovers from reverse to front reduces.

An advantage of the rib stitch fabrics is that they do not curl at the edge and thus create no difficulty in cutting. The reason for the lack of curling is that the wales tend to counterbalance each other's effect.

- Doubled sided
- Thick/medium weight
- Excellent width stretch/recovery
- Balanced structure/fairly elastic [66].

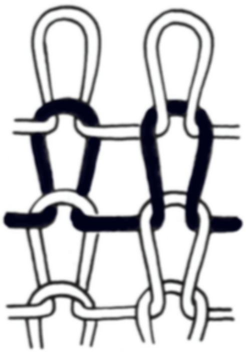


Figure 2-11 Rib stitch formation [66].

Figure 2-11 shows the formation of loop insertion in knitting of knit rib [66] .The important thing in knitted rib is its structure and surface profile. There is a strong tendency in rib structure to contract or shrink horizontally, which produces small pleats. Due to its stretching tendency, knitted rib is commonly used for cuffs, waistband, hems, sweaters, and for fitted garments. There is a built-in elasticity in knitted rib, which depends on the number of knit/purl transitions, which are expressed in numbers like; 1x1, 2x2, etc. knitted rib having the structure 1x1 is more elastic than 2x2 ribbing.

Knitted rib is made using two sets of needles. One is used to make the front, and other is used to make the back. No sinker is used, which is required for single knit fabric, i.e., single jersey; fleece etc. A single strand of yarn is used to make both sides. However, different designs are possible on both sides. The dominant feature of knitted rib is its surface profile. Its surface is featured with two types of areas; one is the base and other is the elevated area.

2.17 Knitted rib and its surface roughness

Consumers use their sense of touch instinctively to evaluate a garment's quality and faculty for specific use. The roughness of textiles is an important parameter for customers' choice of garments. The physical roughness describes the geometry of a surface. The roughness is decorated as a characteristic parameter of a surface that intervenes in the variation in normal strength and tangent strength [67].

3 METHODOLOGY DEVELOPMENT, RESULTS AND DISCUSSION .

3.1 Porosity, thermal absorptivity, and heat capacity

Nield and Bejan [10] said that porosity plays a vital role in the transient heat conduction in porous bodies , but they did not use it for the determination of thermal absorptivity of porous bodies like textiles. However, work on the thermal absorptivity of textiles as porous bodies was published by the author of this thesis and his supervisor, as explained in detail in this thesis. It can be said that the authors have created a local thermal equilibrium, which is depicted by the following equation

$$t_s = t_f = t \tag{3.1}$$

Where t_s and t_f indicates the temperature of the fluid and solid. The authors assume that the heat flow is only in one direction. The authors admit that the situation is quite complex, and the solution is only possible by considering a simple heat transfer process.

$$(1-\varphi)(\rho c)_s \frac{\partial T_s}{\partial t} = (1-\varphi)\nabla.(k_s\,\nabla T_s) + (1-\varphi){q^{///}}_s \tag{3.2}$$

$$\varphi(\rho c_P)_f \frac{\partial T_f}{\partial t} + (\rho c_P)_f V.\nabla T_f = \varphi\nabla.\left(k_f\,\nabla T_f\right) + \varphi {q^{///}}_s \tag{3.3}$$

Here the subscription, s and f represent solid and fluid phases, c is the specific heat of solid, cp refers to specific heat at constant pressure of fluid, k indicates the thermal conductivity and q is heat produced (Wm^{-3}) heat thermal conductivity. In both equations, the authors have assumed that the surface porosity is equal to the porosity. This is pertinent to the conduction terms that Nield and Bejan [10] reached on the final equation 3.4. This equation shows that the heat capacity is a sum of the heat capacity of fluid and solid but adjusted using φ, where 1- φ is the ratio of the volume occupied by solid to the total volume of the element, which is referred as porosity.

$${q^{///}}_m = (1-\varphi){q^{///}}_s + \varphi {q^{///}}_f \tag{3.4}$$

The above discussion shows that heat capacity is mainly an outcome of the porosity of the material. Every material is composed of fluid and solid. As discussed thermal absorptivity is a product of heat capacity. Based on this discussion, it can be concluded that thermal absorptivity is highly linked with porosity.

Porosity indicates the ratio of fabric and fibre density. It is the area, which represents the space in the fabric. This may be at the macro level or at the micro level. It demonstrates the ability of fabric to trap air or water. Higher porosity means that fabric has more space for air and water. The amount of water and air in a fabric has a significant impact on its thermal conductivity, thermal absorptivity, and thermal resistance. It shows that porosity plays a significant role in thermal resistance [68-70].

The following equation is the most suitable for the calculation of porosity of fabric. It takes into account the macro and micro areas of fabric as proposed by Militky [19].

$$\varepsilon = \frac{\rho_w}{\rho_f} \tag{3.5}$$

$$P_d = 1 - \varepsilon \tag{3.6}$$

Where:

P_d is porosity "density" with reference to density, ρ_w and ρ_f are the densities of the fabric and fibre respectively. In this equation ε represents the amount of fibre ratio in the total system. To quantify the density of a fabric, the weight of fabric per square meter was measured and used. It is obvious from the equation that porosity within Fibres and between yarns has also been included here. This equation describes the porosity of the fabric. In other words, it describes the amount of gap available in the fabric that can be filled with air or moisture. This study preferred the Militky method for measuring porosity. A microscope was used to identify the porous area in a fabric, the doted area below figure shows the content of the fibre and rest is the porous area of the fabric. The average porosity is above 70 %. The images show that the fabric contains quite a bit of space in the shape of airgaps. This is due to the knitted structure property, and insertion of loops makes this sample. The microscopic image of the fabric is just a counter of porosity calculated by the formula and shows that more than 70% of area of fabric is porous.

3.2 Porosity calculation

Porosity of knitted fabric was calculated by two methods and both have the same results, porosity plays a vital role in the thermal properties of the fabric. The influence of several factors such as fabric structure, thickness, porosity, fibre type and moisture content on the thermal properties of common fabrics has been observed by previous researchers. The porosity determines the moisture content, which further influences the thermal conductivity of the structure [71].

Das calculated the porosity of fabric by

$$\text{Porosity (p)} = 1 - \frac{\textbf{Volume of the yarn in unit cell}}{\textbf{volume of the unit cell}} \qquad (3.7)$$

Same formula was used in this study to find the porosity of the sample study however porosity was measured using another formula and got the same results. The model of Militky was used to find the porosity of the fabric [72]

$$P_{HW} = 1 - \frac{\text{volume coverd by yarn}}{\text{whole accessible volume}} \qquad (3.8)$$

Table 3-1: Porosity by density

Sample no	GSm	[Kg]	h[mm]	h [m]	Porosity on volume base				
					Volume of fabric [m^3]	Density [$Kg.m^{-3}$]	Density of fibre	Fibre to fabric ratio	Porosity
1	501	0.50	1.40	0.0014	0.0014	357.86	1300	0.28	0.73
2	400	0.40	1.40	0.0014	0.0014	285.71	1300	0.22	0.78
3	541	0.54	1.40	0.0014	0.0014	386.43	1300	0.30	0.70
4	560	0.56	1.40	0.0014	0.0014	400	1300	0.31	0.69
5	462	0.46	1.40	0.0014	0.0014	330	1300	0.25	0.75
6	523	0.52	1.40	0.0014	0.0014	373.57	1300	0.29	0.71
7	477	0.48	1.40	0.0014	0.0014	340.71	1300	0.26	0.74
8	471	0.47	1.40	0.0014	0.0014	336.43	1300	0.26	0.74
9	485	0.49	1.40	0.0014	0.0014	346.43	1300	0.27	0.73
10	548	0.55	1.40	0.0014	0.0014	391.43	1300	0.30	0.70
11	540	0.54	1.40	0.0014	0.0014	385.71	1300	0.30	0.70
12	540	0.54	1.40	0.0014	0.0014	385.71	1300	0.30	0.70
13	378	0.38	1.40	0.0014	0.0014	270	1300	0.21	0.79
14	422	0.42	1.40	0.0014	0.0014	301.43	1300	0.23	0.77
15	447	0.45	1.40	0.0014	0.0014	319.29	1300	0.25	0.75

$$\boldsymbol{P_{HW} = 1 - \frac{v_y}{v_V}} \tag{3.9}$$

Where P_{HW} represents the porosity based on volumetric density, $\boldsymbol{v_y}$ shows the volume covered by fibre, and $\boldsymbol{v_V}$ depicts the whole accessible volume.

Table 3-2: Porosity by Volumetric method

Yarn volume				**Unit volume**			
Yarn diameter [inch]	**Yarn diameter [m]**	**r2**	**pai*r2*l**	**Wale [cm]**	**[m]**	**Course [cm]**	**Course [m]**
0.007985957	0.000202947	1.03E-08	1.55E-10	0.080645161	0.000806452	0.092592593	0.000925926
0.007985957	0.000202947	1.03E-08	1.52E-10	0.089285714	0.000892857	0.076923077	0.000769231
0.007985957	0.000202947	1.03E-08	1.49E-10	0.104166667	0.001041667	0.089285714	0.000892857
0.007985957	0.000202947	1.03E-08	1.58E-10	0.106382979	0.00106383	0.083333333	0.000833333
0.007985957	0.000202947	1.03E-08	1.58E-10	0.119047619	0.001190476	0.083333333	0.000833333
0.007985957	0.000202947	1.03E-08	1.58E-10	0.096153846	0.000961538	0.092592593	0.000925926
0.007985957	0.000202947	1.03E-08	1.58E-10	0.111111111	0.001111111	0.111111111	0.001111111
0.007985957	0.000202947	1.03E-08	1.42E-10	0.104166667	0.001041667	0.083333333	0.000833333
0.007985957	0.000202947	1.03E-08	1.36E-10	0.125	0.00125	0.076923077	0.000769231
0.007985957	0.000202947	1.03E-08	1.36E-10	0.119047619	0.001190476	0.096153846	0.000961538
0.007985957	0.000202947	1.03E-08	1.62E-10	0.096153846	0.000961538	0.083333333	0.000833333
0.007985957	0.000202947	1.03E-08	1.58E-10	0.12195122	0.001219512	0.1	0.001
0.007985957	0.000202947	1.03E-08	1.65E-10	0.142857143	0.001428571	0.111111111	0.001111111
0.007985957	0.000202947	1.03E-08	1.65E-10	0.1	0.001	0.083333333	0.000833333

0.007985957	0.000202947	1.03E-08	1.52E-10	0.12195122	0.001219512	0.1	0.001
0.007985957	0.000202947	1.03E-08	1.52E-10	0.138888889	0.001388889	0.111111111	0.001111111
0.007985957	0.000202947	1.03E-08	1.55E-10	0.128205128	0.001282051	0.090909091	0.000909091
0.007985957	0.000202947	1.03E-08	1.55E-10	0.128205128	0.001282051	0.111111111	0.001111111

Volume of unit	**Ratio of yarn volume and unit cell volume**	**Porosity**
1.43E-09	0.108814667	0.891185333
1.37E-09	0.110627567	0.889372433
1.82E-09	0.081754631	0.918245369
1.77E-09	0.089442478	0.910557522
2.04E-09	0.07782397	0.92217603
1.83E-09	0.086718138	0.913281862
2.55E-09	0.062173531	0.937826469
1.75E-09	0.08121161	0.91878839
1.91E-09	0.071254633	0.928745367
2.58E-09	0.052537827	0.947462173
1.65E-09	0.097843066	0.902156934
2.72E-09	0.058151496	0.941848504
3.38E-06	4.88E-05	0.999951229
1.67E-06	9.89E-05	0.999901064
2.40E-06	6.33E-05	0.999936747
2.87E-06	5.29E-05	0.999947059
2.31E-06	6.73E-05	0.999932749

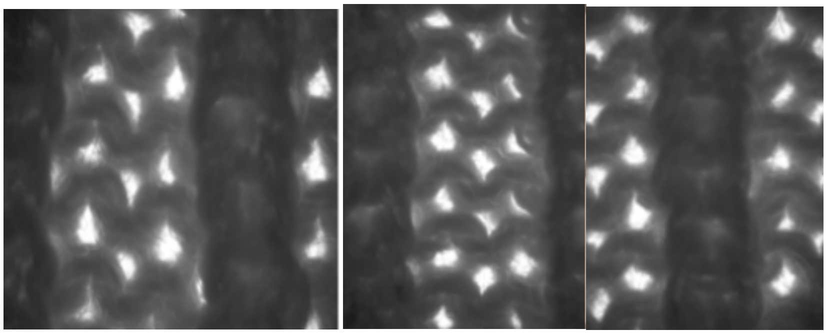


Figure 3-1: White dots showing porous media in studied sample (microscopic view)

Samples were made by using 100% pure polyester yarn no blending with any other to avoid the role of moisture impact on thermal absorptivity. The core focus of this study is to evaluate the impact of relative contact are on thermal absorptivity of the fabric. Comfort properties of polyester fabric are much better in terms of wicking when compared with polyester micro/cotton blends and pure polyester non- micro Fibre fabrics [73]. Better wicking is found in samples having greater proportion of polypropylene and they also dry fast. Maximum water vapour permeability and air permeability is seen on fabrics having polypropylene on both faces of fabrics [74] .

Polyester yarn was purchased from local supplier and yarn used for making studied samples properties is as below 100% polyester spun yarn was used all above data was supplied by manufacturer.

Table 3-3: Physical properties of the yarn used in this experiment

Tenacity [gm/den]	**Fineness [dtex]**	**Yarn tenacity [cN/dtex]**	**Diameter [mm]**	**Tensile strength [Mpa]**
6.3	56	4.05	0.7	450
Number of fibrils	**Elongation at break [%]**	**Twist [T/m]**	**Linear density [Denier]**	**Twist**
36	22%	495	1	S/Z
Yarn count	**Weight of cone [kg]**	**Moisture Regain [MR%]**	**Cut length [mm]**	**No of crimps**
20s/2	1.67	0.40%	38	12

Knitting processes are usually classified into two categories: warp and weft knitting, referring to the direction in which two consecutive loops of the same yarn are knitted. In the specific vocabulary related to weft knitting processes, a set of stitches made by a single needle, aligned in the warp direction, is called a wale. A course is a set of stitches aligned in the weft direction and each knitted successively by a different needle [75].

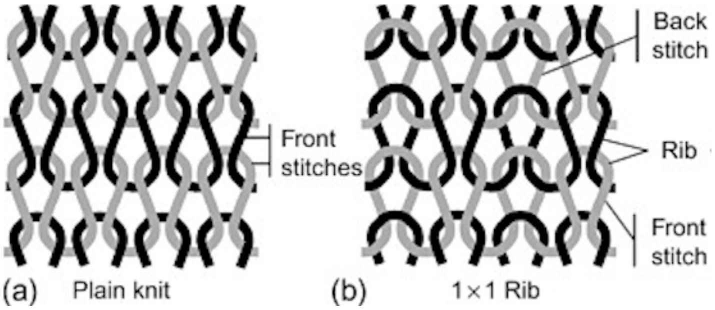


Figure 3-2: Schematic diagram of a weft knitted principle for rib structure [75].

3.2.1 Cam setting

Cam plays an important part in knitting machine and its movement is from right to left while needle moves in opposite direction. It's working mechanism that it pushes the needle foot to move up and down. It's an independent knitting machine setting. Together with yarn tension settings, yarn friction properties, knit structure, etc, it determines loop length. However, it is not a knit parameter describing the fabric but rather a machine parameter to engineer a fabric to a particular set of fabric specifications (viz. loop length, GSM, etc). It may vary between knitting machines and even for the same machine during its lifetime (e.g. state of machine maintenance, needle wear and tear, variable mill conditions (e.g. temperature, relative humidity).

3.2.2 Knitting parameters

The five most important knit parameters are

- Yarn Count (Tex)
- Yarn Friction,
- Loop Length (mm)
- Knit Structure (plain, rib) and

- Relaxation State.

3.2.2.1 Yarn count

Yarn count play an important role in knitting and it is determined by the knitter for more fineness of yarn more yarn count will be used, and yarn will be finer.

3.2.2.2 Yarn friction

It was managed by prior yarn processing and pre-treatment; it played a great role in yarn machine for loop length .

3.2.2.3 Loop length

It depends on the need of required fabric and it can be controlled by yarn tension settings , cam settings and yarn quality.

Figure 3-3: Flat knit machine for the manufacturing of the studied samples

Figure 3-4 Flat knit machine used for the manufacturing of studied samples (Yarn insertion)

A flat knit machine was used in making 100% PES knit rib samples, and a gauge set used to make samples GSM from 400 to 600. The machine gauge of knitting machines is a measure expressing the number of needles per a unit (normally 1 inch) of the needle bed width or circumference. Machine gauge is defined in various units (systems) in various countries. Definition of gauge also depends on the types of knitting machines. Most popularly, it is defined in English system as the number of needles per inch[76]. It's a fact that knitted rib is fairly flexible upon application of any external force/stretching. However, in our experiment, samples were laid flat on the surface to avoid external elastic forces/stretches during calculations for the contact area.

There are two types of weft knitting machines circular and flat machine studied samples were manufactured on flat machine, the two primary forms of flat knitting machines are the V-bed machine, which is useful in the production of spacer fabrics and the flat purl machine. The V-bed has the potential for making both jersey and rib fabrics.

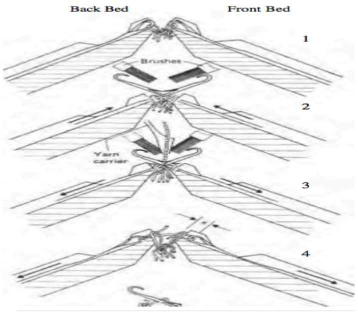


Figure 3-5 Knitting principle of V bed machine (Flat knit machine)

Source : https://textilelearner.blogspot.com/2012/01/v-bed-knitting-machine-working-process.html

Where:

Position 1: The rest position. The tops of the heads of the needles are level with the edge of the knock- over bits.

Position 2: Clearing. The needle butts are lifted until the latches clear the old loops

Position 3: Yarn Feeding. Yarn is fed to the needles as they begin to descend.

Position 4: Knocking over. The new loops are drawn through the old loops, thus completing the cycle [77].

Pure polyester yarn was used to avoid the factor of moisture effecting the thermal absorptivity. Simple wash without any soap and no finishes applied only simple wash done to eliminate the role of shrinkage.

In knitted and woven fabrics, the curvature of yarn axis is comparable with yarn diameter. It is one of the reasons why yarn cross-section in fabric is non-circular, because bend induces tensile stress on one side on the yarn and pressure on the opposite side. Second reason is mutual force between yarns in contact (in so called binding points)[78].

Rib knit fabrics can be characterized either by correcting the relations derived for single needle bar fabrics on the basis of the differences to be found between the two types of fabric or by generalizing the formulae obtained, to such an extent that they may he applied more or less to any type of weft-knit fabrics. These investigations are primarily based on geometrical analysis, as the various types of fabrics showing otherwise also different properties have been developed on the basis of the differences in the geometrical arrangement of the yarn [79] .

The loop axis is divided into elements (particles) with equal length. Since the forces in each node are calculated, if this initial form is not the optimal loop form, after several computational steps this optimal form will be reached. Since the contact forces change mainly the cross section of the yarns of current example, the changes in the loop axis are small and cannot be identified [78].

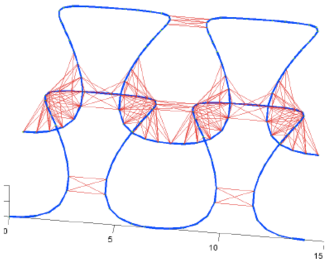


Figure 3-6 Loops with directions of acting contact forces [78].

Properties of rib knit fabrics were investigated to consider it for basic fabric before rib knits were only used in trims for cuff or waist band etc. Investigations were concerned with rib knit fabrics which could be considered as basic fabric having the simplest structure of weft-knitted double-knit fabrics. In order to render the loop diagram more descriptive it is shown in a somewhat elongated form in. This type of fabric is often used for producing fully fashioned fabric sheets requiring exact dimensions. In the technical literature there are many calculations and investigations dealing with the determination of the values of the main dimensions of fabrics.

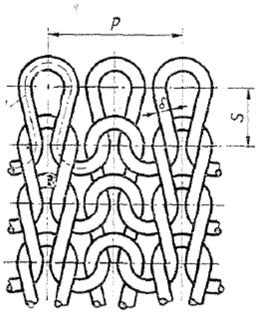


Figure 3-7 Loop diagram of rib knit fabric diameter of the yarn (δ) the wale spacing (P), the course spacing (S) [80] .

3.3 Testing of knitted rib

This study used the following tests to establish the impact of thermal parameters on the fabric by changing the relative contact area of fabric with human skin.

1. Thermal conductivity using Alambeta
2. Thermal absorptivity using Alambeta
3. Thermal resistance using Alambeta
4. Thickness using Alambeta
5. Surface profile using image analysis
6. Air permeable in two directions
7. Water vapour permeability
8. Surface friction using the Kawabata Evaluation System (KES)
9. Subjective evaluation for warm-cool feeling

3.4 Sample development and description

For experimental purposes, the following three sets of fabrics were produced.

1. Knitted rib fabric using pure polyester spun
2. Knitted rib using polyester and cotton blends for enzymatic treatment
3. Fabrics for singeing effect

Table 3-4 Sample description.

Sample no	Rib Type	Wales per [cm]	Courses per [cm]	Stitch length [mm]	Square mass [gm^{-2}]	Machine Gauge [gg]
1	1x6	10	12	1.2	501	12
2	1x3	11.2	13	1.3	400	15
3	1x2	9.6	11.2	1.12	541	11
4	2x3	9.4	12	1.2	560	10
5	2x4	8.4	12	1.2	462	14
6	3x4	10.4	10.8	1.08	523	12
7	1x4	9	9	0.9	477	14
8	2x2	9.6	12	1.2	471	13
9	1x1	8	13	1.3	485	13
10	3x3	8.4	10.4	1.04	548	11
11	4x4	10.4	12	1.2	540	11
12	2x1	8.2	10	1	540	11
13	4x3	7	9	0.9	378	16
14	4x2	10	12	1.2	422	15
15	3x1	8.2	10	1	447	14

3.5 Instruments used for testing of knitted rib

Modern and highly sophisticated instruments were used to test the different parameters of knitted rib. A brief description of these instruments is given here.

3.5.1 Almabeta: A unique instrument for testing thermal parameters

The figure 3.8 shows a simplified schematic of the Alambeta. An ultra-thin heat flow sensor 4, has been applied and is attached to a metal block 2. Block 2 has a constant temperature, which varies from the sample temperature. At the start, the measuring head 1, which contains the heat flow sensor, drops down and touches the sample *5.* The sample sits on the instrument base 6 under the measuring head. During the touch, the surface temperature of the sample swiftly fluctuates, and the instrument's computer registers the heat flow. In the meantime, a photoelectric sensor calculates the sample thickness. The computer then processes the data. Then a mathematical calculation is made to give the character of the transient temperature field in the thin slab subjected to different boundary conditions. To create a real-life situation of a warm-cool feeling, the instrument measuring head is heated to 32ºC (see the heater 3 and the thermometer 8), which corresponds to the average human skin temperature. The fabric is kept at the room temperature 22ºC. The touch is completed in a very short period of time, (0.07 seconds), and the heat flow sensor measures the heat flow, which is quite similar to human skin. By doing so, a full signal response is achieved within 0,2 sec.

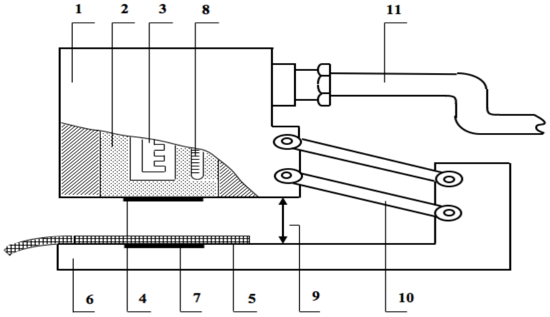


Figure 3-8: Simple scheme of the Alambeta

3.5.2 Permetest to measure water vapour resistance

Sensora Instruments, in the Czech Republic, produced Permetest, another fast response measuring instrument (skin model) for the non-destructive measurement of water vapour and thermal resistance of fabrics. This instrument gives full response while measuring the water vapour permeability (resistance) of synthetic fabrics within 2-3 minutes and for dry thermal resistance the measurement is completed within one minute (for the simulated human skin temperature 35°C). Because of its size and easy operation, the unit can be operated in the laboratory and in factory conditions. Small samples can be measured using Permetest. The company used a new concept using high sensitivity to measure very small changes in the amount of water absorbed in the fabric during an unsteady state of diffusion and records the heat of absorption and the effects of the fabric composition and structure [61-63]. Permetest presents in a digital format both on the instrument display and on the screen of any modern computer. The instrument provides all kinds of measurements, which are very similar to the ISO Standard 11092 and the results are evaluated by an identical procedure as required in ISO 11092 [81]. In this study, Permetest has been used to check the effects of the surface profile on water vapour resistance and permeability. The figure, below, shows the working of Permetest.

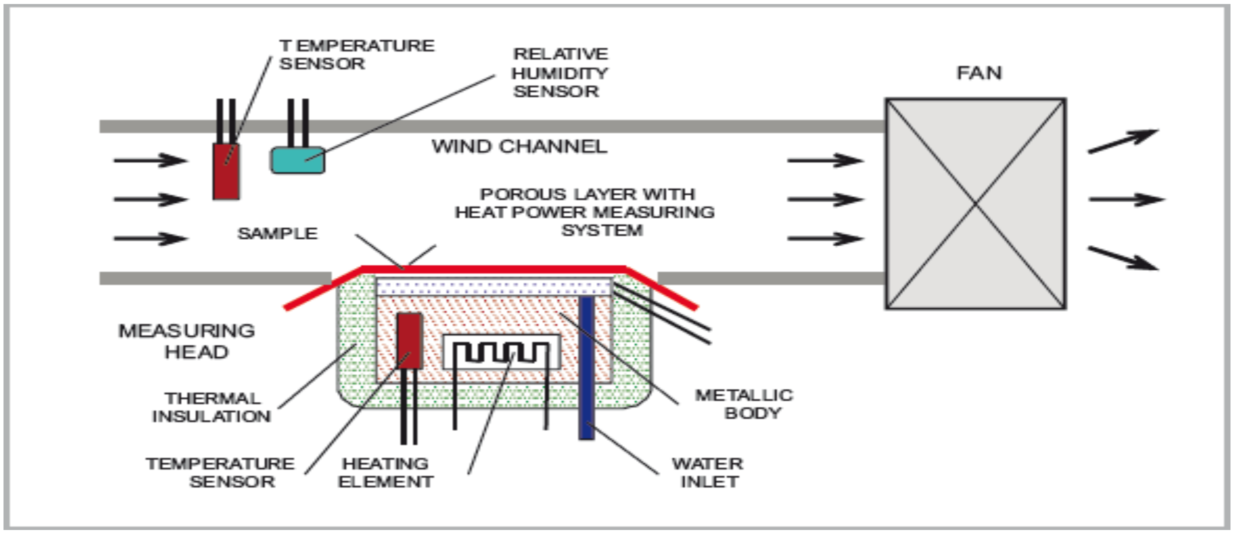


Figure 3-9: water vapour resistance tester [81].

3.6 The effect of contact pressure on thermal absorptivity

Samples were tested under different pressure to analyse its effect on thermal properties of fabric; however, these fabrics are specially designed for comfort purpose there was not big difference on thermal absorptivity on fabric.

Table 3-5: Effect of contact pressure on thermal absorbtivity

Sample Number	Thermal absorptivity [$Ws^{0.5}m^{-2}K^{-1}$] with 200 Pascal	Thermal absorptivity [$Ws^{0.5}m^{-2}K^{-1}$] with 100 Pascal
1	79.70	119.80
2	85.60	127.80
3	102.30	130.60
4	115.50	137.90
5	120.30	142.70
6	122.40	143.80
7	129.50	159.00
8	135.40	165.40
9	139.70	170.90
10	140.20	173.80
11	145.40	176.90
12	149.50	185.80
13	153.40	190.60
14	179.50	195.60
15	176.50	197.50

Samples were tested with the help of Alambeta and two different weight bars were used under 200 pascal and 1000 pascal , measurements were taken after 10 repetitive readings to avoid the error of accuracy.

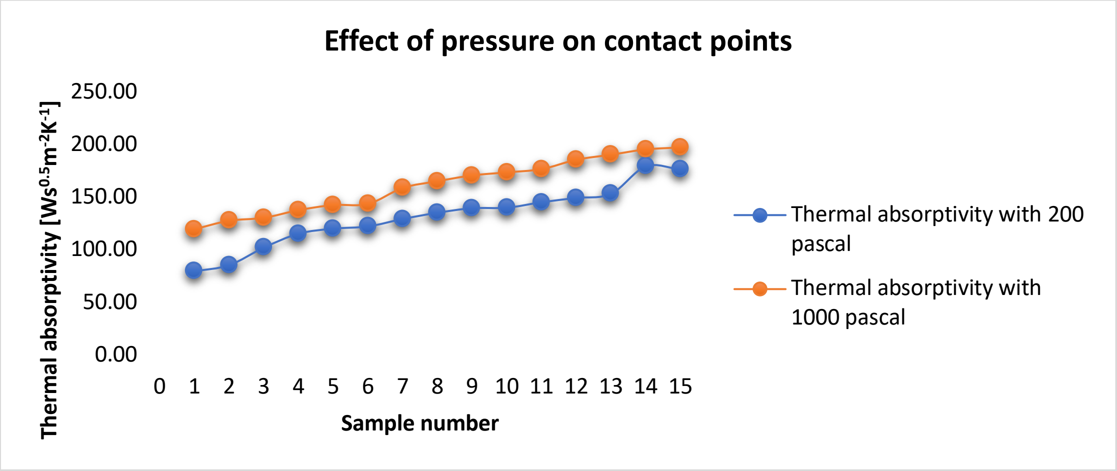


Figure 3-10: Effect of pressure on contact points

In figure 3-10 it was clear from analysis that studied samples were much compact that two different weight pressure were applied and there is not significant impact on thermal properties of fabric.

3.7 Contact Length area calculation

The surface of knitted rib can be divided into two main categories. There are fins on the surface of knitted rib. These fins are called vertical stripes (columns) and are also called wales. The rest of the area is called the base of the knitted rib fabric. Relative contact points of rib define the area, which touches the human hand.

$$C = \frac{F}{F + B} \times 100 \tag{3.10}$$

C is the Relative contact area (%), F is the length of fin on top (elevated courses), and B is the length between two adjacent rows of courses.

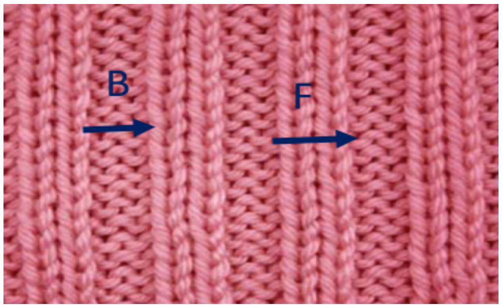


Figure 3-11 calculation of relative contact area

In above figure 3-11 is the length between the courses and F is the length of the fin on the top.

3.7.1 Contact area calculation by microscope

Using a microscope was the most precise way to calculate the relative contact area as the margin of error is very much less with this method. The figure shows how the microscope was used to find the real contact area. 10 readings were taken for each sample to reduce the chance of error. Another way to measure the surface profile of knitted rib is the paint effect. In this process, the surface of the knitted rib is painted with a brush of heavy density paint. In this way only the raised area of knitted rib gets painted. These are used to calculate the relative contact area % of the knitted rib when it was made to contact human skin. After getting two sets of values using two different techniques, a comparison was made, and no significant difference was found. This study uses image analysis techniques to get the values. The standard deviation was calculated by using the mean values

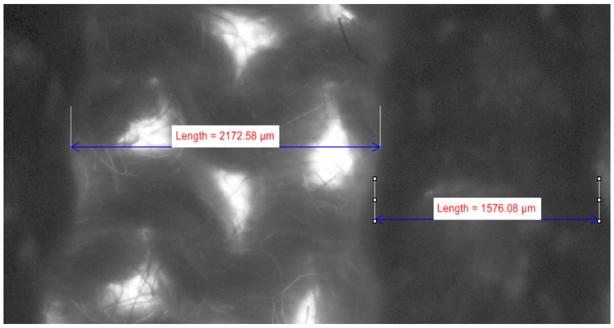


Figure 3-12 Microscopic view to calculate the relative contact area

3.7.2 Image Analysis of samples for measuring the contact area

As discussed in the previous pages, two techniques were used to measure the contact or interaction points between human skin and knitted rib. It was found that there was no significant difference between the two techniques used. Image analysis was the preferred method of measuring contact area for this study. This was because it is more scientific than the painting technique. Using image analysis, the raised area of knitted rib which touches the skin was calculated if knitted rib is brought to close to the skin. A few figures are given here to show the images using a high-resolution camera fitted microscope.

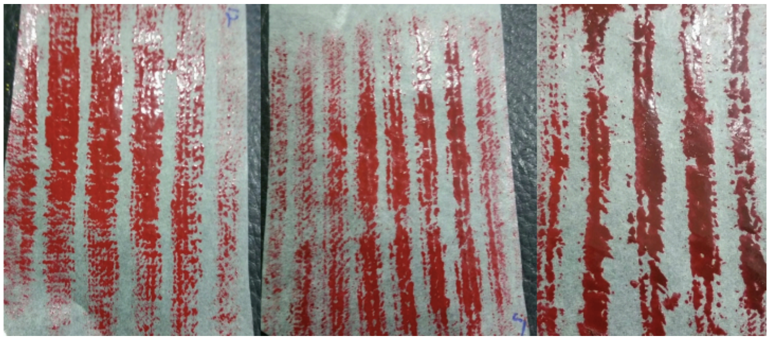


Figure 3-13: Image analysis paint technology

The paint method is likely less acceptable in industry as it shows less contact point under pressure however the samples were measured under Alambeta with standard pressure and got the results satisfying the other methods readings.

Figure 3-14: Image Analysis by Microscope for measuring contact area

Table 3-6: Comparison by paint and microscope method

Sample	F (length of fin on top) [mm]	Average	Standard Deviation	B length between courses [mm]	Average	Standard Deviation	Relative contact area by paint method	Real Contact area [%] by paint	Microscope Reading [%]
1	1.2	1.2	0.15	8.1	8.11	0.771	0.13	12.89	13
2	1.24	1.24	0.176	4	3.92	0.545	0.24	24.08	23
3	1.77	1.77	0.1	2.15	2.16	0.408	0.45	45	46
4	3.49	3.49	0.235	3.3	3.28	0.309	0.52	51.55	51
5	3.31	3.31	0.25	3	3	0.338	0.52	52.43	52
6	5.15	5.15	0.106	4.33	4.36	0.978	0.54	54.18	54
7	2.4	2.4	0.283	2	2.12	0.656	0.53	53.09	55
8	3.42	3.42	0.443	2.4	2.39	0.85	0.59	58.84	59
9	1.47	1.47	0.224	1	1.12	0.43	0.57	56.72	60
10	4.92	4.92	0.435	3.14	3.13	0.455	0.61	61.17	61
11	6.26	6.26	0.308	3.3	3.37	0.831	0.65	65.01	65
12	3.16	3.16	0.296	1.26	1.25	0.172	0.72	71.64	71
13	6.31	6.31	0.515	2	2.6	1.238	0.71	70.84	76
14	5.93	5.93	0.474	1.6	1.6	0.57	0.79	78.76	79
15	4.73	4.73	0.429	1.1	1.6	0.957	0.75	74.68	81

Table 3-7: Paired sample t-test

	Real Contact area [%] by paint
Mean	55.392
Variance	320.388
Observations	15
Pearson Correlation	0.994
Hypothesized Mean Difference	0
df	14
t Stat	-1.7591043
P(T<=t) one-tail	0.050193
t Critical one-tail	1.76131014
P(T<=t) two-tail	0.10038599
t Critical two-tail	2.14478669

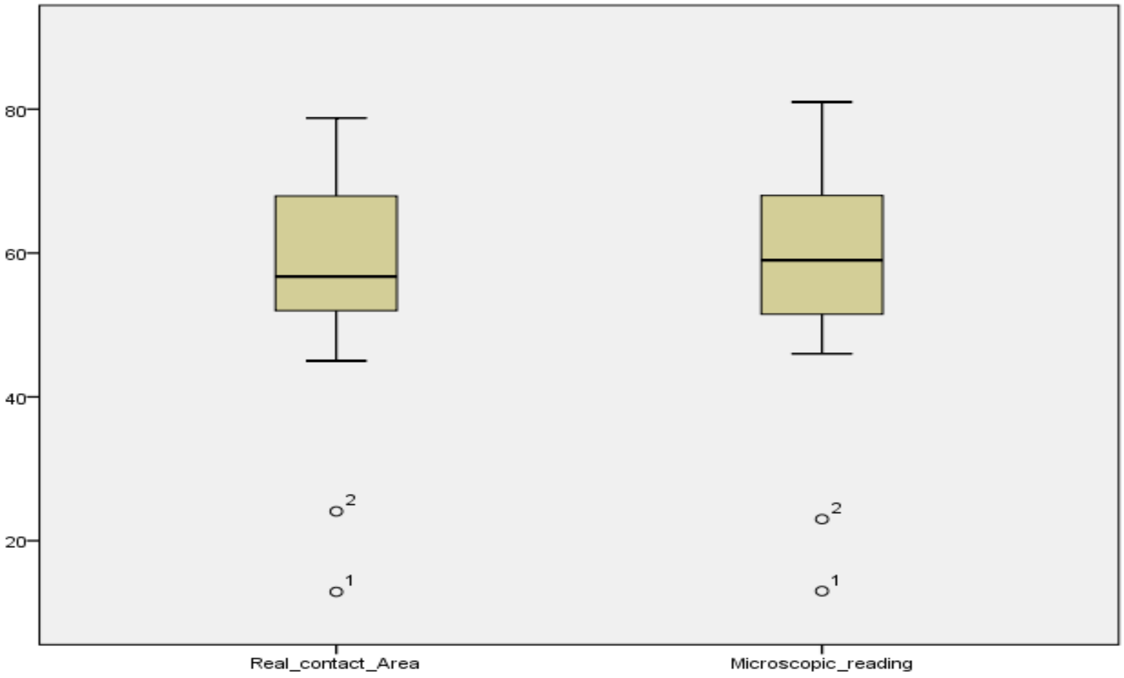


Figure 3-15: Boxplot of real contact and microscopic reading

Table 3-7 implores the paired sample t-test to determine if there is no big difference between paint method and microscope test. The mean of the paint method is 55.392 and variance 320.388, while the microscopic test has a mean value of 56.4 and a variance value 356.543. Pearson correlation value of 0.994 was deduced between the two methods, which means there exist a strong relationship between the two method. Lastly, the t-test value is given as (-1.759) which has a p-value 0.100. We therefore do not reject the researcher's hypothesis and conclude there is no big difference between paint method and microscope test since p-value is greater than 0.05 level of significance.

3.8 Thermal conductivity of knitted rib with a distinguished surface profile

As discussed earlier the thermal conductivity of fabric is the total of the impact of the fibre chemistry and the fabric composition. Fabric is composed of polymer, air, and moisture. Thermal conductivity of polymer is quite different to the thermal conductivity of fabric made from the same polymer. For example, the thermal conductivity of polyester is different to the thermal conductivity of fabric made using 100% polyester. This is due to the presence of other factors like air, moisture, textile auxiliaries, dyes molecules, and other factors. If you keep this point in mind, it is more likely that the thermal conductivity of different knitted ribs will be different as there is a lot of variation in structure of knitted rib even though all ribs have been made using 100% polyester. The thermal conductivity of all the ribs was measured using Alambeta. There is a strong correlation between thermal conductivity and contact area. An increase in area of contact increases the thermal conductivity. This is mainly due to having fewer spaces for the air to be trapped as the surface of knitted rib becomes flatter and more contact points are available to touch the skin. It facilitates the heat flow, and more heat flow is a sign of higher thermal conductivity. In the below tables there is different kinds of ribs were used for example 1x1 rib which means 1 stitch, 1 purl stitch all across the knitting needle, 2x3 rib means 2 stitch, 3 purl stitch all across the knitting needle.

Table 3-8: Thermal conductivity and contact area (%)

Sample no	Rib Type	Thermal conductivity [$Wm^{-1}K^{-1}$]	Average of 15 readings Thermal conductivity [$Wm^{-1}K^{-1}$]	Standard Deviation	Contact Area [%]
1	1x6	0.0465	0.047	0.003	12.9
2	1x3	0.0485	0.049	0.004	23.08
3	1x2	0.0513	0.051	0.004	45.57
4	2x3	0.0523	0.052	0.005	50.75
5	2x4	0.0559	0.056	0.005	52.38
6	3x4	0.0557	0.056	0.004	54.32
7	1x4	0.0570	0.057	0.005	55.06
8	2x2	0.0546	0.055	0.003	58.62
9	1x1	0.0554	0.055	0.004	59.51
10	3x3	0.0547	0.055	0.004	60.95
11	4x4	0.0579	0.058	0.005	65.26
12	2x1	0.0559	0.056	0.002	71.49
13	4x3	0.0592	0.059	0.005	75.9
14	4x2	0.0575	0.057	0.002	78.95
15	3x1	0.0584	0.058	0.002	81.03

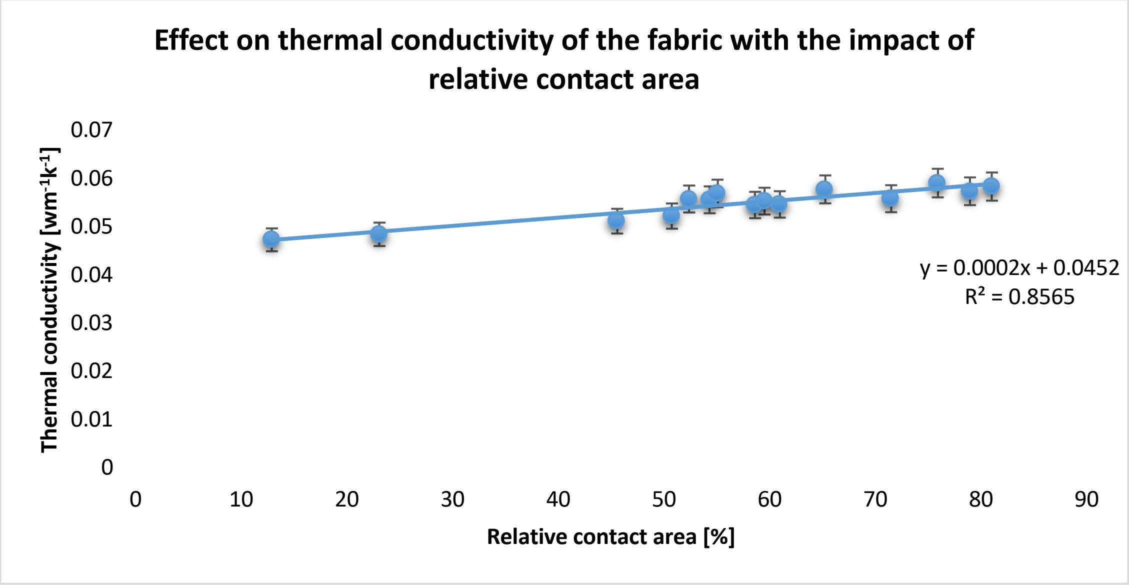


Figure 3-16 : Effect on thermal conductivity of the fabric with the impact of relative contact area [%].

Table 3-9 : Regression model estimate of Effect on thermal conductivity of the fabric with the impact of relative contact area

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.92944824					
R Square	0.86387403					
Adjusted R Square	0.85340281					
Standard Error	0.00139064					
Observations	15					
ANOVA						
	df	***SS***	***MS***	***F***	***Significance F***	
Regression	1	0.00015954	0.00015954	82.4997812	5.43E-07	
Residual	13	2.51E-05	1.93E-06			
Total	14	0.00018468				
	Coefficients	**Standard Error**	**t Stat**	**P-value**		**Upper 95.0%**
Intercept	0.04465892	0.00116443	38.3525404	9.22E-15		0.04717452
Contact Area	0.00017844	1.96E-05	9.08293902	5.43E-07		0.00022088

Table 3-9 is regression model shows the relationship between Thermal Conductivity (Dependent Variable) and Contact Area (Independent Variable). From the Anova table above we found that the regression model is significant with (F=82.499 p-value 0.000>0.05 level of significance). Also, the R square which is the amount of variation in the independent variable explained by the dependent variable shows 86% of the variation in the model is explained by the dependent variable. Lastly, the test of significance shows the independent variable is also significant in the model with (t=9.083, p-value 0.000<0.05).

3.9 Thermal resistance of knitted rib with a distinguished surface profile

Thermal resistance is directly proportional to the thickness of the slab and indirectly proportional to the thermal conductivity of the material. The above figure shows that an increase in contact area increases thermal conductivity, and there is significant correlation between the contact points and thermal conductivity. As thermal conductivity increases, there is a definite decrease in thermal resistance. This is obvious from Table 5-2. Moreover, Figure 5-2 shows that there is an indirect correlation between thermal resistance and the contact area of knitted rib. This correlation is quite significant because R square value is .93, which is quite high. It shows that fabric with a smooth surface provides less heat resistance and gives a cool effect, whereas, knitted rib with a low number of contact points is better for maintaining body temperature and provides a thermo-physiological comfort to the wearer. The role of fabric thickness is very minor as they were measured under Alambeta plate with the standard pressure.

Table 3-10 Thermal resistance and relative contact area [%]

Sample no	Rib Type	Thermal resistance [m^2KW^{-1}]	Average of 15 readings Thermal resistance [m^2KW^{-1}]	Standard Deviation	Contact Area [%]
1	1x6	52.00	52.00	3.09	12.9
2	1x3	44.14	44.14	3.09	23.08
3	1x2	43.93	43.93	4.01	45.57
4	2x3	42.38	42.38	2.78	50.75
5	2x4	40.29	40.29	2.37	52.38
6	3x4	39.74	39.74	3.09	54.32
7	1x4	36.44	36.44	2.13	55.06
8	2x2	35.40	35.40	3.59	58.62
9	1x1	34.34	34.34	2.81	59.51
10	3x3	32.96	32.96	3.30	60.95
11	4x4	32.68	32.68	3.50	65.26
12	2x1	31.95	31.95	3.02	71.49
13	4x3	30.56	30.56	2.97	75.9
14	4x2	32.99	32.99	3.04	78.95
15	3x1	31.95	31.95	2.84	81.03

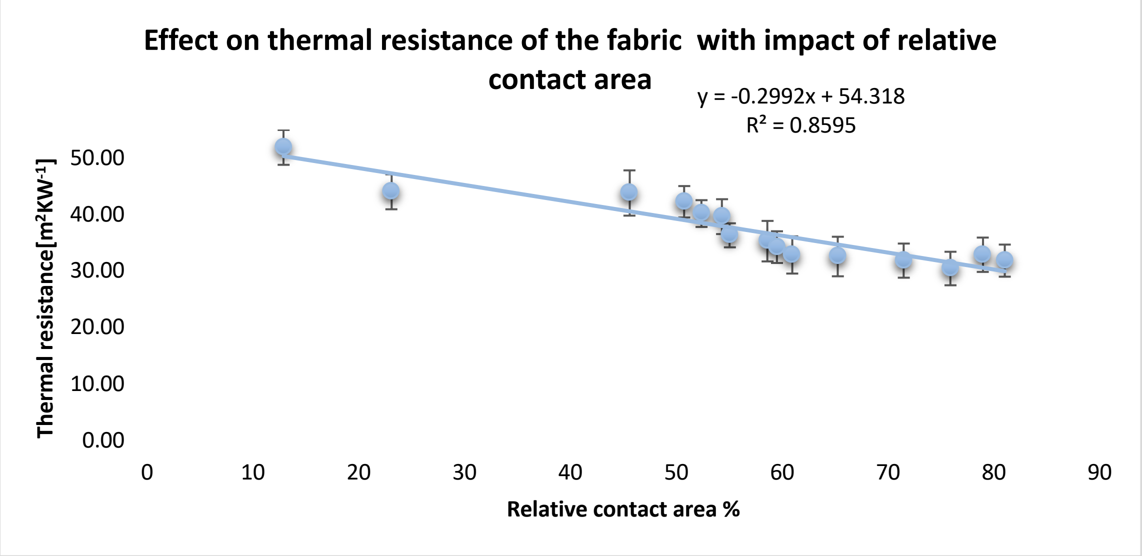


Figure 3-17: Effect on thermal resistance of the fabric with impact of relative contact area (%)

Table 3-11: Regression estimate of effect on thermal resistance of the fabric with impact of relative contact area

SUMMARY OUTPUT

Regression Statistics

Multiple R	0.92708561
R Square	0.85948773
Adjusted R Square	0.8486791
Standard Error	2.37470916
Observations	15

ANOVA								
	df	*SS*	*MS*	*F*	*Significance*			
Regression	1	448.424833	448.424833	79.5186138	6.68E-07			
Residual	13	73.3101667	5.63924359					
Total	14	521.735						
	Coefficients	*Standard Error*	*t Stat*	*P-value*				*Upper 95.0%*
Intercept	54.3174562	1.98843344	27.3167082	7.21E-13				58.6132055
Contact Area	-0.2991497	0.03354704	-8.917321	6.68E-07				-0.2266757

Table 3-11 shows regression model shows the relationship between Thermal resistance (Dependent Variable) and Contact Area (Independent Variable). From the Anova table above we found that the regression model is significant with (F=79.519 p-value 0.000> 0.05 level of significance). Also, the R square which is the amount of variation in the dependent variable explained by the independent variable shows 85% of the variation in the model is explained by the independent variable. Lastly, the test of significance shows the independent variable is also significant in the model with (t=-8.917, p-value 0.000<0.05).

3.10 Thermal absorptivity of knitted rib with a distinguished surface profile

Thermal absorptivity has been discussed at length previously, and it is an indicator of warm-cool feeling. It is directly proportional to the square root of thermal capacity and the thermal conductivity of material. It is obvious from Figure 5-3 that thermal absorptivity increases with the increase in thermal conductivity of material. Nevertheless, the thermal capacity of the material is constant. Table 6 and Figure 5-3 show that there is an increase in thermal absorptivity due to an increase in contact area. There is a significant correlation between thermal absorptivity and contact area between the top plate of Alambeta and the knitted rib. It shows that flatter fabric will give a cool feel compared to a rough surface. This is one of the reasons that undergarments are made with knitted rib because it has fewer contact points when compared with plain jersey fabric. This correlation is quite significant because the R square value is .91, which is quite high. It shows that fabrics with smooth surfaces provide less thermo-physiological comfort and give a cool effect, whereas, knitted rib with a low number of contact points is better at maintaining body temperature and provides a thermo-physiological comfort to the wearer.

Table 3-12: Thermal absorptivity and contact area (%)

Sample no	**Rib Type**	**Thermal absorptivity [$Ws^{0.5}m^{-2}K^{-1}$]**	**Average of 15 readings Thermal absorptivity [$Ws^{0.5}m^{-2}K^{-1}$]**	**Standard Deviation**	**Contact Area [%]**
1	1x6	79.53	78.974	2.250	12.90
2	1x3	82.73	83.913	2.678	23.08
3	1x2	101.13	101.731	4.177	45.57
4	2x3	113.10	112.835	3.593	50.75
5	2x1	120.53	120.055	1.912	52.38
6	3x4	121.87	122.040	3.806	54.32
7	1x4	127.97	127.702	2.345	55.06
8	2x2	133.30	135.567	4.062	58.62
9	1x1	138.40	138.234	1.425	59.51
10	3x3	140.33	140.943	3.324	60.95
11	4x4	145.10	145.316	4.924	65.26
12	2x1	148.90	148.190	3.601	71.49
13	4x3	151.63	151.702	2.748	75.90
14	4x2	176.30	176.598	2.696	78.95
15	3x1	173.50	173.599	4.302	81.03

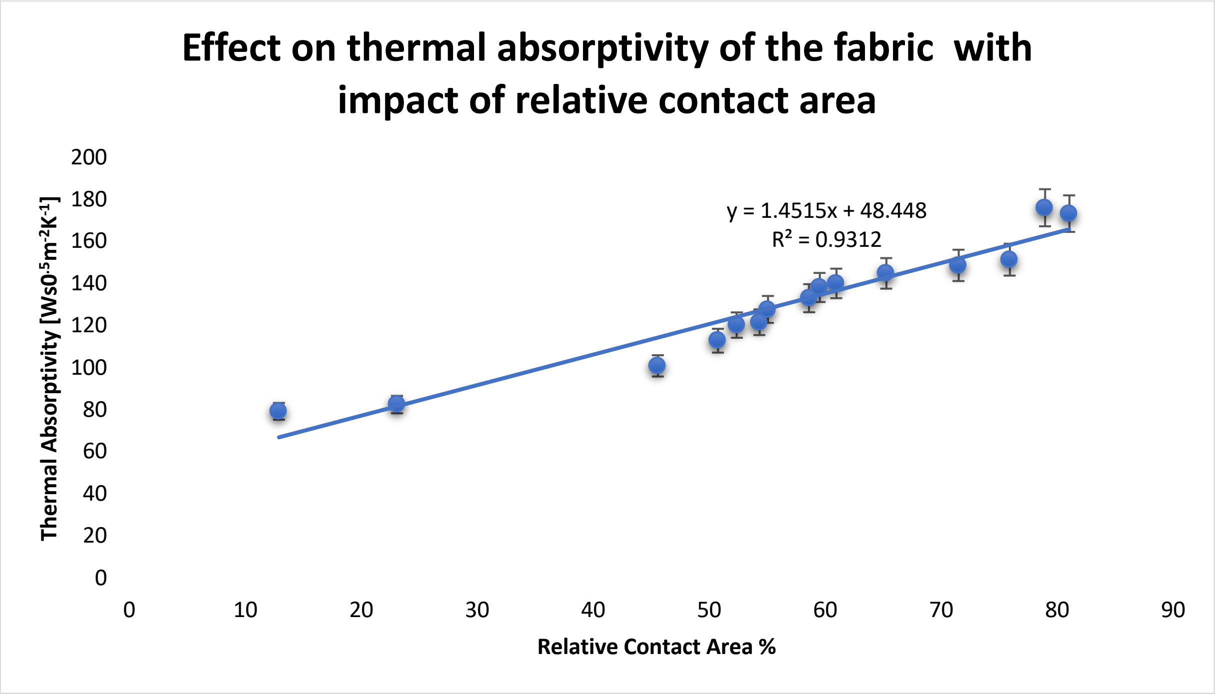


Figure 3-18: Effect on thermal absorptivity of the fabric with impact of relative contact area %

Table 3-13: Regression estimate of effect on thermal absorptivity of the fabric with impact of relative contact area

SUMMARY OUTPUT

Regression Statistics

Multiple R	0.965
R Square	0.931
Adjusted R Square	0.926
Standard Error	7.74578
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	10556.628	10556.628	175.952	0	
Residual	13	779.963	59.997			
Total	14	0.00018468				
	Coefficients	*Standard Error*	*t Stat*	*P-value*		*Upper 95.0%*
Intercept	48.448	6.486	7.47	0		0.04717452
Contact Area	1.451	0.109	13.265	0		0.00022088

Table 3-13 shows regression model shows the relationship between Thermal Absorptivity (Dependent Variable) and Contact Area (Independent Variable). From the Anova table above we found that the regression model is significant with (F=175.952 p-value 0.000>0.05 level of significance). Also, the R square which is the amount of variation in the dependent variable explained by the independent variable shows 93.1% of the variation in the model is explained by the independent variable. Lastly, the test of significance shows the independent variable is also significant in the model with (t=13.265, p-value 0.000<0.05).

3.11 Thermal absorptivity and singeing effect

Singeing is a process where fabric is passed through a flame. The thermal absorptivity of singed and un-singed fabrics were measured. Results showed there is a significant change in thermal absorptivity values after singeing. A Pilling test was carried out for both sets of fabrics. Different statics rules were applied, and the following conclusions were reached:

1. Significant difference in Pilling values before and after singeing (p value 0.003), which is quite high, significant decrease in p values after singeing

2. Significant difference in thermal absorptivity values before and after singeing (p value 0.000), much higher and significant, thermal absorptivity of the singed fabric increases significantly

3.11.1 Pilling test

Pilling is basically coming tiny balls of fibres above the fabric (pills) it normally occurs by rubbing, wear n tear abrasion. It's the ability of loose fibre to come from a fabric surface and form balled particles of fibres.

3.11.1.1 Causes of pilling

1. Due to wear and abrasion.
2. Due to rubbing action of fabric with particular parts of garments and body.
3. Due to soft twisted yarn.
4. Due to excess short fibres.
5. Due to migration of fibres from constituent yarn in fabric.
6. Due to protruding fibre / yarn hairiness.
7. Due to heat in case of thermoplastic fibres.

3.11.1.2 Testing method

A piece of fabric measuring 10×10 inch is sewn to a firm fit when placed round a rubber tube. The out end of the fabrics is covered by cellophane tape and metal plates are placed on the tester .Run the tester for 300 cycles. Remove the sample and compare the sample with standard scale. There is a drastic change in contact points after singeing because the surface becomes smoother. There is 5 to 10% increase in thermal absorptivity values after singeing, which provides proof that surface profile has a strong correlation with the thermal absorptivity. This experiment endorsed the outcome of the study which says that the surface profile of knitted rib has a strong impact on thermal absorptivity. In this study 13 woven fabric samples were used to measure the changes in thermal parameters after singeing. These samples were made using cotton, viscose and polyester. All samples were passed through a singeing machine. These samples were not desized to avoid any change due to desizing process. Selection of woven fabric is based on the available technology needed for singeing of fabric. Moreover, a variety of fabric has been selected to expand the testing results on different fabric of versatile fibre ratio and thickness and density.

Table 3-14: Sample description for singeing.

Sample No	**Warp Per cm**	**Warp Tex**	**Weft per cm**	**Weft Tex**	**Fibre Content**	**Grams per Meter Square**
1	23.6	36.9	22.8	36.9	100 % Cotton	184
2	39.4	31.1	19.7	31.1	100 % Cotton	210
3	30.7	29.5	26.8	29.5	100 % Cotton	184
4	23.6	29.5	23.6	29.5	100 % Cotton	147
5	23.6	26.8	22.0	26.8	100 % Cotton	123
6	19.7	19.7	19.7	19.7	100 % Cotton	80
7	28.3	22.7	23.6	3.9	Cotton 30%, Polyester 70%	109
8	23.6	26.8	22.0	26.8	Cotton 40 %, Polyester 60%	122
9	29.9	19.7	21.3	19.7	Cotton 50%, Polyester 50%	118
10	31.5	16.9	20.5	16.9	Cotton 50%, Polyester 50%	96
11	29.9	19.7	17.3	19.7	Cotton 60%, Polyester 40%	95
12	26.8	24.6	24.4	24.6	Cotton 80%, Polyester 20%	172
13	20.5	29.5	15.7	3.9	Cotton 80%, Polyester 20%	105

Table 3-15: Thermal absorptivity of singed and un-singed fabrics

Sample No	Pilling Test Before Singeing	Pilling Test After Singeing	Thermal absorptivity of un-singed [$Ws^{0.5}m^{-2}K^{-1}$]	Thermal absorptivity of singed fabric [$Ws^{0.5}m^{-2}K^{-1}$]
1	2.5	3.00	183	190
2	3.5	4.50	200	206
3	2.5	4.00	155	170
4	2.5	2.50	169	208
5	2.5	2.50	162	174
6	2.5	4.50	157	171
7	3.0	4.00	147	161
8	4.5	4.50	156	167
9	4.5	4.50	145	151
10	2.5	3.00	148	153
11	3.0	3.00	120	131
12	2.5	4.00	117	126
13	2.5	4.00	124	139

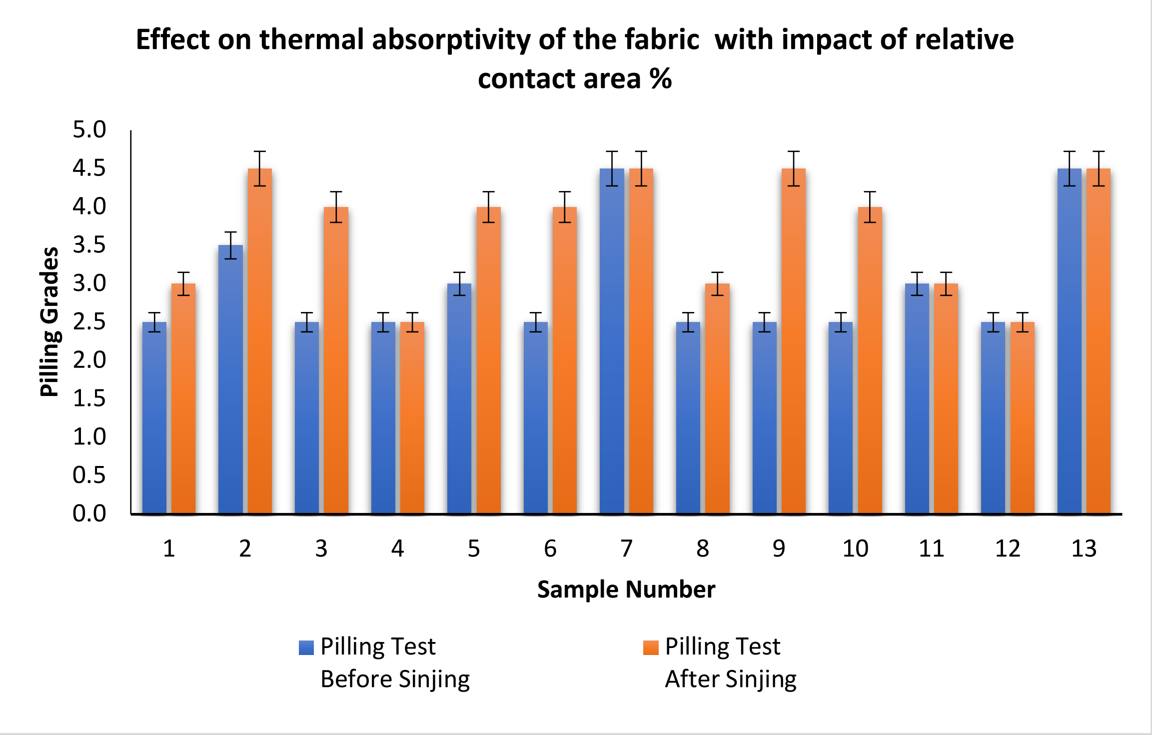


Figure 3-19: Pilling Grades before and After Singeing

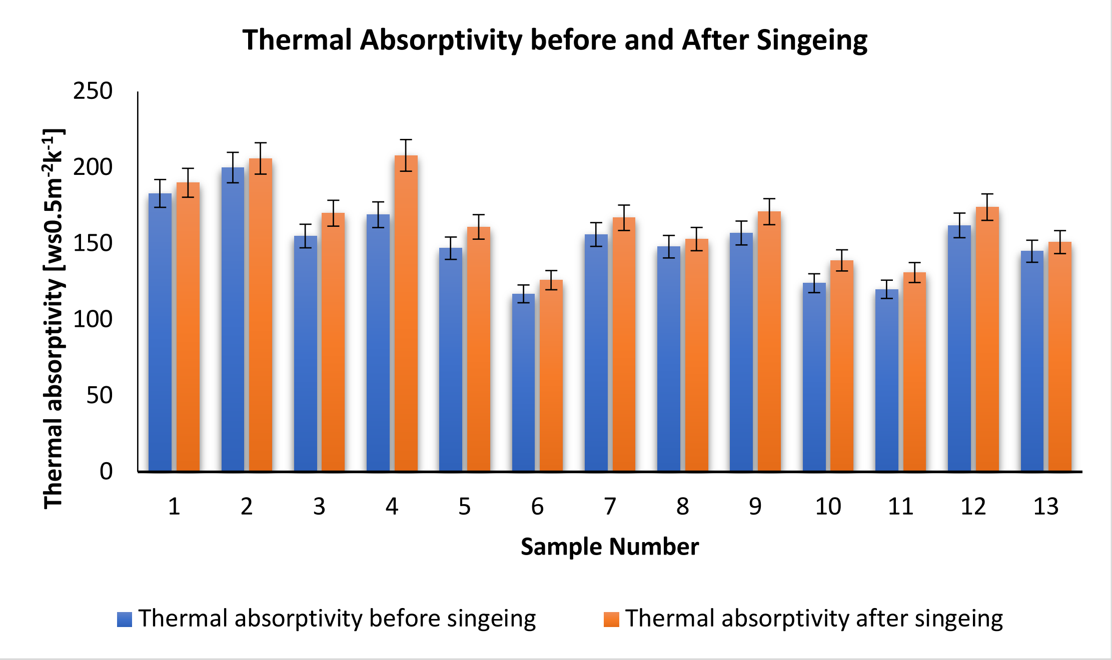


Figure 3-20: Thermal Absorptivity before and After Singeing

Table 3-16: Thermal resistance before and after singeing

Sample	Thermal resistance before singeing [m^{2}KW^{-1}]	Thermal resistance after singeing [m^{2}KW^{-1}]
1	9.5	9.7
2	8.3	6.8
3	9.2	8.8
4	8	7.5
5	8	7.8
6	8.5	8.5
7	7	5.8
8	8.4	8.1
9	6.4	6.6
10	8.1	6.9
11	8.3	8.1
12	7.4	6.9
13	8.1	7.2

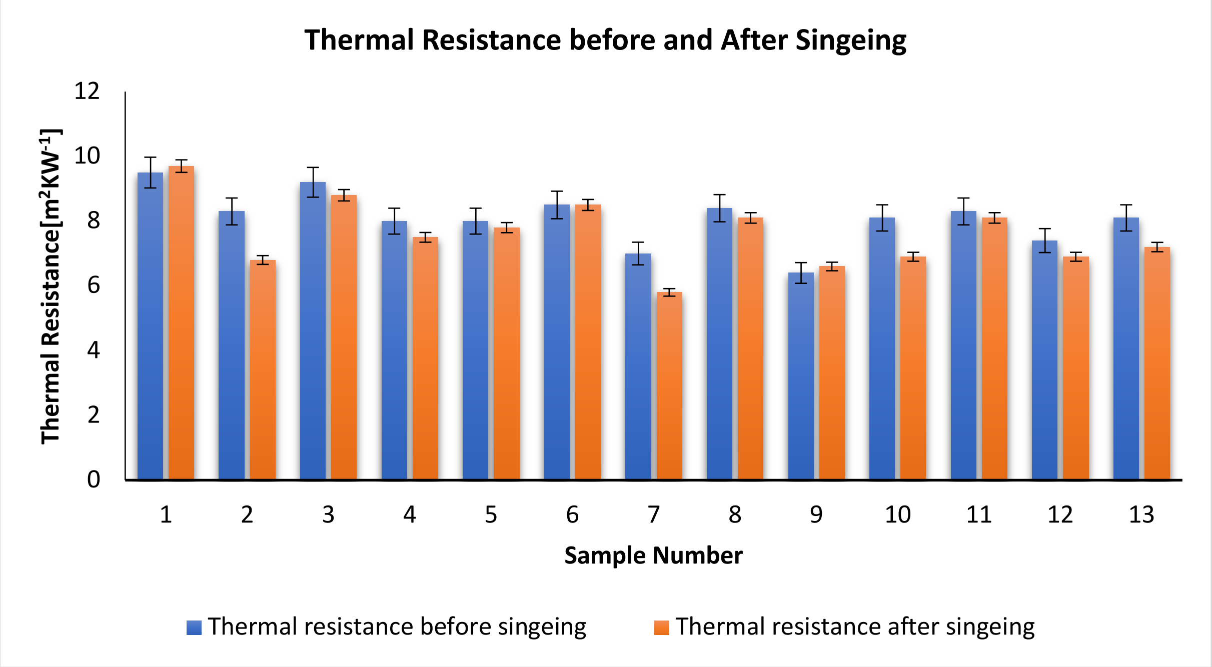


Figure 3-21: Thermal Resistance before and After Singeing

Total 13 samples of woven fabric were prepared composed of 6 pure cotton and seven cotton and polyester blend. Whole samples were divided into two sets; one singed and other un-singed. Samples were tested using different equipment to find thermal absorptivity, thermal resistance, thermal conductivity and pilling values. It was found that thermal absorptivity increases with the increases of weight per unit area of fabric (Grams Per Square Meter). It endorsed thermal absorptivity theory that less porosity will help in increasing thermal absorptivity and will provide a cool effect. There is a significant difference in pilling values, which shows that singeing process was quite effective. There is substantial increase in thermal absorptivity values after singeing, which proves that higher contact points provide more channel for heat loss from the skin. However, there is a meaningful decrease in thermal resistance after singeing. It is due to drastic change in surface profile. Surface becomes smoother and provides more area for heat transfer. It was also found that there is no notable difference in thermal conductivity values since material is same. This study suggests that for better look and low chances of pilling outside of the fabric should be singed while inner surface must be kept uneven by doing brushing so that thermal absorptivity and thermal resistance values must not be changed.

3.12 Thermal absorptivity and enzymatic treatment

To test the impact of enzymatic treatment for measurement of thermal absorptivity, 31 different kinds of knitted fabric samples were produced using cotton and polyester/cotton combinations on various knitting machines with a variety of fabric. All samples were scoured and dyed simultaneously on a sample-dyeing machine. After dyeing, the samples were grouped into two sets. One set was given enzyme treatment and the second set was left untreated. Enzyme treatment is kind of finishing which applied during dyeing process of the fabric, this helps to remove all the protruding Fibres from the surface of the Fibre and make its surface cleaner and this treatment is widely appreciated because of fine side of fabric.

Table 3-17: Samples descriptions used for treated and untreated fabric

Sr #	Fabric	Cotton [%]	Polyester [%]	Square mass[1]
1	Single Jersey	100	0	180
2	Slub Jersey	100	0	115
3	Fleece	60	40	230
4	Low Shrinkage Fleece	60	40	264
5	Pique	60	40	272
6	Interlock	50	50	176
7	Low Shrinkage Fleece	70	30	255
8	Single Jersey	60	40	125
9	Interlock	100	0	177
10	Cut Jersey	80	20	185
11	Fleece	100	0	293
12	Fleece	80	20	241
13	Jersey	80	20	232
14	Pique	100	0	165
15	Single Jersey	80	20	176
16	Fleece	100	0	257
17	Single Jersey	50	50	153
18	Pique	100	0	157
19	Terry	100	0	243
20	Thermal	60	40	136
21	Pique	100	0	201
22	Terry	100	0	241
23	Fleece	80	20	213
24	Pique	100	0	241
25	Single Jersey	100	0	172
26	Single Jersey	100	0	175

27	Fleece	70	30	213
28	Fleece	50	50	269
29	Pique	60	40	151
30	Slub Fleece	100	0	240
31	Single Jersey	100	0	219

[1] Planar weight of fabric (grams per square meter)

Table 3-18: thermal absorptivity (Untreated and Treated With Enzymes)

Sample #	Thermal absorptivity (Untreated) [Ws$^{0.5}$m^{-2}K^{-1}]	Thermal absorptivity (Treated with Enzymes) [Ws$^{0.5}$m^{-2}K^{-1}]
1	183	165
2	136	132
3	167	160
4	155	161
5	203	183
6	133	138
7	161	161
8	145	144
9	163	154
10	134	152
11	161	167
12	179	185
13	121	126
14	157	145
15	161	162
16	176	188
17	141	146
18	162	158
19	152	121
20	130	111

Sample #	Thermal absorptivity (Untreated) [$Ws^{0.5}m^{-2}K^{-1}$]	Thermal absorptivity (Treated with Enzymes) [$Ws^{0.5}m^{-2}K^{-1}$]
21	181	177
22	192	144
23	167	165
24	172	164
25	156	136
26	189	172
27	153	148
28	179	180
29	159	141
30	184	172
31	170	161

Table 3-19 Anova anaylsis Thermal absorptivity treated and un-treated

SUMMARY OUTPUT

Regression Statistics

Multiple R	0.3665332
R Square	0.5829
Adjusted R Square	0.10449647
Standard Error	18.6273393
Observations	31

ANOVA	df	MS	F	Significance F
Regression	1	1561.64469	4.5007053	0.04254946
Residual	29	346.977769		
Total	30			
	Coefficients	**t Stat**	**P-value**	
Intercept	127.28262	7.6202859	2.11E-08	
Thermal Absorptivity (Treated with Enzymes)	0.23247409	2.12148658	0.04254946	

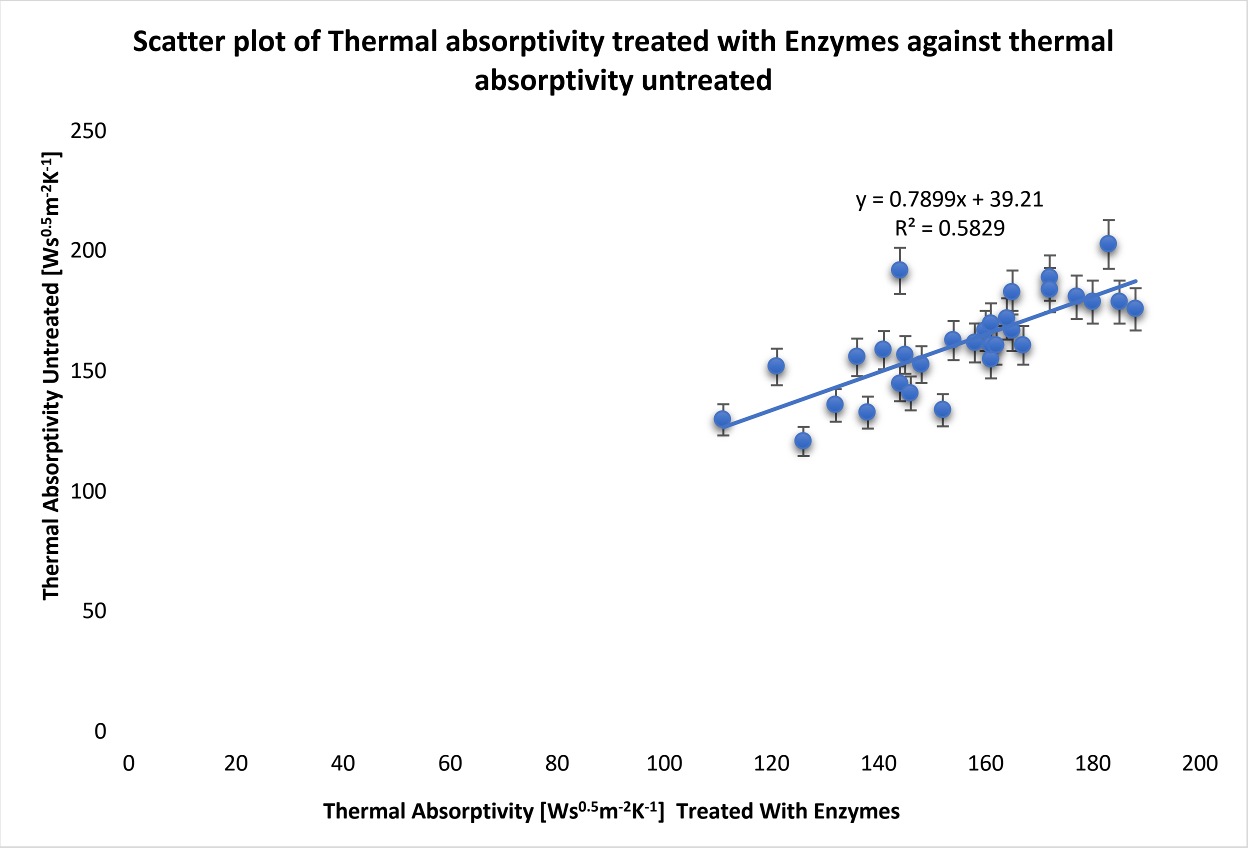


Figure 3-22 : Scatter plot of Thermal absorptivity treated with Enzymes against thermal absorptivity untreated

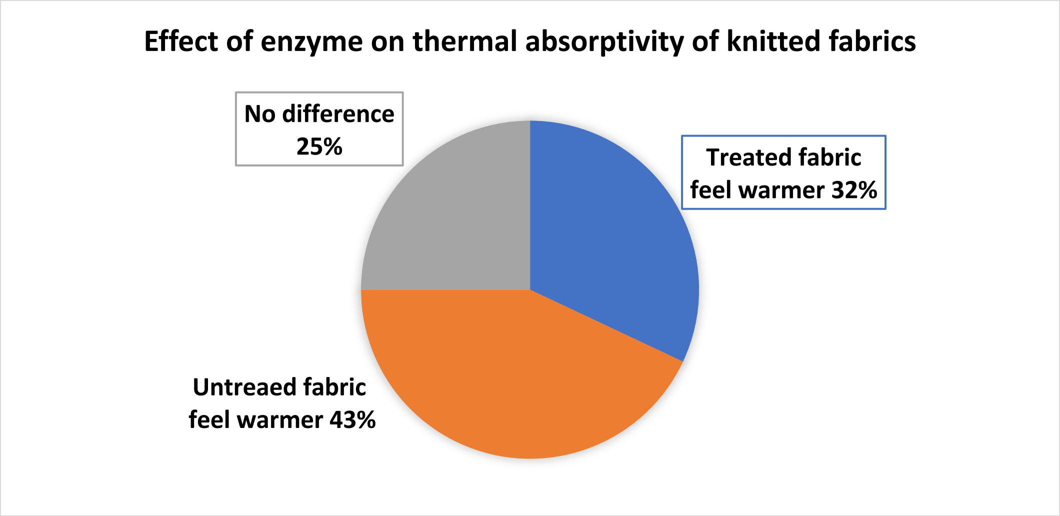


Figure 3-23: Effect of enzyme on thermal absorptivity of knitted fabrics

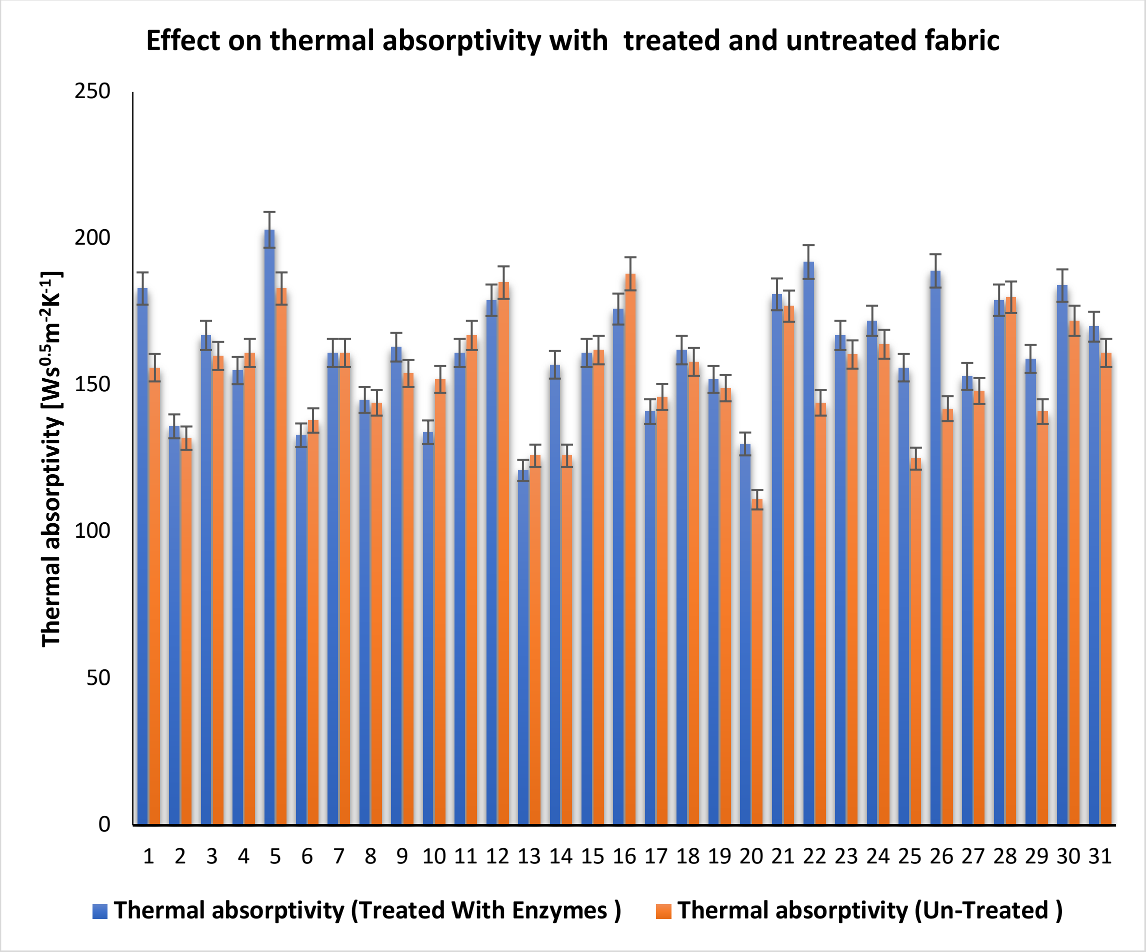


Figure 3-24: Effect on thermal absorptivity with treated and untreated fabric

Table 3-19 shows a regression model shows the relationship between Thermal Absorptivity (Untreated) and Thermal Absorptivity (Treated with Enzymes). From the Anova table above we found that the regression model is significant with (F=4.5, p-value 0.043> 0.05 level of significance). Also, the R square which is the amount of variation in the independent variable explained by the dependent variable shows 13.4% of the variation in the model is explained by the dependent variable. Lastly, the test of significance shows the independent variable is also significant in the model with (t=2.121, p-value 0.043<0.05).

3.13 Sensorial comfort appraisal of knitted rib by objective assessment of surface mechanical characteristics

Kawabata Evaluation System (KES) was used to measure the following three main parameters of knitted rib:

1. Mean frictional coefficient (MIU)
2. Mean deviation of frictional coefficient (MMD)
3. Mean deviation of surface contour (SMD, 10^{-5}m)

KES was used to test knitted rib samples and showed that there was a significant variation. The minimum value of the mean frictional coefficient (MIU) of the front is 1.197, and the highest value is 1.976. It shows that because of the variation on the surface profile of knitted rib, there is a drastic change in the friction coefficient. On the back of the knitted rib, the lowest value is 1.099, and the highest value is 1.975. The data shows that knitted rib has similar values on both sides. Higher friction will provide less smooth comfort, but at the same time, it will give a low number of contact points, which is one of the reasons for a warm feeling.

The range of mean deviation of frictional coefficient (MMD) is quite large. The minimum is 0.63, and the maximum value is value is 1.63 on the front, and lowest value on the back is 0.79, and highest value is 5.75. It shows that knitted rib has different frictional coefficients on the front and back. It has been observed that industry does not take care of the side. Results show that there is a significant difference in the properties of both sides. Such variation shows that the type of rib structure has a strong influence on frictional deviation. [82]

It is the same case with the mean deviation of surface contour (SMD). The front has 3.13 as its lowest values, while its highest value is 5.75. A similar variation is found on the back of knitted rib, where the lowest value is 3.29, and the highest value is 5.73.

There is a significant impact of surface profile on thermal absorptivity. KES results show that the surface profile of knitted rib has a huge variation. By considering this fact, one can infer that thermal absorptivity of different knitted rib samples will have a significant variation. It is further proof that surface profile has a significant correlation with thermal absorptivity.

Table 3-20 Kawabata Evaluation measuring of MIU,MMD and SMD

Sample no	Rib Type	MIU		MMD		SMD [10^{-5}m]	
		Front	Back	Front	Back	Front	Back
1	1x6	1.792	1.538	1.240	1.003	4.136	4.097
2	1x3	1.753	1.396	1.011	0.918	3.848	3.633
3	1x2	1.738	1.46	0.967	1.045	5.127	4.380
4	2x3	1.714	1.450	0.815	0.840	5.132	3.955
5	2x4	1.548	1.187	0.894	0.903	3.135	3.296
6	3x4	1.509	1.099	1.635	0.991	5.75	5.737
7	1x4	1.465	1.465	1.021	0.967	4.355	4.609
8	2x2	1.455	1.528	1.050	1.152	4.395	3.887
9	1x1	1.357	1.143	0.630	1.099	5.625	5.322
10	3x3	1.348	1.133	1.157	0.796	4.346	4.233
11	4x4	1.323	1.201	0.850	0.947	5.015	5.093
12	2x1	1.211	1.211	0.854	0.962	3.765	3.374
13	4x3	1.197	1.198	0.851	0.984	4.565	5.621
14	4x2	1.976	1.975	0.842	0.985	4.782	5.213
15	3x1	1.965	1.932	0.839	0.942	3.745	4.987
Minimum		1.197	1.099	0.630	0.796	3.135	3.296
Maximum		1.976	1.975	1.635	1.152	5.750	5.737
Average		1.556	1.394	0.977	0.970	4.514	4.495

3.14 Influence of airflow direction on thermal resistance

Thermal resistance and water vapour permeability play a critical role in thermo-physiological comfort. There are many factors which can influence values of thermal resistance and water vapour permeability. One of those factors is airflow direction. Knitted rib samples were tested to identify the impact of airflow direction on thermal resistance and water vapour permeability. Rib direction on the surface of rib knit fabrics provides a channel for airflow. The thermal resistance and the water vapour permeability in perpendicular and parallel directions of the ribs against the airflow were measured. It was found that rib directions have an impact on thermal resistance and on water vapour permeability. Results indicate that thermal resistance increases when the ribs lie parallel with the direction of airflow and the water vapour permeability has a tendency to decrease when the ribs lies parallel with the direction of airflow.

The results of ratios show that the parallel arrangement of ribs against the airflow mostly leads to higher thermal resistance and lower relative water vapour permeability compared to the perpendicular arrangement.

3.15 Airflow direction and water vapour permeability

There is a statistical difference when a comparison of mean values is carried out. The water vapour permeability ratio is higher (mean 51.96%) when water vapour permeability is measured when the fabric is in a horizontal shape and is less (mean 50.75) when we put the fabric in a perpendicular position. This might be due to gravity on the water molecules or due to any other reason, which is unknown to us and would need another study to find out.

Results show that a parallel arrangement of ribs leads to a decrease in relative water vapour permeability. However, a difference higher than 10% was only for one sample. Therefore, the orientation of ribs in respect to airflow does not play a big role for relative water vapour permeability as at the thermal resistance.

The textile rib fabric which humans wear they need a good heat transfer to get in thermal comfort zone, rib fabric worn parallel and perpendicular against the air surface orientation. In summer hot wet climate human needs a high cooling effect which can only be done by rate of moisture transfer their orientation of ribs may bring high value of (b). There is no significant impact of orientation of knit rib were published however this study may help the designer while designing the fabric.

3.16 Airflow direction and heat transfer coefficient

Rib knit fabrics have wales (ribs) on their surface. The height of a rib is about 50% of the total thickness of a fabric. The height varies from 0.9 to 1.1 mm in current study samples. Moreover, the width of the rib varies depending upon the type of knitting. Thermal resistance and relative water vapour permeability were measured in two directions when putting knitted rib in parallel and perpendicular directions in relation to the airflow direction. One can make clothing with perpendicular ribs (top to bottom direction), and parallel direction (from right to left) see the figure below.

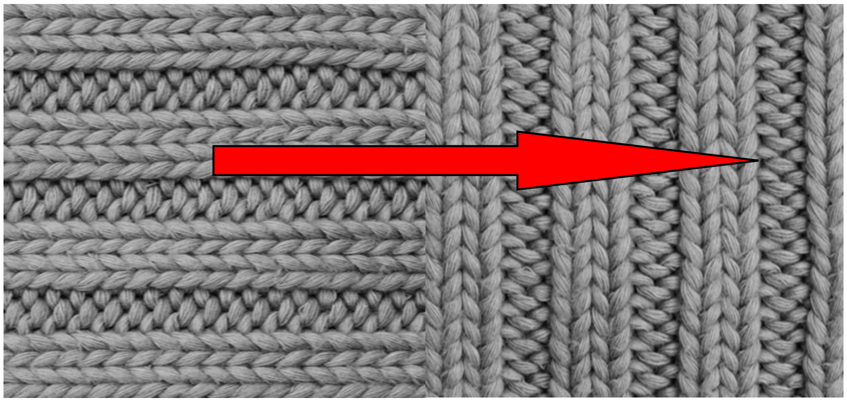


Figure 3-25 Ribs vs. airflow – a: Parallel, b: perpendicular

Tests show the values of thermal resistance and relative water vapour permeability of 18 samples in a perpendicular and a parallel direction. The paired sample t-Test was applied to measure the significance of means of the two sets of values. There is a statistically significant difference between two sets of values. As discussed earlier we measured water vapour permeability along two directions: x-axis (parallel) and y-axis (perpendicular). In both cases, there is no difference in the material or area. The only difference was direction of the wales. Data analysis shows that two-tale difference significance is 0.004 at the 95% confidence level. It shows the behaviour of fabric if the airflow direction is changed. Moreover, the water vapour permeability ratio is higher (51.96%) when we keep knitted rib in an horizontal position.

Statistical analysis shows there is a statistically significant difference when means of two sets of values were compared. Data analysis also shows that there is a significance difference (0.000) at the 95% confidence level in two sets of values of thermal resistance. Moreover, the mean thermal resistance of knitted rib in a parallel position is 0.036, while in a perpendicular position it is 0.034. One can deduce that ribs in a parallel position provide better thermal resistance than ribs in a perpendicular position.

Table 3-21 T-test between Thermal resistance Parallel and Thermal Resistance Perpendicular

		Parallel		Perpendicular	
Sample No	Rib type	Thermal Resistance [m^2KW^{-1}]	Relative Water Vapor Permeability [%]	Thermal Resistance	Relative Water Vapor Permeability [%]
1	1x6	0.03673	50.7	0.03327	51.85
2	1x3	0.03647	48.5	0.03373	51.35
3	1x2	0.03530	48.2	0.03063	49.65
4	2x3	0.03650	51.2	0.03207	51.05
5	2x4	0.03750	51.6	0.03643	53.60
6	3x4	0.03907	49.9	0.03563	49.25
7	1x4	0.03757	53.0	0.03580	54.15
8	2x2	0.03817	49.6	0.03557	51.30
9	1x1	0.03213	42.6	0.03170	48.40
10	3x3	0.03087	53.3	0.03073	54.65
11	4x4	0.03260	47.6	0.03023	49.60
12	2x1	0.03370	56.1	0.03490	56.75
13	4x3	0.03753	53.2	0.03533	53.75
14	4x2	0.03917	50.9	0.03697	53.00
15	3x1	0.03903	53.1	0.03663	53.65

Table 3-22: t-Test: Paired Two Sample for Means

	Thermal Resistance[m^2KW^{-1}]	**Thermal Resistance**
Mean	0.036156	0.03397467
Variance	7.12E-06	5.60E-06
Observations	15	15
Pearson Correlation	0.80866876	

Hypothesized Mean Difference	0
df	14
t Stat	5.33458149
P(T<=t) one-tail	5.27E-05
t Critical one-tail	1.76131014
P(T<=t) two-tail	0.00010535
t Critical two-tail	2.14478669

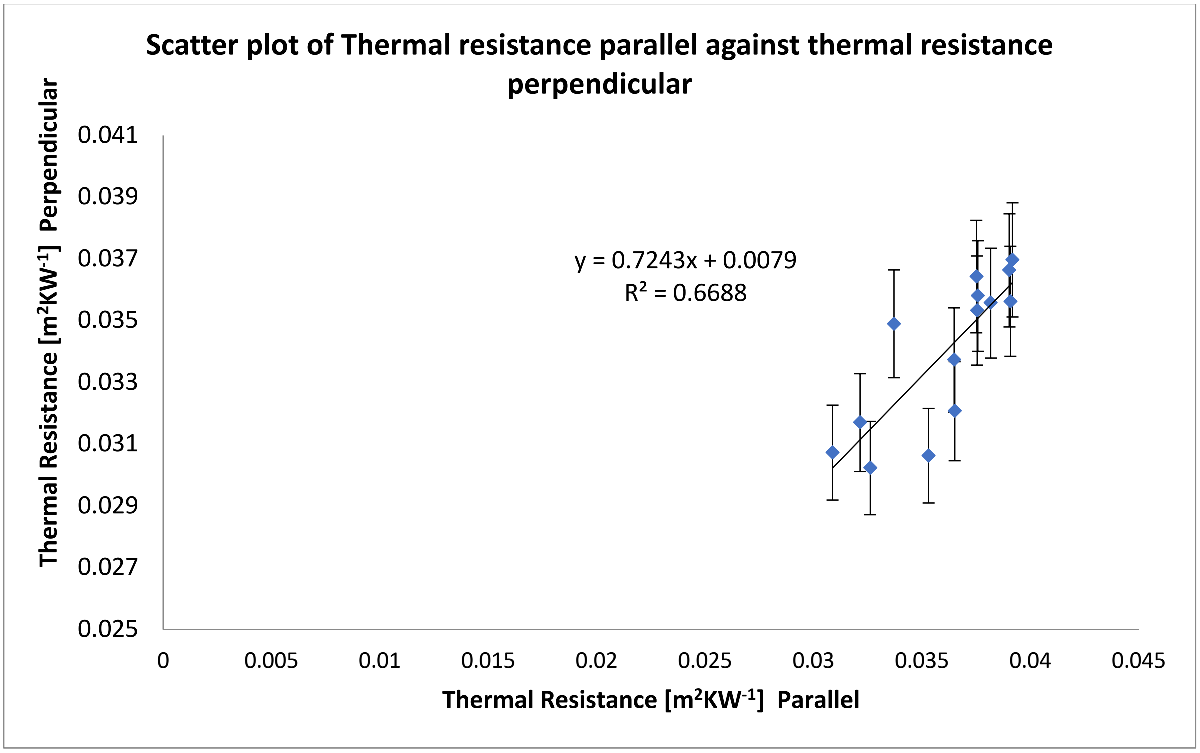


Figure 3-26: Scatter plot of Thermal resistance parallel against thermal resistance perpendicular

The regression model in figure 3-26 shows the relationship between Thermal resistance perpendicular (Dependent variable) and Thermal resistance parallel (Independent variable). From the table above we found that the regression model is significant with (F=24.566, p-value 0.000> 0.05 level of significance). R square which is the amount of variation in the independent variable explained by the dependent variable shows 66% of the variation in the model is explained by the dependent variable. Lastly, the test of significance shows the independent variable is also significant in the model with (t=4.956, p-value 0.000<0.05).

Table 3-23: T test between Parallel Relative Water Vapor Permeability and Perpendicular Relative Water Vapor Permeability

t-Test: Paired Two Sample for Means

	Parallel (Water Vapor Permeability)	**Perpendicular (Water Vapor Permeability)**
Mean	50.6553333	52.13333333
Variance	10.2504267	5.494880952
Observations	15	15
Pearson Correlation	0.89932864	
Hypothesized Mean Difference	0	
df	14	
t Stat	-3.8192338	
P(T<=t) one-tail	0.00093907	
t Critical one-tail	1.76131014	
P(T<=t) two-tail	0.00187813	
t Critical two-tail	2.14478669	

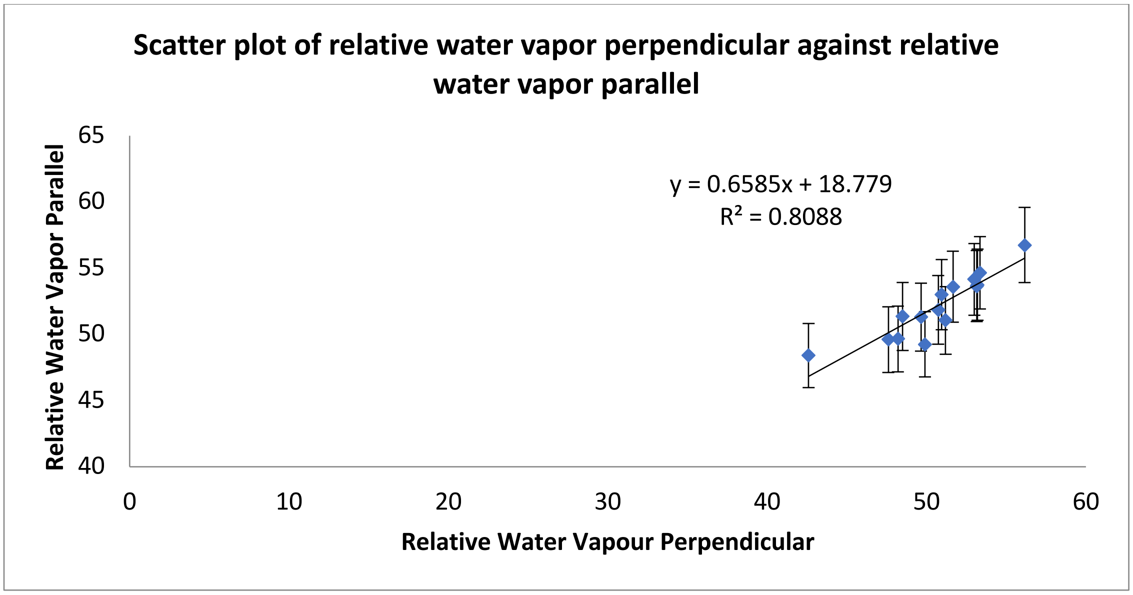


Figure 3-27: Scatter plot of relative water vapor perpendicular against relative water vapor parallel

Similarly, in Table 3-23 The regression model above shows the relationship between water vapor permeability perpendicular (Dependent variable) and water vapor permeability (Independent variable). From the table above we found that the regression model is significant with (F=54.989, p-value 0.000> 0.05 level of significance). R square which is the amount of variation in the independent variable explained by the dependent variable shows 80.9% of the variation in the model is explained by the dependent variable. Lastly, the test of significance shows the independent variable is also significant in the model with (t=7.415, p-value 0.000<0.05).

3.17 Physical model for prediction of thermal absorptivity

One of the objectives of this study was to develop a model for the prediction of thermal absorptivity with the change in contact points between human skin and fabric. This model has been developed using a novel approach. Furthermore, the results from a physical model and actual measured values have a significant correlation, which proves that the model developed can be used for the prediction of thermal absorptivity of any fabric by exploiting the contact area between human skin and a fabric surface.

3.17.1 Porosity calculation

Porosity is a concept, which is commonly used in various fields. Militký and Havrdová [69] introduced the following methods to calculate porosity:

1- Volumetric porosity based on the ratio of the density of fibres and fabric

2- Based on cover factor of fabric

3- Hydraulic pore approach.

In this study the volumetric approach proposed by Militky and Havrdova [69] has been used to measure the porosity.

Density-based porosity (P_{HW}) is computed from the equation

$$\mathrm{P_{Hw}} = 1 - \frac{\rho_f}{\rho_p} \tag{3.11}$$

Where ρ_f and ρ_p represent the density of fabric and the density of polymer respectively. In our case, it is the density of knitted rib and the density of polyester. Where P_{HW} [1] represents the porosity based on volumetric density.

3.17.2 Thermal absorptivity of pure polyester (cake form)

Thermal absorptivity of pure polyester (cake form) is quite different to the thermal absorptivity of a fabric made using polyester fibre. It is caused by the presence of air and moisture in the fabric. The Fibre Survey Book, published by [83] Wiley-VCH, has been used to note thermal conductivity, density, and the specific heat capacity values of polyester.

Table 3-24 Thermal conductivity, density, and specific heat of polyester.

Description	Values
Thermal conductivity	0.30 [$Wm^{-1}K^{-1}$]
Density	1450 [$kg\ m^{-3}$]
Specific heat	1600 [$Jkg^{-1}K^{-1}$]

$$b = \sqrt{0.3 * 1450 * 1600} \tag{3.12}$$

The result of equation 5.2. is 834 [$Ws^{0.5}m^{-2}K^{-1}$]. This value has been used as thermal absorptivity of polyester in cake form for the calculation of thermal absorptivity of knitted rib.

3.17.3 Final equation for thermal absorptivity prediction

Discussion of the development of thermal absorptivity based on porosity in section 2.5 . This discussion shows The following equation has been developed for the prediction of thermal absorptivity of rib knit fabrics.

$$b = b_p A\ (1-P_{HW}) \tag{3.13}$$

Where b represents the thermal absorptivity [$Ws^{0.5}m^{-2}K^{-1}$] of fabric and bp is the thermal absorptivity of polyester in cake form, PHW shows porosity [1], and A is the relative contact area [1] between human skin multiplied by the porosity and the relative contact area of knitted rib to find the thermal absorptivity of rib knit. In this approach, the value of thermal absorptivity of polyester was calculated using the standard values of thermal conductivity, density, and specific heat capacity values of polyester in solid form and entering them in equation 3. Then the calculated value of thermal absorptivity of polyester in solid form is multiplied by the porosity and contact area of knitted rib to find the thermal absorptivity of rib knit fabrics. This is a novel approach, which proves that by using this method the thermal absorptivity of any material can be predicted.

$$b \propto A \text{ (Contact Area)} \tag{3.14}$$

$$b \propto \text{Porosity } (1-PHW) \tag{3.15}$$

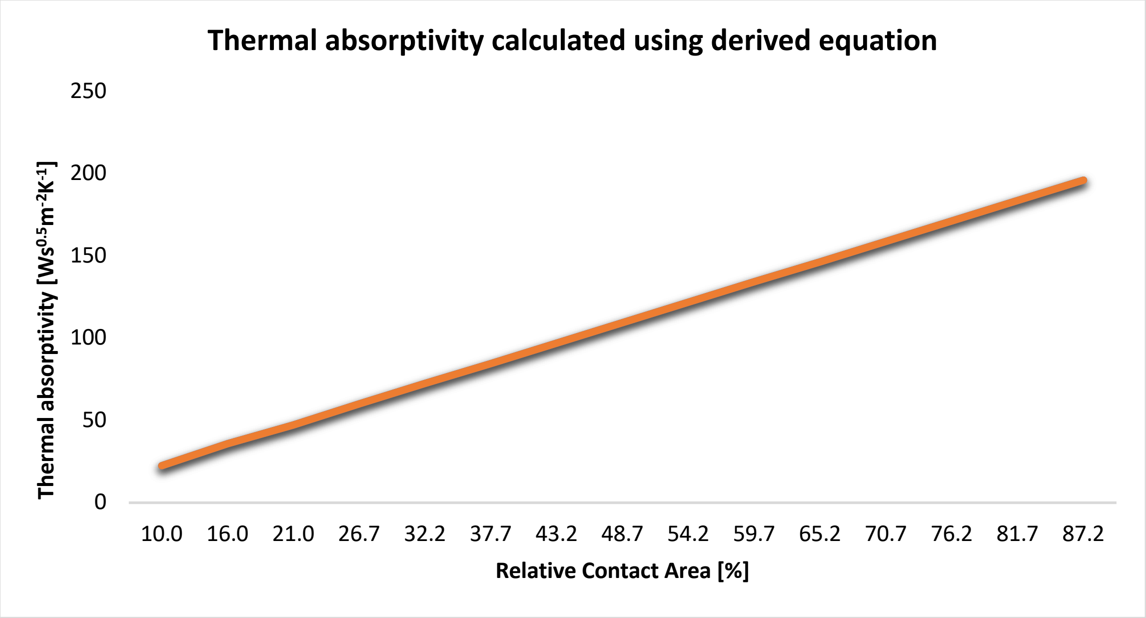


Figure 3-28 Thermal absorptivity calculated using derived equation

The contact area is the only parameter which has been used as an independent variable. The thermal absorptivity of polyester in solid form is a constant. However, all 15 samples have different porosity values. For calculation purposes, the average value of porosity has been taken. This is done to measure the impact of the contact area on thermal absorptivity of rib knit fabrics alone. There are two reasons to take the constant value of porosity. Firstly, there is no significant difference in porosity in all the 15 samples, the maximum value is 0.762, and the lowest value is 0.697, and the average is 0.72. Secondly, there are many earlier studies where the less significant factor with a minor variation has been taken as a constant, and its values have been kept constant to get a better view of the impact of the most significant factor on the dependent variable [84-86].

The outcome of the research tells us that there is a significant correlation between actual and simulated values of thermal absorptivity. This model is based on the concept of thermal contact absorptivity, which explains the role of contact points and thermal absorptivity in solid form or thermal absorptivity in cake form of any polymer when there is no foreign element like, air, moisture, or any other polymer present. The average porosity is 0.28, and the thermal absorptivity for all measured samples was above 834 [$Ws^{0.5}m^{-2}K^{-1}$].

Table 3-25: Contact area, porosity and thermal absorptivity

Paired Samples Statistics					
		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	Simulated Thermal Absorptivity	116.6667	15	52.14905	13.46483
	Measured Thermal Absorptivity	131.6267	15	35.09742	9.06212

Paired Samples Correlations				
		N	Correlation	Sig.
Pair 1	Simulated Thermal Absorptivity & Measured Thermal Absorptivity	15	.982	.000

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Simulated Thermal Absorptivity - Measured Thermal Absorptivity	-14.96	18.88816	4.8769	-25.41991	-4.50009	-3.068	14	0.008

Table 3-26: Thermal absoprtivity calculated and measured=

Sample no	Contact Area [%] assumed	Contact area [%] measured	Porosity	Thermal absorptivity of polyester in solid form [$Ws^{0.5}m^{-2}K^{-1}$]	Thermal absorptivity of rib calculated [$Ws^{0.5}m^{-2}K^{-1}$]	Thermal absorptivity of rib measured [$Ws^{0.5}m^{-2}K^{-1}$]
1	0.10	0.13	0.27	834	23	37.8
2	0.16	0.23	0.27	834	36	50.2
3	0.21	0.46	0.27	834	47	102
4	0.27	0.51	0.27	834	60	114
5	0.32	0.52	0.27	834	72	107
6	0.38	0.54	0.27	834	85	115
7	0.43	0.55	0.27	834	97	120
8	0.49	0.59	0.27	834	110	129
9	0.54	0.6	0.27	834	122	135
10	0.60	0.61	0.27	834	134	139
11	0.65	0.65	0.27	834	147	145
12	0.71	0.71	0.27	834	159	163
13	0.76	0.76	0.27	834	172	171.3
14	0.82	0.79	0.27	834	184	181.5
15	0.87	0.81	0.27	834	196	195.6

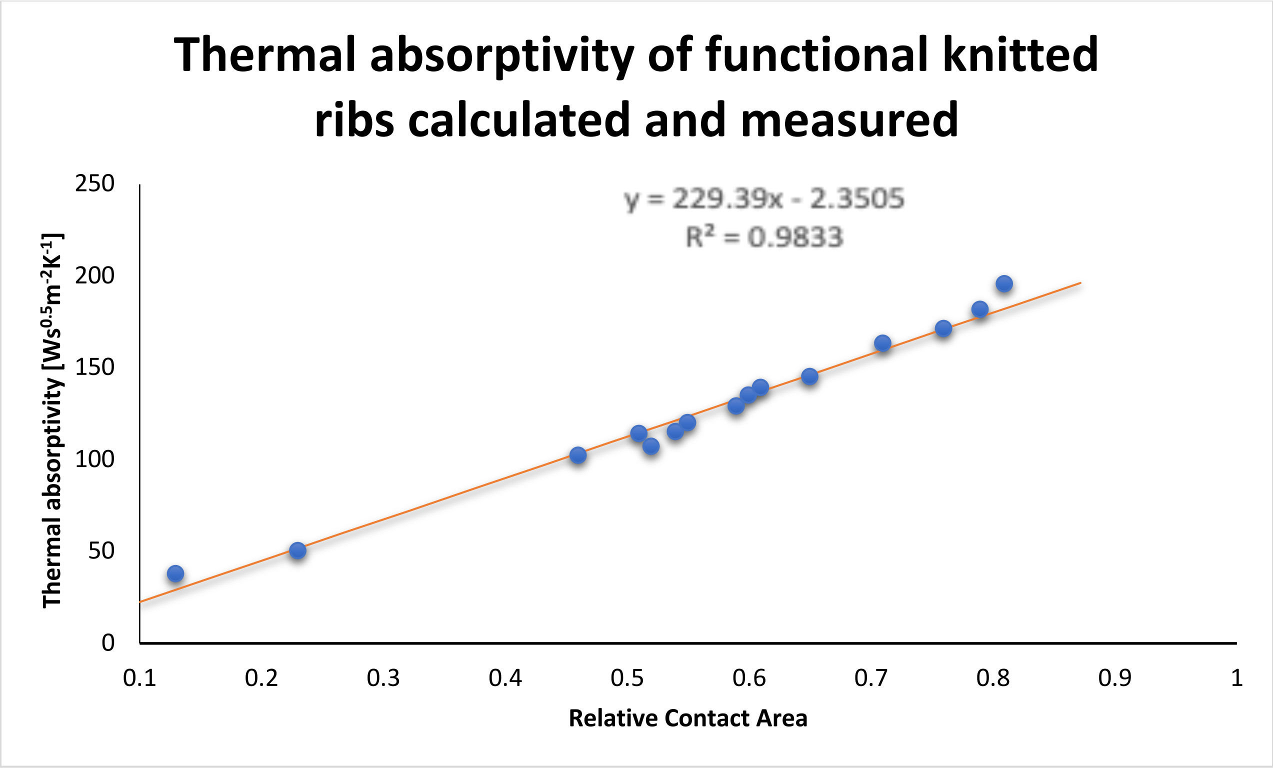


Figure 3-29: Thermal absorptivity of functional knitted ribs calculated and measured

Table 3-27: Regression model estimate

	Thermal absorptivity [Ws$^{0.5}$m^{-2}K^{-1}] of rib calculated			Thermal absorptivity [Ws$^{0.5}$m^{-2}K^{-1}]of rib Measured		
Coefficient	**B** (Std. Err.)	**t-value**	**p-value**	**B** (Std. Err.)	**t-value**	**p-value**
Intercept	-0.2 -0.1978	1.011	0.33	37.586 -8.3131	4.5213	0
Relative Contact Area	2.34 -0.004	644.386	0	1.639 -0.1402	11.684	0
R-Square Adjusted R-Square	0.9999 0.9999			0.9555 0.913		
F-Value	415233					136.508 0
Pr(F>0)	0					

The regression models above shows the relationship between Thermal absorptivity of rib calculated/Measured (Dependent variables) and Relative Contact Area (Independent variable). From the table above we found that the regression models are highly significant with (F=415233, p-value <0.001). R square which is the amount of variation in the independent variable explained by the dependent variable shows that relative contact area explained 99.99% of the variation in Thermal absorptivity of rib calculated and 98 % of the variation in Thermal absorptivity of rib Measured. Therefore, we can conclude that there is significant and strong relationship between measured and calculated value of Thermal absorptivity of rib.

(Model published in Autex Research Journal Published online: 2017-04-22)

3.18 Subjective evaluation

Subjective and objective evaluation methods were applied to measure the impact of change in the surface profile because of the enzymatic treatment on a warm–cool feeling. For subjective evaluation, a group of 30 people were engaged. Alambeta was used for objective evaluation of thermal absorptivity, which is an indicator of the warm–cool feeling. Subjective evaluation is a process where people are asked to express their feeling. A number of studies have been conducted to measure the impact of any physical change in textile material through subjective evaluation [18-23].

3.18.1 Comparison of functional and traditional knitted rib

For this study the following procedure was adopted for subjective evaluation of two different types of knitted rib samples:

1. Two knitted rib samples were prepared for testing.
2. Six areas were marked for evaluation and comparison of the hand values (tactile comfort).
3. Evaluation sheets were prepared using an ordinal scale 1-7 (where 1 means poor property, 7 means excellent property).
4. People were chosen indiscriminately from different social groups. There was a total of thirty people (15 males and 15 females) **to be used as evaluators**.
5. The evaluators were expressly informed about the importance of the tests in question and the ways to provide their observation.

6. A closed evaluation box was used so that the evaluators could give their feeling without visual observation of the samples. This was done to avoid any influence of the sample’s visual appearance.
7. Air-conditioned rooms, where the temperature was between 20-22° C and relative humidity was 50-60 % were used to record the observations.

The objective of the study is to find any diversity between the two different knitted rib fabrics. Tactile properties of fabric have a strong link with its construction, type of yarn (ring, rotor or friction), and twist level of yarn. Keeping that in mind and the following questions were selected to investigate the impact of weft variation.

These six questions were formulated:

1. What is your opinion on the overall comfort of this sample?
2. Do you feel that the fabric surface is smooth?
3. Do you feel that the fabric is stretchable?
4. In the initial two seconds, do you feel that the fabric is cool?
5. Do you feel that the fabric is handful and bulky?
6. Do you feel that the fabric is soft?

The evaluators had previously been informed about the evaluation procedure. They were asked to give their judgment on a scale of 1-7. One meaning the lowest value, while seven means the highest value.

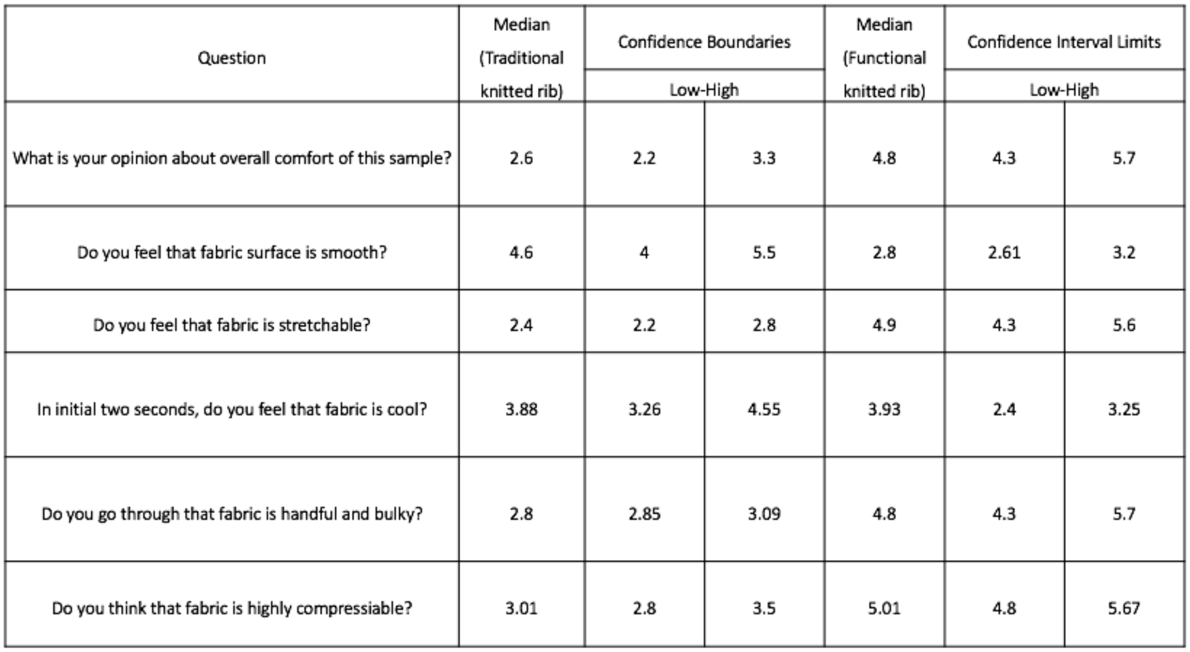
Thirty evaluators were engaged in the evaluation process to compare two knitted rib fabrics having distinguished surface profile. The group of evaluators was 50% male and 50% female. Their age ranged from 20 years to 35 years old. The minimum education criteria were graduates or people who were due to graduate. This precaution was adopted to ensure a more mature evaluation. Furthermore, all observers were users of knitted rib clothing.

One can derive the following conclusions from the Table 5-14

1. People feel that the overall comfort of functional knitted rib is higher than traditional knitted rib.
2. The surface of traditional knitted rib is smoother than functional knitted rib.
3. Functional knitted rib is more stretchy than traditional knitted rib.

4. Traditional knitted rib provides a cool effect. It is an indicator that traditional knitted rib takes heat from the human body as compared to functional knitted rib.
5. People view traditional knitted rib as bulky in nature.
6. Functional knitted rib is more compressible compared to traditional knitted rib.

Table 3-28: Median comparison of functional and conventional knitted ribs



Question	Median (Traditional knitted rib)	Confidence Boundaries		Median (Functional knitted rib)	Confidence Interval Limits	
		Low-High			Low-High	
What is your opinion about overall comfort of this sample?	2.6	2.2	3.3	4.8	4.3	5.7
Do you feel that fabric surface is smooth?	4.6	4	5.5	2.8	2.61	3.2
Do you feel that fabric is stretchable?	2.4	2.2	2.8	4.9	4.3	5.6
In initial two seconds, do you feel that fabric is cool?	3.88	3.26	4.55	3.93	2.4	3.25
Do you go through that fabric is handful and bulky?	2.8	2.85	3.09	4.8	4.3	5.7
Do you think that fabric is highly compressiable?	3.01	2.8	3.5	5.01	4.8	5.67

3.19 Subjective evaluation of enzymatic treatment effect

A group of 30 people was asked about the warm-cool feeling of the samples. They were provided with a set of two samples. One sample was treated with enzymes, and the other was untreated. They were asked: "Which sample gives a warmer feeling? They were also provided with an option that they could say if they found no difference. Table 5.16 depicts that 32% evaluators felt that the enzyme-treated fabric gives a warm feeling and 43% of them felt that untreated fabric gives a warm feeling and 25% of the evaluators said that they felt no difference between the enzyme-treated and the untreated fabrics. Subjective evaluation shows that that the enzyme-treated fabric gives a cool feeling. This might be due to the contact points. A smooth surface provides more contact points with the skin when a hand is put on it. Our subjective evaluation confirms the objective evaluation measured using Alambeta.

Table 3-29: Subjective evaluation of treated and untreated fabric

Sample No	Treated Fabric (Feels warmer)	Untreated Fabric (Feels warmer)	No Difference between Treated and Untreated fabric
1	3	6	21
2	15	9	6
3	3	18	9
4	12	15	3
5	18	6	6
6	9	12	9
7	6	18	6
8	9	15	6
9	12	6	12
10	3	18	9
11	9	15	6
12	6	18	6
13	3	21	6
14	9	9	12
15	12	15	3
16	6	18	6
17	6	21	3
18	6	15	9
19	15	15	0
20	9	6	15
21	12	9	9
22	15	6	9
23	18	6	6

Sample No	**Treated Fabric (Feels warmer)**	**Untreated Fabric (Feels warmer)**	**No Difference between Treated and Untreated fabric**
24	15	12	3
25	12	12	6
26	6	12	12
27	6	21	3
28	9	9	12
29	9	15	6
30	9	9	12
31	12	12	6
Total	294 (32%)	399 (43%)	237 (25%)

4 CONCLUSION

- The main objective of this study was to find the effect of contact points on thermal parameters. For testing purposes, knitted rib samples were produced using polyester yarn. Different testing equipment was used to measure the correlation between contact points and thermal absorptivity. The results demonstrate that there is a significant change in thermal parameters, with respect to changes in contact points between human skin and fabric. It shows that the surface profile of fabric plays a significant role in thermal parameter values. Thermal parameters are the factors, which determine the clothing comfort.
- An increase in contact points increases the heat flow from one side to the other, which will result in heat flow transferring from the skin to the environment and a cool feeling being observed. Moreover, the thermal resistance of fabric will be high in cases where the contact points between human skin and fabric is on the lower side. This is primarily due to the presence of fluid (air) on the surface of fabric.
- The warm-cool feeling is one parameter, which is usually always noticed by users during a touch between fabric and human skin. This property is called the thermal absorptivity. There is a significant correlation between thermal parameters and contact points (surface profile). This can be observed from the data obtained from testing the knitted rib. The data further confirms that a minimum touch between human skin and the knitted rib provides a warm feeling during an initial touch and provides better clothing comfort for the user.
- Bio-polishing and singeing processes were carried out to make fabric surface clean and smooth. It was found that fabric with a smooth surface after enzymatic treatment and singeing treatment provided a cool feeling and their thermal absorptivity values were higher than when untreated.
- The prediction of thermal absorptivity was one of the problems which was solved and the main outcome of this research. A model was developed using a unique technique for the simulation of thermal absorptivity with reference to contact points. For this purpose, a new term, “thermal contact absorptivity” was coined.

- Thermal contact absorptivity is the property of any fabric and is related to the surface profile of the fabric. Surface profile is the factor that determines the contact points between human skin and a fabric. The proposed model based on simulation was matched with the actual values, and a significant correlation was found. This confirms the validity of the proposed model.
- For subjective evaluation, a group of thirty people was asked to give their opinion about warm-cool feeling by touching the fabric. Data was analysed to find the significant difference between two sets of values. Both objective and subjective evaluations show that there is a significant difference between fabric treated with enzymes and untreated fabric.
- Some effort in this study focused on the behaviour of water vapour permeability and thermal resistance of rib knit fabrics. This was carried out using the orientation of ribs, when airflow direction was considered and was given in the parallel and perpendicular way. The ratio of parallel/perpendicular to the orientation of the ribs with respect to airflow was used for evaluation. It was found that thermal resistance was higher for the parallel samples, and the increase reached at least 10% compared to a perpendicular orientation of ribs with respect to the airflow. It means that a parallel arrangement of ribs leads to a decrease in relative water vapour permeability. However, a difference higher than 10% was only found in one sample. Therefore, the orientation of ribs in respect to the airflow does not play a big role for relative water vapour permeability. Whereas, for thermal resistance, it was found that the orientation of ribs can play a role for thermo-physiological comfort.
- A test was carried out to find the impact of knitted rib orientation on relative water vapour permeability. Results show that orientation of ribs in respect to the airflow does not play as big a role for relative water vapour permeability as it does for thermal resistance.
- KES was used to measure the surface profile of knitted rib. It was found that there was a significant difference in friction when different techniques are applied to develop knitted rib.
- For testing purpose, 15 knitted rib samples were produced. One was similar to the traditional knitted rib fabric produced and used for inner clothing. This is called a traditional knitted rib fabric and has maximum contact points when brought into touch with human skin. Using different knitting techniques, a sample was produced that is not in common use, which has the lowest contact points when put onto human skin. This sample is called “Functional Knitted Rib”. This

functional knitted rib has the lowest thermal parameters and provides warm-feeling during initial touch and gives better clothing comfort. This is the second major outcome of the research.

4.1 Patent application

It is quite difficult to develop a knitted rib which only has 12.9% contact area, while traditional knitted rib has 78.00 % contact area when it is put on human skin. Such a knitted rib was developed by the author for the purpose of this thesis. Moreover, it is a stable knitted rib fabric that clothing can be made with. This new product was tested systematically, and it was proved that the new knitted rib fabric is much more feasible for human beings. Based on our results, the Evaluation and Testing department, Faculty of Textile of Technical University have decided to apply for its patent.

4.2 Future research

Further research has already been initiated to develop a knitted rib fabric from singed yarn and conduct systematic testing to find the impact singed yarn has on its thermal parameters.

4.3 Author publications

1) Qurbat.Z., Mudassir.A., **Mangat. A**., Sajid.H. Air and moisture comfort properties of woven fabric from selected yarns Industria Textila Volume .69, nr.3 March 2018 Impact **Factor 0.57**
2) **Mangat, A**., Hes, L., Bajzik, V and Mazari, Adnan., Thermal absorptivity model of knitted rib fabric and its experimental verification Autex Research Journal Published Volume.18, No 1 March 2018, DOI: 10.1515/aut-2017-0003 **Impact factor (0.716)**
3) **Mangat, A**., Bajzik, V., Mazari, A., Zuhaib. A. Influence of airflow direction on thermal resistance and water vapour permeability of rib knit fabrics Tekstil ve Konfesyon, Volume 27, Issue 1, Pages 32 – 37, 2017 ISSN: 1300-3356, [Thompson ISI/Scopus] Impact **Factor 0.26**
4) **Mangat, A.,** Hes, L., Bajzik, V., Funda, B., Model of Thermal Absorptivity of Knitted Rib in Dry State and its Experimental Authentication Industria Textila, accepted 2017 [Thompson ISI/Scopus] **Impact Factor 0.57**
5) **Mangat, A**., Hes, L., Bajzik, V., Funda, B. Impact of Surface Profile of Polyester knitted rib structure on Its Thermal Properties, Industria Textila, ISSN: 1222–5347, 2016 volume 67 nr 2 p. 103-108 [Thompson ISI/Scopus] **Impact Factor 0.57**
6) **Mangat, A.,** Hes, L., Bajzik, V., Funda., B, the use of artificial neural networks to estimate thermal resistance of knitted fabrics”. Tekstil ve Konfesyon, ISSN: 1300-3356, 2015. 25(4): p. 304-312[Thompson ISI/Scopus] 2016 **Impact Factor 0.26**
7) **Mangat, A.,** Hes, L., Bajzik, and V. Effect of Bio-Polishing on Warm-Cool Feeling of Knitted Fabric: A subjective and objective evaluation, Autex Research Journal, ISSN 1470-9589 **2016** Impact **Factor 0.716**
8) **Mangat, A.**, I. A. Shaikh, F. Ahmed, S. Munir, M. Baqar, Fenton Oxidation Treatment of Spent Wash-Off Liquor for Reuse in Reactive Dyeing, Technical Journal, University of Engineering and Technology (UET) Taxila, Pakistan ISSN: 1813-1786 (Print), Vol (19), 2014

4.3.1 Under Review / Process International Journals

9) **Mangat. A**., Hes. L., Bajzik, V. Effect of surface area and relative moisture content on thermal resistance of knitted rib Fabrics Vlakna Textil, (Scopus) (Submitted)

4.3.2 Conferences and workshops

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2. **Mangat, A.**, Hes., L., Bajzik, V Effect of surface profile on knitted ribs This, Textile Conference RMIT, Melbourne 2016
3. **Mangat, A.,** Effect of verticalization in textile industry Strutex, 2012
4. **Mangat, A.,** Effect of thermal conductivity and thermal absorption on 100 % knitted ribs by changing rib structure Svetlanka 2014
5. **Mangat, A.,** experimental analysis of effect of rib geometry on thermal absorptivity of PES knits Svetlanka 2015
6. Muhammad Mushtaq Mangat, Tanveer Hussain, Lubos Hes and **Asif Elahi Mangat**, "Impact of Fibre Content and Porosity on Overall Moisture Management Capability of Fleece Fabrics", 2nd International Conference on Value Addition and Innovations in Textiles COVITEX-2013, Venue: Faisalabad, Pakistan, (2013)

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