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Faculty of Textile Engineering

THERMAL ABSORBTIVITY AND OTHER THERMAL COMFORT PARAMETERS OF RIB KNITTED FABRICS

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SUMMARY OF THE THESIS

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Abstract

The objective of this study is to find out the impact of changing the profile of functional knitted ribs on the thermal properties of fabric, including thermal conductivity, thermal absorptivity, and thermal resistance. This introduces 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 samples. The study endorses the finding that variation in surface profile has a substantial impact on 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 contact points between two surfaces. The model was developed using a novel approach and has 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 is predominantly due to the increase in contact points, which provides 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 also measured and it was found that there is a significant impact from direction of air and water permeability. The study concludes that 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 gives 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, že 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, že 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, že 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, že směr má významný vliv na propustnost vzduchu a vody. Studie dospěla k závěru, že 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 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 fiber 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.

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 Objectives of the Thesis

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. 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.

5. Fair analysis of air and moisture permeability, geometrical roughness, and surface friction of conventional and functional knitted rib.
6. 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.

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 [$Jkg^{-1}K^{-1}$][1-6].

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. 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

$$\alpha \ (t_1 - t_2) = - \ \lambda \cdot \frac{dt}{dx} \tag{2.1}$$

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).

2.2 Thermal absorptivity - an indicator of warm-cool feeling

Thermal absorptivity was discussed in detail by Nield and Bejan [7]. 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 [7]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 [8].

Hes and Dolezal [5] 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 [8] 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

[9] 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 [9] 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 [8]. 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 [9] 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 [10]. 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 [11].

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

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

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, h_1 and contact time is:

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

The above figure 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 [9].

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 [12] 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. 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. 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.

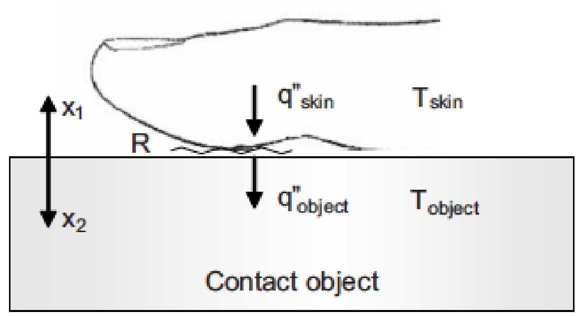

Figure 2-1 Schematic representation of the heat transfer during hand-object interactions

Figure 2-1 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 [13].

2.3 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 [12] 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.

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 [7] 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 [7], 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.

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

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.

2.4 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 [14].

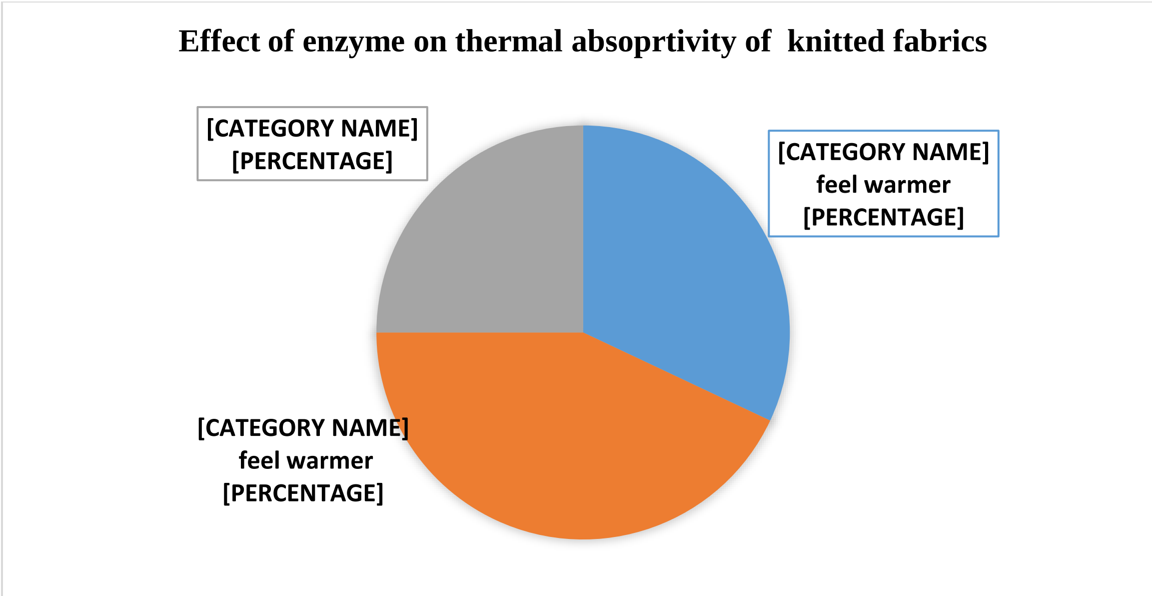

Figure 2-2 Effect of enzyme on thermal absorptivity of knitted fabrics

2.5 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 [15] 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.

2.6 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 [16].

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

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 [17-19]. 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.

$$R_{rat} = \frac{R_{\mathrm{par}}}{R_{per}} \tag{2.13}$$

$$RWVP_{rat} = \frac{RWVP_{par}}{RWVP_{per}} \tag{2.14}$$

2.8 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.

3 Porosity and its measurement

3.1 Porosity, thermal absorptivity, and heat capacity

Nield and Bejan [7] 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. This equation also ignores the micro volume of the fabric. 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 [20].

$$\varepsilon = \frac{\rho_w}{\rho_f} \tag{3.1}$$

$$P_d = 1 - \varepsilon \tag{3.2}$$

Where:

$P_d$is porosity "density" with reference to density, $\rho_w$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 fibbers and rest is the porous area of the fabric. The average porosity is above 70 %.. 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 [21].

Das calculated the porosity of fabric by

$$\text{Porosity (p)} = 1 - \frac{\text{Volume of the yarn in unit cell}}{\text{volume of the unit cell}} \tag{3.3}$$

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 [22]

$$P_{HW} = 1 - \frac{\text{volume coverd by yarn}}{\text{whole accessible volume}} \quad (3.4)$$

$$P_{HW} = 1 - \frac{\upsilon_y}{\upsilon_V} \quad (3.5)$$

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

4 Experimental Part

Samples were made by using 100% pure polyester no blending with any other fibber 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 fibber fabrics [23]. 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 [24] . A flat knit machine was used in making 100% PES knit rib samples, and a gauge was set from 8 to 12 have been 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[25].

4.1 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 4-1 Sample description.

Sample no	Rib Type	Wales per [cm]	Courses per [cm]	Square mass [gm^{-2}]	Contact area [%]
1	1x6	10	12	501	13
2	1x3	11.2	13	400	23
3	1x2	9.6	11.2	541	46
4	2x3	9.4	12	560	51
5	2x1	8.4	12	462	52
6	3x4	10.4	10.8	523	54
7	1x4	9	9	477	55
8	2x2	9.6	12	471	59
9	1x1	8	13	485	60
10	3x3	8.4	10.4	548	61
11	4x4	10.4	12	540	65
12	2x1	8.2	10	540	71
13	4x3	7	9	378	76
14	4x2	10	12	422	79
15	3x1	8.2	10	447	81

4.1.1 Image Analysis of samples for measuring the contact area

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 4-1 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.

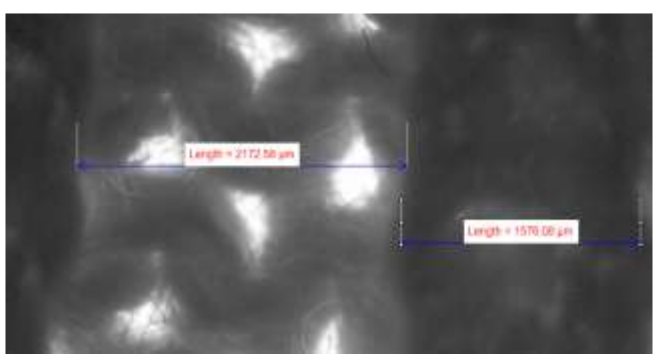

Figure 4-2 Image Analysis by Microscope for measuring contact area

4.2 Relative Contact 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.

$$C = \frac{F}{F + B} \times 100 \tag{4.1}$$

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

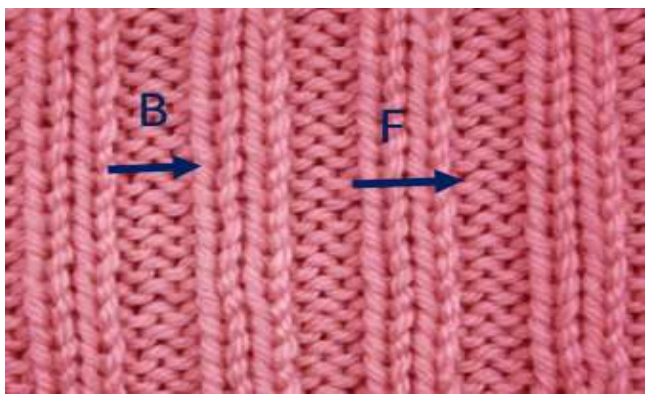

Figure 4-3 calculation of relative contact area by fin and area between two rows of courses

In above figure B is the area between the courses and F is the area of the fin on the top.

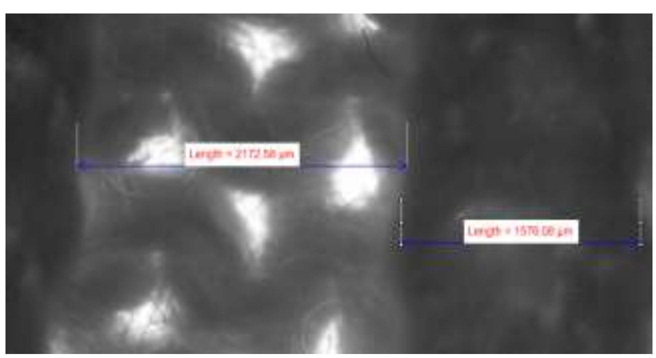

Figure 4-4 Microscopic view to calculate the relative contact area

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. More than 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.

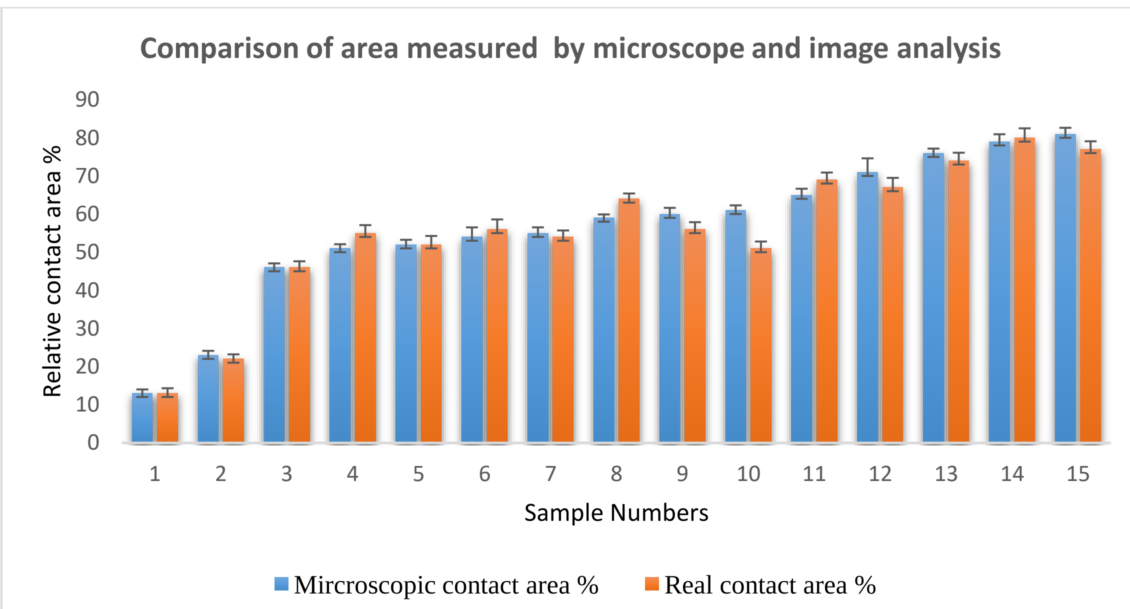

Figure 4-5 Comparison of Image analysis of different methods

5 Evaluation of results and discussion

5.1 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.

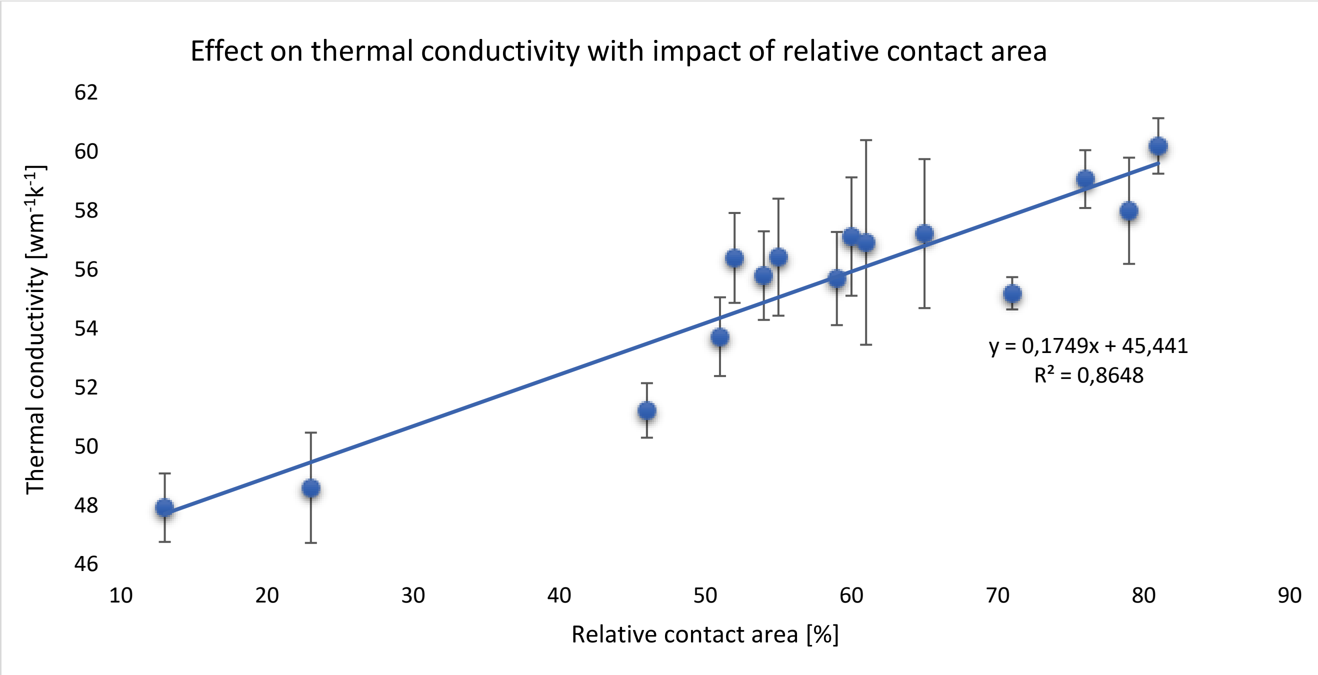

Figure 5-1 Effect on thermal conductivity of the fabric with the impact of relative contact area [%].

5.2 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.

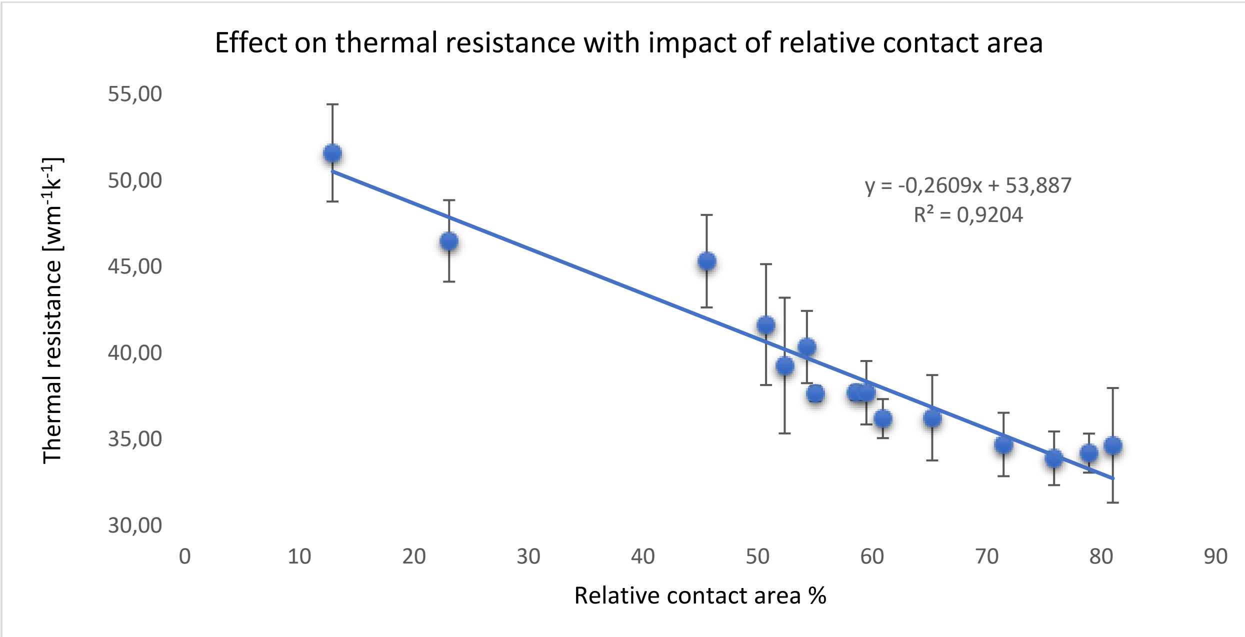

Figure 5-2 Effect on thermal resistance of the fabric with impact of relative contact area (%)

5.3 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. 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.

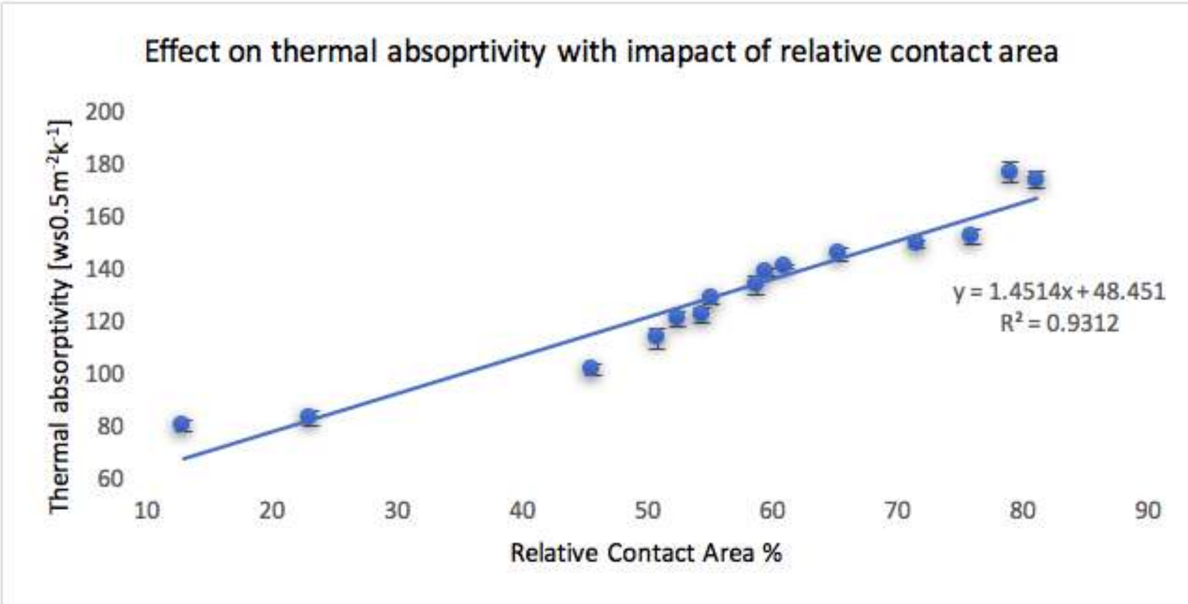

Figure 5-3 Effect on thermal absorptivity of the fabric with impact of relative contact area %

5.4 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 1.099, and the highest value is 1.538. 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 0.63, and the highest value is 1.635. 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 0.796, and the maximum value is value is 1.152 on the front, and lowest value on the back is 3.135, 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 [26] .

It is the same case with the mean deviation of surface contour (SMD). The front has 3.296 as its lowest values, while its highest value is 5.737. A similar variation is found on the back of knitted rib, where the lowest value is 1.211, and the highest value is 1.792.

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 5-1 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	2x1	1.792	1.538	1.24	1.03	4.136	4.097
2	2x1	1.753	1.396	1.011	0.918	3.848	3.633
3	3x1	1.738	1.46	0.967	1.045	5.127	4.38
4	1x1	1.714	1.45	0.815	0.84	5.132	3.955
5	1x2	1.548	1.187	0.894	0.903	3.135	3.296
6	6x1	1.509	1.099	1.635	0.991	5.75	5.737
7	2x3	1.465	1.465	1.021	0.967	4.355	4.609
8	2x2	1.455	1.528	1.05	1.152	4.395	3.887
9	1x1	1.357	1.143	0.63	1.099	5.625	5.322
10	3x4	1.348	1.133	1.157	0.796	4.346	4.233
11	3x3	1.323	1.201	0.85	0.947	5.015	5.093
12	4x4	1.211	1.211	0.854	0.962	3.765	3.374
Minimum	1.211	1.099	0.63	0.796	3.135	3.296	1.211
Maximum	1.792	1.538	1.635	1.152	5.75	5.737	1.792
Average	1.518	1.318	1.010	0.971	4.552	4.301	1.518

5.5 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.

5.6 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,

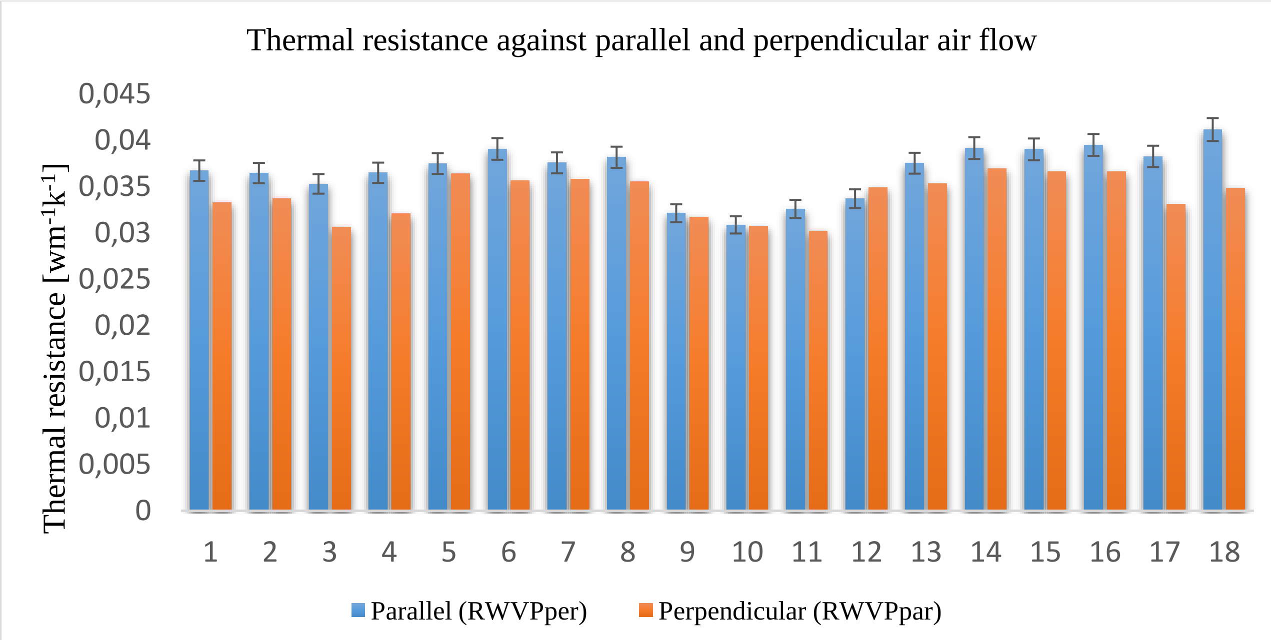

Figure 5-4 Thermal Resistance of fabric measured parallel and perpendicular against the airflow

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.

5.7 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.

5.7.1 Porosity calculation

Porosity is a concept, which is commonly used in various fields. Militký and Havrdová [27] 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 [27] has been used to measure the porosity.

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

$$P_{Hw} = 1 - \frac{\rho_f}{\rho_p} \tag{5.1}$$

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.

5.7.2 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 [28] Wiley-VCH, has been used to note thermal conductivity, density, and the specific heat capacity values of polyester.

Table 5-2 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 [$Jkg^{-1}K^{-1}$]

$$b = \sqrt{0.3 * 1450 * 1600} \qquad (5.2)$$

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.

5.7.3 Final equation for thermal absorptivity prediction

Discussion of the development of thermal absorptivity based on porosity. This discussion shows

The following equation, 5.3, has been developed for the prediction of thermal absorptivity of rib knit fabrics. Equation 5.3 is based on simulation.

$$b = b_p \mathrm{A}\ (1\text{-}P_{HW}) \qquad (5.3)$$

Where b represents the thermal absorptivity [$Ws0.5m^{-2}K^{-1}$] of fabric and bp is the thermal absorptivity of polyester in cake form. P_{HW} 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 (Contact Area)
- b $\propto$ Porosity (1-P_{HW})

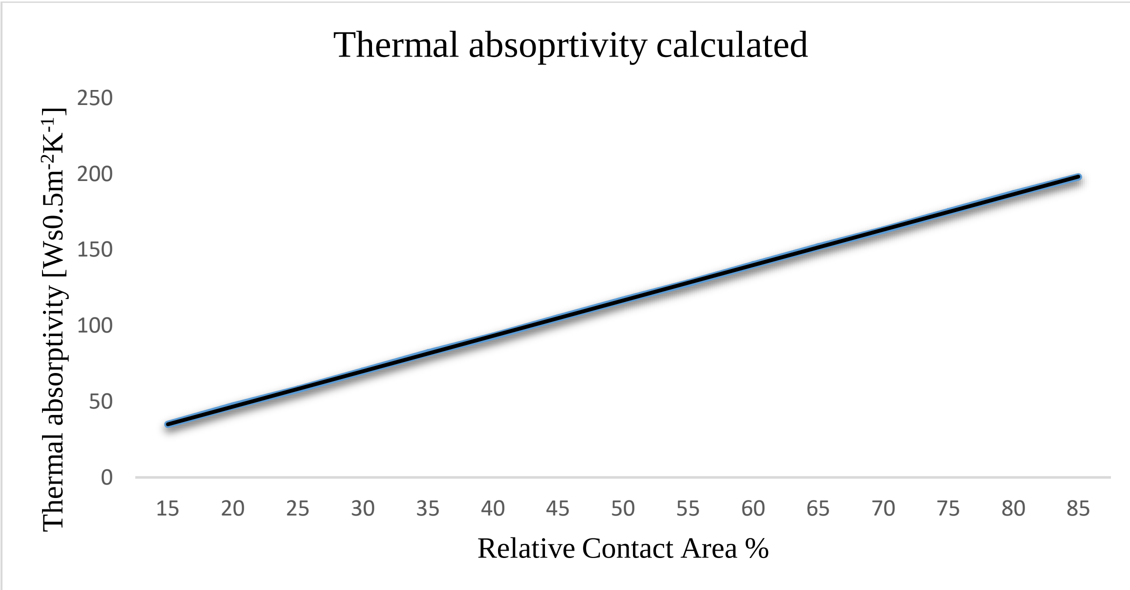

Figure 5-5 Thermal absorptivity calculated using derived equation

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 [29-31]

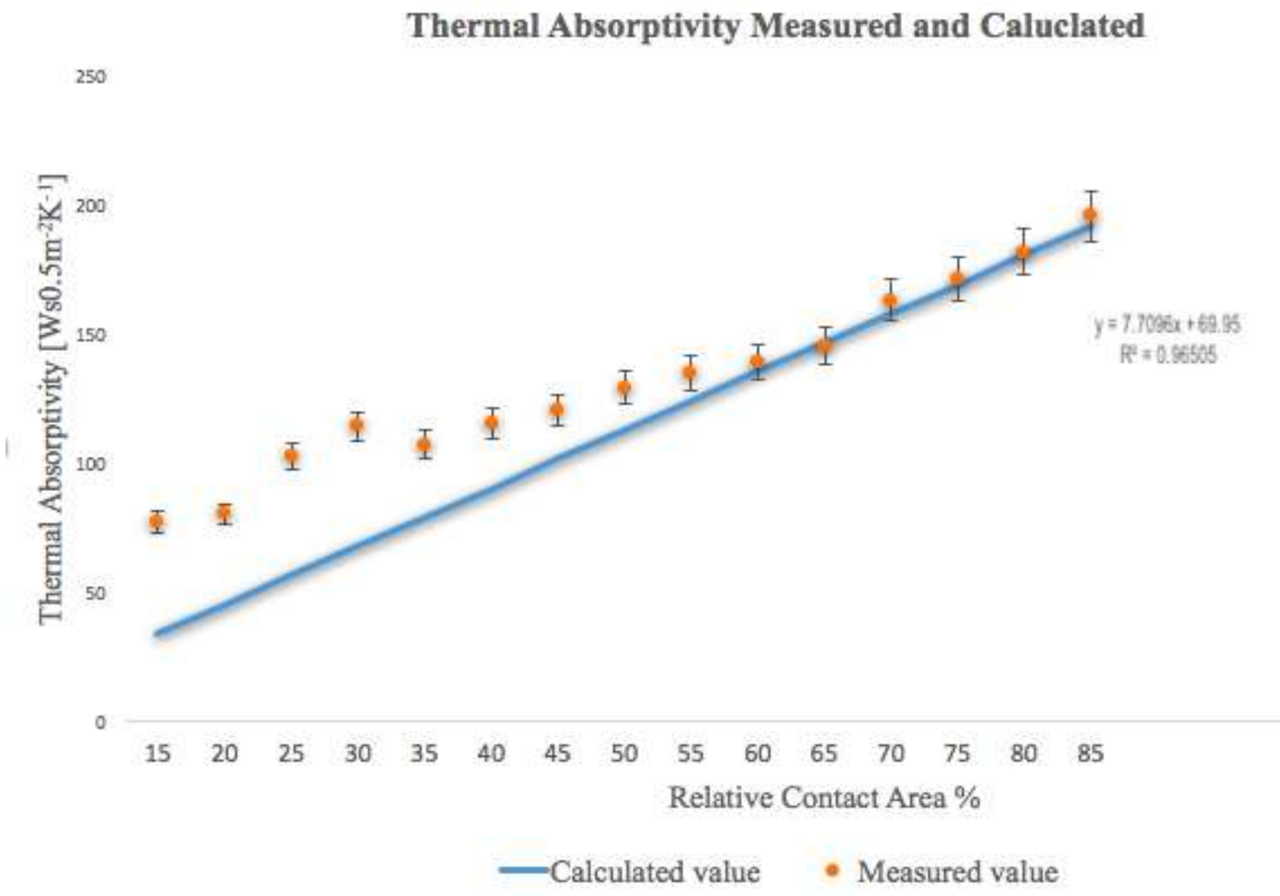

Figure 5-6 Thermal absorptivity of functional knitted ribs calculated and measured

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

6 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.

6.1 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.

6.2 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

6.2.1 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)

6.2.2 Conferences and workshops

1. **Mangat, A.**, Lubos Hes., "Effect of enzymes on thermal absorptivity of knitted fabrics "International conference on Textile clothing (ICTC-2017) Venue Lahore Pakistan. (2017)

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 Fiber 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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6.3 Curriculum Vitae

Asif Elahi Mangat

Date of Birth: 20th June 1986

PROFILE

- A well presented, self motivated graduate with versatile experience in ***garments manufacturing, merchandizing, and textile teaching.***
- A creative individual having excellent sense of teamwork to get the results with his commitment, trust, fairness and loyalty.
- Seeking a challenging and rewarding opportunity to demonstrate substantial abilities in healthy academic environment.

EDUCATION

PhD in Textile engineering **2012-2018**

- Clothing comfort
- Textile Clothing
- Textile Production
- Textile management
- **Technical University of Liberec Czech Republic.**

Masters of Science, Textile Clothing and management **2010-2012**

- (Trade and Retail)
- Human Resources Management / Financial Management
- Product Development
- International Trade, Global Marketing,
- **Advanced Management Skills**
- Supply Chain Management
- Special Textile Technologies

- **The University for the Niederrhein, Germany.**

Masters of Business Administration **2009 – Continue**

- (Supply chain management)
- **University of Management & Technology, Lahore, Pakistan**

Bachelors of Science, Textile Engineering **2004-2008**

- (Garment manufacturing)
- **University of Management & Technology, Lahore, Pakistan**

EMPLOYMENT HISTORY

- **Garment Production engineer** in Made for School **(Australia)** November 2017 till now.
- Lecturer University of management and technology Lahore January 2017 till July 2017
- Postgraduate teaching assistant in faculty of textile clothing, **Technical University of Liberec**.
- Volunteer teaching fellow at **Hochschule Niederrhein Monchengladbach, Germany**
- Research project assistant at **Textile department, Punjab university, Pakistan**
- Internship in **Jakob Muller AG Switzerland**
- Internship in **Uster Technologies Switzerland**
- Internship in **Reiter Management Switzerland**
- Internship in **Lindauer Dornier GmbH Austria**
- Volunteer teaching at **The citizen foundation (TCF)**
- **Assistant Manager Production 2009 – 2010** *Lahore, Pakistan*
- **Moderno apparels Merchandiser- 2008-2009** *Pakistan*

Record of the state doctoral exam

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Fakulta textilní

ZÁPIS O VYKONÁNÍ STÁTNÍ DOKTORSKÉ ZKOUŠKY (SDZ)

Jméno a příjmení doktoranda:	**Asif Elahi Mangat, M.Sc.**
Datum narození:	**20. 6. 1986**
Doktorský studijní program:	**Textilní inženýrství**
Studijní obor:	**Textile Technics and Material Engineering**
Termín konání SDZ:	**6. 10. 2016**

prospěl ~~**neprospěl**~~

Komise pro SDZ:

		Podpis
Předseda:	doc. Ing. Antonín Havelka, CSc.	
Místopředseda:	prof. Ing. Jiří Militký, CSc.	
Členové:	prof. Ing. Karel Adámek, CSc.	
	doc. RNDr. Miroslav Šulc, Ph.D.	
	doc. Ing. Martina Viková, Ph.D.	
	Ing. Irena Lenfeldová, Ph.D.	
	Ing. Adnan Ahmed Mazari, Ph.D.	

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Recommendation of the supervisor

Supervisor´s recommendation on PhD Thesis or Mr. Asif Mangat

„Thermal absorbtivity and other thermal comfort parameters of rib knitted fabrics“

The Thesis begins with systematic and comprehensive survey of state of art in the area of thermal absorbtivity of textile fabrics. In the next text, the basic theory some of thermal aborbtivity of materials and a new term was introduced and explained there: thermal contact absorbtivity. The main objective of the Thesis, which is the deveploment of a simple model of thermal contact absorbtivity of fabric and its experimental verification, was initiated by an introduction of an original simple algebraic model of thermal contact absorbtivity of fabrics. From the analysis of the partial differentical equation of transient heat transfer in a semiinfinite porous body resulted, that the fabric porosity can be also used in the new simple model (expression) for thermal contact absorbtivity of fabric.

This theoretical model was succesfully verified by experimental determination of thermal contact absorbtivity of 31 rib knitted fabrics with warying geometry of these ribs. This very large set of knitted polyester fabrics was manufactured personally by the candidate. The surface structure if the rib fabrics used in the study was systematically determined by means of the special TALYSURF instrument and by the Image analysis paint technology. Then the correlation between the predicted and experimental results was determined by means of advanced statistical method, and the results were very satisfactory.

Next study on thermal absorbtivity of knits involves the original analysis oft he effect of singeing on thermal contact properties of 12 samples, and the results were evaluated by means of advanced statistical methods.

Even more systematic was the study of the effect of ezymatic treatment on thermal absorbtivity and other sensorial comfort properties on altogether 31 knitted fabrics on thermal of these knits, and correlated with the subjective thermal contact assesments by 30 testing persons. All experimental results were treated by modern statistical methods, which confirmed the strong effect of treatment on all the studied properties.

Among the unique results presented in the Thesis belongs the study of the effect of the direction of air flow passing parallel with the surface of the knitted fabrics on thermal resistance and water vapour permeability The results of this extensive and very systematic study, based theoretical assumptions and on recent statistical methods confirmed, that the perpendicular air flow causes in all cases lower thermal resistance and higher water vapour permeability of the studied knits.

From the above survey follows, that the Thesis submitted by Mr. Asif Mangat presents a very original study, such as new theory of thermal contact absorbtivity of fabrics along with its experimental verification, new results on the effect of singeing on their thermal (contact) absorbtivity, the efect of enymatic treatment on thermal and sensorial comfort of the rib knits, confirmed by subjective evaluation, and last but not least, the effect of the direction of the air flow passing parallel with the surface of the knitted fabrics on thermal resistance and water vapour permeability. During his PhD studies, the candidate exhibited large creativity, originality, patience and high exprimental skills. The originality and importance of the achieved results acknowledges the publication of his results in six textile professional journals with high impact factors.

However, the Thesis still contains some imperfections and mistakes, but they are mostly formal, and do not lower the high level of this original contribution to the area of Textile Science. That is why I recommend the Thesis by Mr. Asif Mangat for the defence at the Faculty of Textile Engineering of the Technical University of Liberec, Czech Republic.

In Liberec, on Nov. 5th, 2018

Prof. Ing. Lubos Hes, PhD, DSc, Dhc
PhD supervisor

Opponent's reviews

Title of dissertation:	**Thermal absorptivity and other thermal comfort parameters of rib knitted fabrics**
Author:	Asif Elahi Mangat, M.Sc
Examined by:	Prof. Ing. Karel Adámek, CSc.

The presented work contains 100 pages, divided in several parts, as Introduction (7 p.), Review of the current state (32 p.), Porosity (5 p.), Evaluation and discussion of results (30 p.) and conclusion (4 p.). At the end author presents 85 references mentioned in the work and adequate number of 9 own publications and 6 conferences focused on the topic of the work.

Parameter of the thermal absorptivity was developed and defined at TUL in the 80's. This dissertation observes this parameter on set of 15 different anisotropic samples of knitted rib fabrics, in addition with different treatment of produced samples, really prepared, tested and discussed by the author.

Methods used by author are very complex, detailed, transparent and understandable – discussion of references, own theoretical and experimental procedures and comparison of their results.

The main topic of the dissertation – the thermal absorptivity of fabrics – is completed by observing of next thermal parameters influencing the comfort of clothing.

Schematic sample of ideal simulated surface – Fig. 2-16 and 2-17 (p. 40-41), taken over from study of image processing, seems to be ideal case for knitted rib after the Fig. 2-14 (p. 38), where the rib loops are very free. But the scheme of woven fabric after the Fig. 3-1 (p. 44), used for porosity definition, is very idealized. A real fabric is very deformed in both weft and warp directions (see for instance microscopic observation on TUL) and such simplification cannot be really used, I think.

Experimental data are really very extensive, so it could be useful to continue in evaluations. For instance, several bar diagrams, showing the values before and after treating, are not demonstrative enough. It should be better to create the correlation before/after and from received value of R^2 to state strong or feeble correlation for observed case. For instance, in the Fig. 5-5 the correlation is feeble, $R^2 = 0{,}3$, in the Fig. 5-6 the correlation is good, $R^2 = 0{,}8$ (both for quadratic function).

Similarly, to correlate the thermal conductivity and thermal absorptivity (Fig. 5-1, 5-3) p. 62 and 65, or to correlate the thermal resistance and relative water vapour permeability, Fig. 5-7 and Fig. 5-8 (p. 79) etc.

Some remarks or questions for discussion about the dissertation:

What about the model, mentioned in the Par. 1.2 (p. 5) as the aim No. 3?

White areas on the microscopic Fig. 4-12 (p. 57) are hollows in the low base or in the high ribs of knitted fabric? Relative contact area should characterize the ribs contacts, I think.

Water vapour permeability in the Tab. 5-13 (p. 77-78) is mentioned as the relative value, only. What about the absolute value.

Conventional versus "functional" fabric – I think that any clothing must be functional, otherwise is not usable – maybe a marketing term?

The defined goal – thermal absorptivity - is achieved, together with necessary focusing on many other parameters, influencing the comfort of clothing.
At the conclusion of my review I would state that presented dissertation fulfils all requirements of relevant internal rules of TUL and I do recommend the dissertation submitted by Mr. Asif Mangat for next procedure at the Faculty of textile engineering of the TUL.
In the case of the positive result of the defence of the dissertation I recommend to award the title of Ph.D.

Liberec, 25.11.2018
Karel Adámek

Review of doctoral thesis

Student: **Asif Elahi Mangat, M.Sc.**

Supervisor: prof. Luboš Hes, Dr.Sc., Dr.h.c.

Title of the thesis: **Thermal Absorptivity and Other Thermal Comfort Parameters of Rib Knitted Fabrics**

Field: Textile Technics and Materials Engineering
Working place: Department of Textile Evaluation, Faculty of Textile Engineering, Technical University of Liberec

This submitted doctoral thesis is devoted of studying of thermal absorptivity of rib knitted fabrics. Other thermal comfort parameters and properties of several different group of weft knitted samples including one group of woven fabric were also studied and mentioned.

The structure of thesis conforms to principles and requests to the structure of the scientific thesis. The topic of thesis is current and relevant in the context of up-to-date research in theory of thermal comfort parameters.

The author has performed good orientation and wide knowledge of the theory of thermal comfort considered in the thesis: theory of thermal absorptivity and heat transfer, as well as the thermo-physiological comfort are pointed the author's ability to perform the scientific work on the good level. It is evident that there are the theoretical knowledge and good view to the problem performed in this thesis, but only in the area of thermal comfort properties. The part of the structural yarn (multifil) properties and objectives as an input parameters which influenced the comfort properties of the produced knitted fabric – samples in submitted doctoral thesis are missing or are not very well discussed.

Chapters 1-2 are theoretical background of the research. In Chapter 2.16 *Knitted fabric structure and porosity*, the porosity is not mentioned and there were used knitted terminology with inaccuracy, i.e. terms:
Title of Figure 2 – 13 *Knitted fabric structure 1 x 1*, (both resources, original from prof. D.J. Spencer and other copied source, cited in this thesis, named that structure as Interlock). According author, this structure belongs to the rib knitted?
Is a term "*Rib loop*" the term for face (front) or reverse (back) loop/stitch?

Study of M.J. Pac (p.39) investigated the single jersey knitted fabric (36 tex, stitch length values 0,4 – 0,6 cm/stitch – totally different to the sample of this doctoral thesis) with the assumptions, and conclusions are not valid generally for all knitted structures. It is the same problem as the work of Semnani et all (p. 41) who mentioned 15 different knitted structures including single, double and interlock fabrics with different yarn count and different loop/cm^2, but they evaluated only two structure (double cross tuck and interlock with different structural parameters).

In Chapter 2.17 *Knitted rib and its structure* the "*rib stitch*" is described as "*blend of the two sides of the jersey stitch*". The sentences "*The rib stitch has the same appearance on both sides ...*"is not really correct. The knitted stitch is the basic unit of intermeshing, both side of that element has not same appearance and therefore we talk about face loop-side and reverse-loop side. If the term, which author used, „*the rib stitch*" consists of two loops (Fig. 2 -15, p. 40), the first element is reverse stitch and second is face stitch. When we turn the structure to the back side, the first element will be face and second will be reverse stitch. The appearance are not same.
The author mentioned (p. 39 and 40) that "*extensions of rib structures is about 140 %*" and advantage of rib stitch fabrics is "*fairly stable*". Those statements are in contrary.

The chapter 3.1 performed the porosity and its measurement for the textile fabric, but not knitted. The binding points of the stitch, the structure of rib knitted fabric which is not 2D, is totally different from the mentioned fabric (plain weave). There was written that the porosity was calculated by two methods, probably with using equations 3.9 and 3.11 (p.46).

The chapter 4 introduces the experimental part. It is the author's attempt to find firstly the connection between the structure (the geometrical parameters of knitted samples) and comfort prediction and secondly, the influence of the rib structures on the results from measuring of the properties with Alambeta, Permetest, Air Permeability Tester and Kawabata Evaluation System.

The part which deals with threads (yarns) only and their properties which influenced the knitted structures is still missing. We can find that the used material was "*100% pure polyester no blending with any other fibber...*" (p.47). This characterization is not enough for doctoral thesis. The knitting machine parameters and setting of working part (e.g. stitch cam, comb, take-off device) are still missed too. The author did not specify, which yarn count and which gauge were used for individual samples (the machine gauge is fixed by the producer, it is not possible to "*set from 8 to 12*" (p.48) or adjust) and other condition which is useful for anybody who will carry on the same experiment. The notice "*They were knit under normal tension force*" (p. 49) are insufficient.

The knitted samples are not deeply specified (i.e. course and wale spacing, loop length), the parameter „Stitch length per [cm]" for 15 types of rib structure (Table 4-1) was erased from previous thesis version. The standards or condition for measuring data from Table 4-1 are not mentioned. The contact area % was calculated according the equations 3.9 and 3.11 (p.46)? The input parameters for that equations are "*volume of the yarn*" and "*volume of the unit cell*" and they are not described. Why is the value "*contact area*" of rib structure 1 x 4 higher than in the structures 1 x 6, 1 x 3 and 1 x 2?

The elasticity and flexibility of the rib knitted fabrics (and author comments (p. 39) "*the extensions for rib structures up to 140 % can be achieved*") significantly influenced the methods of *painting technique* and afterwards the values of the "*contact area*".

An unanswered question from previous thesis version still remains. Why in equation (4.1) are mentioned area, but in the Figure 4-12 is showed the length (p. 57). With respect to the scale (length app. 2,2 mm) and 10 or more? readings we taken only the small area of that samples, it is not "*most* *precise way*". In the case of longitudinal view into the yarn, researchers measure yarn diameter 100, 200 or 300 times. On the basis of this very inaccurately determined parameter – "*real contact area*", further comfort properties are evaluated and discussed.

The Talysurf instrument and method for measuring were not specified (p.60).

Samples no 5 and 12 have the same rib type 2 x 1, but different "*contact area [%]*" in Table 5-1. Why? It is possible to produce the same structure with several different parameter of that area?

Other group of tested material were woven fabrics. In my opinion is not necessary to join that Chapter 5.4 to doctoral thesis (p. 65 – 69) with knitted fabrics topic.

The paired sample statistical procedure for thermal absorptivity of different knitted structure from different yarn material and linear density are not an appropriate tool for comparison and interpreting the measured results. Thermal absorptivity depends on type of fibres in case of the same knitted structure (i.e. see the single jersey 1, 8, 15, 17, 25, 26 and 31), but it is not discussed.

The group of fabric for KES measuring (Chapter 5.6) included 12 samples (Table 5-12) without described characteristics (sample 1, 2 are the same samples 5, 12 in Table 4-1?). Sample 6 (in Table 5-12) is the back-side of the sample 1 in Table 4-1? The discussion about the results are with mistakes of the values, because data – minimum and maximum are partly shifted (Table 5-12).

Other group of samples are mentioned in chapter 5.8. *Airflow direction and water vapour permeability* of samples 14 and 15 in Table 5-13 are not correspond with the Table 5-1. The new samples 16 – 18 are not described. We know nothing about the samples S No (Table 5-12), is it knitted?

Development of prediction of thermal absorptivity of rib knitted fabric based on porosity with the equation (5.1) is not described clearly. The parameter "*density of fabric*" (density of knitted rib are not written in previously mentioned tables) are measured or calculated (p.80)?

In Table 5 -16 the values of "*contact area assumed*" and "*measured*" (0,13 – 0.85 %) are very small and not correspond with the Figure 5-10, where relative contact areas reach values from 2 to 14 %.

I am afraid that it is necessary to deeply describe the rib structure and yarn structure before registration of patent application (Chapter 6.1), because in this experimental work it has been confirmed that one can produce the same rib structure 2 x 1 with different value of "*contact area*" (52 and 71 %).

With respect to the above mentioned comments, the doctoral thesis by Asif Elahi Mangat is not fulfils all the conditions for gaining the PhD. degree in Textile Technics and Materials Engineering; therefore it is not recommended.

Liberec, January 9, 2019

Irena Lenfeldová, M. Sc., Ph.D.
Department of Technologies and Structures
Faculty of Textile Engineering, Technical University of Liberec

Review of the doctoral Thesis Thermal Absorptivity and Other Thermal Comfort Parameters of Rib Knitted Fabrics by Asif Elahi Mangat.

The dissertation is re-written version of the dissertation submitted in 2017 under the same title.

The dissertation consists of six chapters in total with 100 pages including the list of references. First chapter defines objectives of the thesis and overview of methodologies. Chapters 2 to 4 describes theoretical principles, definitions of different phenomena linked with the Thesis topic and experimental facilities and instrumentation used for the experimental part of the thesis.

The main contribution and results of the experiments are in chapter 5.

Comparing with the previous version of the thesis, the newly submitted thesis was significantly improved, taking into account suggestions and comments of the previous review. Some formal mistakes remain that however don´t impact on the overall quality of the thesis. For example, there is still inconsistently used t and T for temperature, there is no explanation what is the characteristic dimension for natural convection on surfaces facing up and down – eq. 2.15 and 2.16 (it is definitely not the length in the direction of gravity as stated with the eq. 2.14), there is still a mistake in the eq. 2.5 and some other minor formal mistakes. However as said above, these formal errors don´t reduce the overall good level of the dissertation.

The work represents a good contribution in the field of textile characteristics and meets standards imposed on doctoral thesis. The dissertation presents very useful results that may fulfil a demand from textile industry. Research methods and individual steps undertaken in this study are based on the current knowledge in the field and proved to be appropriate for this kind of studies.

Mr. Mangat so far published a sufficient number of articles in journals ranked in WoS.

I therefore recommend the acceptance of the Thesis to the Faculty of Textile Engineering TU Liberec and after a successful defense to award a PhD degree.

In Brno, 11.2.2019

....

Prof. Ing. Miroslav Jícha, CSc

Odbor termomechaniky a techniky prostředí
Energetický ústav
Fakulta strojního inženýrství
Vysoké učení technické v Brně