TECHNICAL UNIVERSITY OF LIBEREC
Faculty of Textile Engineering

MODELLING OF THERMAL RESISTANCE AND SOME OTHER COMFORT PARAMETERS OF SOCKS IN WET STATE

Tariq Mansoor, M.Sc.

SUMMARY OF THE THESIS

Title of the thesis:	Modelling of thermal resistance and some other comfort parameters of socks in wet state
Author:	Tariq Mansoor, M.Sc.
Field of the study:	Textile Technics and Materials Engineering
Mode of the study:	Full time
Department:	Textile Evaluation
Supervisor:	prof. Ing. Luboš Hes, DrSc., Dr.h.c.

Committee for defense of the dissertation:

Chairman: prof. Dr. Ing. Zdeněk Kůs	FT TUL, Department of Clothing Technologies
Vice-chairman: prof. Ing. Jiří Militký, CSc.	FT TUL, Department of Material Engineering
prof. Ing. Karel Adámek, CSc.	
prof. Ing. Miroslav Jícha, CSc.	University of technology in Brno, Faculty of mechanical Engineering
prof. Ing. Michal Vik, Ph.D.	FT TUL, Department of Material Engineering
prof. Ing. Tomáš Vít, Ph.D. (opponent)	FS TUL, Department of Power Engineering Equipment
doc. Ing. Pavel Pokorný, Ph.D.	FT TUL, Department of Nonwovens and Nanofibrous Materials
doc. Ing. Maroš Tunák, Ph.D.	FT TUL, Department of Textile Evaluation
Ing. Irena Lenfeldová, Ph.D.	FT TUL, Department of Technology and Structures

The second opponent who is not a member of the committee:

Prof. Dr.-Ing. Habil. Yordan Kyosev — ITM, TU Dresden Germany

The dissertation is available at the Dean's Office FT TUL.

Liberec 2021

Abstract

A human foot may exhibit a sweat rate of about 30g and in some cases even up to 50g per hour in a hot environment [1][2]. The average sweat rate reaches around 10g/h per foot during heavy exercise in a cold environment. This sweat rate may reach to 30g/h per foot during very high levels of exercise. During common occupational exposures, the sweat rates are expected to lie between 3-6g/h [3][4]. The thermal resistance of wet fabrics gets substantially reduced due to the considerably higher thermal conductivity of the absorbed water as compared to that of air. Keeping high thermal resistance of their socks is important for people working under wet conditions to be protected from trench foot and hypothermia like issues. Thermal resistance prediction is also very important for product development of different textiles. In the study, an algebraic model and its experimental verification were executed to investigate the effect of moisture content on the thermal resistance of sock fabrics and the results were mutually in good agreement. The results show that increasing moisture content in the studied sock fabrics caused a significant reduction in their thermal resistance. Along with the model and its experimental verification, a novel method to measure thermal resistance and comfort properties of various knitted socks samples under real conditions of their use (it means under extension and in wet state) was proposed. Generally, any level of moisture largely influences all thermophysiological properties of textile fabrics. Therefore, plain knitted socks with different fibre composition were wetted to a saturated level, and then stepwise their moisture content was reduced. When achieving the required moisture content, the socks samples characteristics were determined by the Alambeta testing instrument (as regards thermal resistance and thermal absorptivity), and by the Permetest tester (as for relative water vapor permeability) and by the Horizontal Plate Friction Analyzer (to get the coefficient of friction in the wet state). Moreover, various skin models were also utilized to get thermal resistance values of dry samples for the comparison. One of these thermal models was a special thermal model of the human foot. The experimental results from this model well correlated with the results from the Permetest skin model. Three different existing mathematical models for the thermal resistance of dry fabrics were modified for predicting thermal resistance of knits used in socks under wet conditions. Volume porosity values of the studied fabrics, used in these thermal models, were determined both by means of semi-empirical approach and by a micro-tomography procedure. The results from both ways are in very good agreement for all the socks at a 95% confidence level. In the above-mentioned models, the prediction of thermal resistance presents newly a combined effect of the real filling coefficient and thermal conductivity of the so-called “wet” polymers instead of dry polymers. With these modifications, the used models predicted the thermal resistance at different moisture levels with a significantly high coefficient of correlation. Along with thermal resistance, the thermal absorptivity of the sock fabrics in a wet state (this time experimentally only) was first time investigated in the Thesis. This parameter increases with the increasing moisture content of materials, this time of textile fabrics. It characterises thermal contact feeling from dry to cool, cold, and wet feelings of any objects. The results of this study show that thermal absorptivity values of the studied dry fabrics range from 80 to 180 [$Ws^{1/2}m^{-2}K^{-1}$]. As thermal conductivity and capacity of water are much higher than that of fibres and air entrapped in the textile structure is partly replaced by water and thermal absorptivity of wetted fabrics increases. In these thermal absorptivity measurements, the effect of an extension of socks during their practical use was also newly respected. As already mentioned, moisture in textiles also significantly affects (reduces) the vapor permeability of fabrics. Because the measurement of the vapor permeability of wet textiles by conventional commercial instruments is difficult (the measurement takes too long, so that the moisture evaporates during the measurement), there are very few relevant publications. Given that vapor permeability is the second main parameter of thermo-physiological comfort of textiles, in the last part of the work the influence of moisture on the vapor permeability of socks was also studied experimentally by using the original methodology developed several years ago at the Faculty of Textiles TU Liberec. It was found that the effective relative vapor permeability of wet sock knits made of synthetic fibers is higher than the vapor permeability of wet knits made of natural materials.

Keywords

Thermal resistance; mathematical modelling; relative water vapor permeability; thermal absorptivity; socks; moisture content; filling coefficient; volume porosity; coefficient of friction.

Abstrakt

Lidská noha může v horkém prostředí za hodinu vytvořit 30 gramů, někdy dokonce až 50 gramů potu. Průměrná produkce potu při intenzivním cvičení v chladu činí kolem 10 g/h na nohu. Intenzita pocení může dosáhnout až 30 g /h na nohu při velmi vysokých úrovní cvičení, zatímco během běžných pracovních aktivit bude produkce potu ležet mezi 3-6 g/h [3][4]. Tepelný odpor vlhkých textilií se podstatně snižuje díky mnohokrát vyšší tepelné vodivosti absorbované vody ve srovnání s tepelnou vodivostí vzduchu. Zachování vysokého tepelného odporu ponožek je důležité pro osoby pracující ve vlhkých podmínkách, aby byli chráněni před zákopy a problémy s podchlazením. Predikce tepelného odporu je také velmi důležitá při vývoj různých ochranných a sportovních textilií. Ke zkoumání vlivu obsahu vlhkosti ponožkových textilií na jejich tepelný odpor byl v této práci sestaven matematický (algebraický) model a vypočtené výsledky byly v dobré shodě s výsledky experimentálními. Výsledky ukazují, že zvyšující se obsah vlhkosti ve studovaných textiliích vedl k podstatnému snížení jejich tepelného odporu. Ve zmíněném matematickém modelu, ale při proměřování tepelného modelu vzorků byly nově respektovány (realizovány) konkrétní podmínky užívaní ponožek v praxi, tj. kromě vlivu vlhkosti bylo pří výpočtech i měření simulováno prodloužení ponožek při jejich nošení. Obecně, jakékoli úrovně absorbovaná v textiliích významně ovlivňuje všechny parametry jejich termo-fyziologického komfortu. Proto byly hladké ponožkové úplety s různým složením vláken navlhčeny na maximální úroveň a postupně vysoušeny na požadovaný obsah vlhkosti. Takto připravené vzorky ponožek byly poté proměřovány přístrojem Alambeta (pro zjištění jejich tepelného odporu a tepelné jímavosti), dále byl použit i přístroj Permetest typu Skin model (pro stanovení relativní propustnosti vzorků pro vodní páru) a na zahraničním pracovišti byl k relativně novým měřením použit Horizontální deskovým analyzátorem tření (pro zjištění součinitele tření ponožkových textilií ve vlhkém stavu). Kromě toho byly tepelné odpory nezavlhčených vzorků ponožek pro možnost porovnání výsledků měřeny i na jiných tzv. Skin modelech s různou geometrií. Jedním z nich

byl tepelný model lidské nohy. Výsledky z tohoto modelu velmi dobře korelují s výsledky získaných pomocí malého Skin modelu Permetest. Pro predikci tepelného odporu vlhké textilie byly původním způsobem modifikovány tři různé již existující matematické modely pro suché textilie. Tyto modely sestavené pro predikci tepelného odporu ponožkových textilií jsou nově založeny na kombinovaném účinku skutečného koeficientu objemového zaplnění a tepelné vodivosti tzv. vlhkého vlákenného polymeru namísto polymeru suchého. Hodnoty objemové porozity textilií, nezbytné ke konstrukci uvedených tepelných modelů, byly zjištěny semi-empirickým postupem a také pomocí tzv. mikro-tomografie. Výsledky obou postupů způsobů jsou pro všechny ponožkové textilie na 95% úrovni spolehlivosti prakticky shodné. Algebraické modely, sestavené na základě výše uvedených postupů a modifikací umožňují stanovení a predikci tepelných odporů všech zkoumaných ponožkových textilií při relativně rozsáhlém stupni zavlhčení s významně vysokým součinitelem korelace. Vedle tepelných odporů, byl v této práci také poprvé experimentálné studován vliv vlhkosti na tepelnou jímavost ponožkových textilií. Tento parametr roste se zvyšováním obsahu vlhkosti v materiálech, v našem případě plošných textiliích a postupně může charakterizovat suchý, teplý chladný a mokrý tepelně – kontaktní vjem. Výsledky této studie ukazují, že hodnoty tepelné jímavosti zkoumaných nezavlhčených suchých tkanin se pohybují od 80 do 180 [$Ws^{1/2}m^{-2}K^{-1}$]. Ve vlhké textilií je vzduch o nízké tepelné vodivosti částečně nahrazen vodou o cca 25 x vyšší tepelné vodivosti a vysoké tepelné kapacitě, takže výsledná tepelná vodivost vlhké textilie podstatně vzroste. Jak již bylo uvedeno, při měření tepelných odporů bylo (prakticky ověřeném) prodloužením vzorku simulováno prodloužení ponožek při jejich nošení. Tento přístup byl nově aplikován i při hodnocení tepelné jímavosti zavlhčených ponožkových textilií. Jak již bylo uvedeno, vlhkost v textiliích také významně ovlivňuje (snižuje) paropropustnost plošných textilií. Vzhledem k tomu, že měření paropropustnosti vlhkých textilií klasickými komerčními přístroji je obtížné (měření trvá příliš dlouho, takže vlhkost se při měření odpaří), příslušných publikací je velmi málo. Vzhledem k tomu, že paropropustnost je druhým hlavním parametrem termo-fyziologického komfortu textilií, byl v poslední části práce vliv vlhkosti na paropropustnost ponožkových úpletů rovněž systematicky experimentálně studován, a to pomocí originální metodiky vyvinuté před několika lety na fakultě textilní TU Liberec. Bylo zjištěno, že efektivní relativní paropropustnost vlhkých ponožkových úpletů ze syntetických vláken je vyšší než paropropustnost vlhkých úpletů z přírodních materiálů.

Klíčová slova

Teplotní odolnost; matematické modelování; relativní propustnost pro vodní páru; tepelná nasákavost; ponožky; Obsah vlhkosti; plnicí koeficient; objemová pórovitost; koeficient tření.

Contents

List of symbols/ abbreviations

Symbol	Description	Units
b	Thermal absorptivity	$Ws^{½}m^{-2}K^{-1}$
c	Specific heat	$J\,kg^{-1}K^{-1}$
F_a	Filling coefficient of the air	-
F_w	Filling coefficient of the wet water	-
$F_{wet\ polymer}$	Filling coefficient of the wet polymer	-
GSM	Gram per meter square / areal density	gm^{-2}
h	Thickness	mm
P	Power	W
q	Heat Flow	Wm^{-2}
q_0	Heat flow without sample	Wm^{-2}
q_s	Heat flow with sample	Wm^{-2}
R^2	Coefficient of determination	-
R_{ct}	Thermal resistance	m^2KW^{-1}
R_{ct0}	Thermal resistance without sample	m^2KW^{-1}
R_{ctn}	Thermal resistance with sample	m^2KW^{-1}
RWVP	Relative water vapor permeability	%
TFM	Thermal foot model	-
t_a	Ambient temperature	˚C
α	Coefficient of convection	$Wm^{-2}K^{-1}$
λ	Thermal conductivity	$Wm^{-1}K^{-1}$
λ_a	Thermal conductivity of the air	$Wm^{-1}K^{-1}$
λ_w	Thermal conductivity of the water	$Wm^{-1}K^{-1}$
λ_{fib1}	First fibre thermal conductivity	$Wm^{-1}K^{-1}$
λ_{fib2}	Second fibre thermal conductivity	$Wm^{-1}K^{-1}$
$\lambda_{wet\ polymer}$	Thermal conductivity of the wet polymer	$Wm^{-1}K^{-1}$
λ_{fab}	Thermal conductivity of the fabric (socks)	$Wm^{-1}K^{-1}$
F_w	Water filling coefficient	-
F_a	Air filling coefficient	-
F_{fib1}	First fibre filling coefficient	-
F_{fib2}	Second fibre filling coefficient	-
	Fibre/ yarn diameter (micro meter)	µm
ε	Porosity	%
ρ_0	Fibre density	kgm^{-3}
ρ	Fabric density	kgm^{-3}
a	Thermal diffusivity	ms^{-1}
q_{dyn}	Dynamic (transient) heat flow	Wm^{-2}
q_{steady}	Steady state heat flow	Wm^{-2}
	Convection air velocity	ms^{-1}
ME	Maxwell-Eucken	-
μ	Coefficient of friction (COF)	
	Frictional force	N
β_1	Slope	-
β_2	Intercept	-
EMT	Effective medium theory	-
Mod.	Modified	-

1 Introduction

Most of the studies on thermal resistance/conductivity in the wet state to date are experimental and reported a reduction in thermal resistance by increasing the moisture content. This study will provide a quantitative prediction of the insulation loss with the addition of water in socks. Thermal absorptivity is another important parameter that adversely affected by moisture content. A lot of theoretical and experimental investigations for thermal absorptivity in dry and wet state were reported by the literature. The thermal absorptivity of the common textile products was experimentally investigated by various researches. As per Asif et al. it varies from 20 to 900 [$Ws^{1/2}m^{-1}K^{-1}$], corresponds to dry and wet cotton fabrics [5]. Thermal absorptivity of dry fabrics range 20-300 [$Ws^{1/2}m^{-1}K^{-1}$] reported in the literature and these values increase between 150 and 300 [$Ws^{1/2}m^{-1}K^{-1}$] when the fabrics get wet [6]. Water vapour permeability also significantly affected by humidity. Water vapour transportability is deteriorated significantly by the higher moisture content. A decrease of 70-80% is observed for wool and wool/viscose blended fabrics, which is caused by exchanging the air pores by water. It means that the physiological properties of the wet fabrics are subject to abrupt changes, significantly affects the quality of the apparel [7]. Sweat evaporation from the body into the environment is much quicker compared to the sweat accumulated within an enclosed shoe. It will increase the sock's moisture and in return influence the friction at the plantar skin interface [8]. Furthermore, accumulated moisture in the socks has the potential to bridge air gaps between fibres which consequently increases the contact area between these two surfaces. This could lead to an increase in the available friction [9], in addition to influencing the thermal resistance and thermal conductivity of the sock fabrics [10].

2 Purpose and aim of the thesis

This study deals with the thermal comfort properties of socks in the wet state. Mostly the cold feet sensation is associated with low skin temperatures due to sweating [11]. Even the well-insulated footwear will start feeling cold on wetting. Socks are made of fabrics where the absorbed moisture can strongly influence their thermal comfort properties since a human foot could generate up to 30-50 grams of sweat per hour in a hot environment [1][2]. At a high physical activity, it could be 30g/h even in the cold environment [3][4]. The most recent study reports this range with shoes (10.3 ± 3.6 g/ h) compared to nude (12.6 ± 3.7 g/h) for a single foot [12]. Due to these high sweat rates, the thermal resistance may substantially decrease. Prolonged damp and cold conditions can cause injuries like a trench foot. The trench foot, however, does not require a freezing temperature; it can occur at a hot temperature as well [13].

By using Alambeta fast working tester there were made measurements of thermal resistance and thermal absorptivity of plain surface socks consisting of cotton, viscose, polyester, nylon, polypropylene, wool, and acrylic fibre, with the same plaiting yarn polyester covered elastane, without any special finishing (commercial state). The measurements were executed at different levels of moisture content. Additionally, in these experiments, the extension of socks in their practical use was also observed by using an additional device which made the experiments very realistic. Alambeta testing corresponded well to the use of socks inside a shoe (boundary conditions of first-order). In the next step, the focus was placed on the development of a mathematical model for the prediction of thermal resistance of plain socks in the wet state. Following models have been tried for the prediction of thermal conductivity/ resistance in the wet state. The model's selection criteria based on the assumption that the addition of water changes the volumes and ultimately thermal conduction. These prediction models aren't customized for textiles only but they are being used in the fields of food technology, soil sciences, and civil engineering as well. The first four models involved the moisture effect, but the rest of them are applied by the combined approach of water and polymer components for the determination of thermal conductivity instead of dry polymer.

- Mangat parallel/ series models [14][15]
- R.S Hollies model (parallel model) [16]
- S. Naka model (three parameters model series/ parallel) [17]
- Dias and Delkumburewatte (three parameters series model) [18]
- Fricke's model (100% Series) [19]
- Ju Wei model (considered polymer + air in parallel and air in series) [20]
- Schuhmeister model (considered 30 % parallel+ 70% series) [21]
- Baxter model (considered 21 % parallel+ 79% series) [22]
- Militky (considered 50 % parallel+ 50% series) [23]
- Maxwell Eucken-1 and Maxwell Euken-2(dispersed and continuous phases) [24][25]

Above all models were compared with the experimental data. Unfortunately, none of these models was offering a good correlation with the experimental data from the wetted socks except Maxwell Euken-2, Schuhmeister and Militky's models. The solution was based on modifications of these models has done by adopting a combined approach of water and polymer components for determination of thermal conductivity and introduction of linear changes of the filling coefficient (volume ratio) with the increasing moisture. In this way, the predicted thermal resistance of all samples at different moisture levels with the coefficient of determination R^2 ranging from 0.7691 to 0.9535. Based on the knowledge of the fibre composition (thermal conductivity of the used polymer), fabric areal density and thickness, these original models can predict the thermal resistance of the studied socks at any moisture regain up to 100%.

In addition to thermal resistance, thermal absorptivity also determined experimentally (wet state) by using Alambeta. The results were treated statistically and presented in diagrams. Very interesting results were also achieved when measuring thermal resistance of socks subject to the heat transfer by the convection on their free surface where the socks are worn free, not inside a shoe (boundary condition of 3rd order). A special thermal foot model installed in the laboratory of the Textile faculty in Zagreb (Croatia) was used. It was discovered that the gaps between the heated elements of this commercial device were the source of measuring errors. Consequently, this was fixed by a semi-permeable membrane on the foot model to avoid the turbulence effects. After this improvement, the samples measured on this model had good repeatability. Then these results were compared with the results achieved on the Permetest skin model (which works on similar principle). Both devices showed very good correlations. In addition to thermophysiological comfort, interface of fabrics with the human senses is an important comfort property as textile materials are in contact with the skin [26]. When a fabric is moved along the skin, the perception of the fabric roughness or smoothness is induces. The friction during this contact is the key factor for the perception of unevenness or smoothness. The smooth surface fabrics mostly have the lower friction. Presence of the moisture between the friction interfaces can change the fabric roughness perception. The friction of skin increases, with the increase of the moisture content, and it can activate more feel receptors by bringing discomfort [27]. The information about friction is very essential for the protection of feet against blister formation or slippage issues. The general aims of this study are as follows;

- ❖ To find/ develop simple mathematical models for thermal resistance prediction in the wet state
- ❖ To investigate the effect of different moisture content [%] on the socks porosity, thermal resistance [m^2KW^{-1}], thermal absorptivity [$Ws^{½}m^{-2}K^{-1}$] and relative water vapour permeability RWVP [%].
- ❖ Effect of extension on porosity, thermal resistance, thermal absorptivity & RWVP
- ❖ Thermal resistance (predicted/ experimental) in the extended state (controlled moisture content %) for simulating a real extension and minimizing the effect of the dimensional changes.
- ❖ To compare the thermal resistance (dry state) measured by thermal foot model (TFM), Permetest and Alambeta.
- ❖ Yarn porosity (theoretical and experimental)
- ❖ Volume porosity of socks with and without extension by model
- ❖ Volume porosity and pore size distribution of socks my X-ray micro tomography scanning without extension
- ❖ Effect of moisture content on sock-material (insole) coefficient of friction

3 *Overview of the current state of problem*

3.1 Thermal resistance

The characterization of insulation under wet conditions is very critical. There are many studies for thermal resistance prediction though empirical models available in the literature and these models are specifically volume fractions and their respective thermal conductivities based.

Most of them can measure thermal resistance only in the dry state. Numerical approaches can deal with uneven profiles, solid/liquid/gas phases, different forms of heat transfer, number of boundary conditions, and uneven material properties. Numerical methods also have the potential to attain the utmost precision [28]. There are many soft wares available in the market that allows the user to describe the numerical problem and their solution. However these methods are intrinsically more complex and awkward, and in some conditions, plain methods demonstrated to be more precise for much less stab [29]. Some researchers employed ANN (artificial neural networks) models for thermal resistance and thermal conductivity predictions. In most of the studies, thermal resistance is predicted by statistical models. Some researchers have predicted the thermal resistance of wet fabrics with mathematical approaches. Dias and Delkumburewatte [18] suggested a three parameters series model that predicts the thermal conductivity of knitted fabric in terms of porosity, thickness and moisture content in pores. They have found that by increasing moisture content the porosity of fabric decreases causes to increase the thermal conductivity. Das et al. [30] assumed fabric assemblies as cuboids filled with randomly oriented infinite cylinders (fibres) and heat transfer by conduction can be calculated with the analogy to electrical resistance and Fricke's law. Wie et al. have divided the fabric fundamental unit into three components for heat transfer i.e. 1.solid fibres, 2.series porosity, and 3.parallel porosity to the heat flow direction. Fabric thermal resistance mainly depends on the heat transfer process through this basic unit. In their model, heat flow considered through the fabric in a combination of fibre & air in series plus the air in parallel [20]. Schuhmeister [21] developed a relationship to calculate the thermal conductivity of the mixture of air and fibre with the following assumption:

a) Fibres are distributed homogeneously in all directions;
b) One-third of fibres placed parallel; and
c) Two third were placed series or perpendicular to the heat flow.

Later on, many researchers followed the footprints of Schuhmeister by changing the ratio of series and parallel [22][31]. In recent times, Militky considered 50% fibers placed in series and 50% in parallel to the heat flow [23]. R. S. Hollies and Herman Bogaty have suggested a parallel combination for measuring the effective thermal conductivity of moistening fabric by combining the volume fraction and thermal conductivity of water and polymer [16]. Mangat presented a number of mathematical models for thermal resistance (wet state) in the series and in parallel combinations of air, fibre, and water resistance. His predictions are in good correlation with the experiments by model-3 (air & fibre resistance in series, water in parallel) for denim fabrics while model-5(Ra and Rw in a parallel arrangement and Rf in series) and model-7(Rf and Rw in a serial arrangement and Ra in parallel arrangement) for weft knitted fleece fabrics of differential fibre composition. Furthermore, he concluded that about 70% of the thermal resistance decreased up to 30% moisture content [14][15]. Another study reported a 50% reduction between 10-20% moisture content [7]. S. Naka et.al suggested three parameters (air, water, and polymer) model for thermal conductivity prediction of wet woven fabrics with the combination of parallel and series arrangement [17]. The problem with Mangat's models that; he assumed the filling coefficient or porosity as constant components. But they are changing by varying the moisture levels because water has a different density.

Although, his second assumption that the air is replaced by water is theoretically correct but he didn't quantify it. R. S. Hollies and Herman Bogaty have ignored the series arrangement in their suggested models. It will predict the lower thermal resistance as heat will conduct along with the thickness of the fabric. S. Naka et al. suggested a theoretical approach for thermal conductivity prediction but they didn't use it for calculations. They also involved the warp and weft fabric thickness in their suggested model. Dias and Delkumburewatte three parameters series model is a very simple approach but they ignored the parallel conduction part so it will predict higher thermal resistance. As mentioned earlier, by combining the fibre and water filling coefficients approach, only three models have predicted the reasonable thermal resistance for socks that are in agreement with the experimental results. These models are as under;

2.1.1 Maxwell–Eucken2 (ME2)'s modified model

Maxwell introduced the two-phase concept for the determination of electrical conductivity [24]. Later on, Eucken used the same analogy for the thermal conductivity evaluation [25]. Brailsford and Major (Eq.1) have modified the Maxwell-Eucken models for thermal conductivity of a three-phase mixture assuming first phase as continuous while other two as dispersed [32].

$$\lambda = \frac{\lambda_0 \upsilon_0 + \lambda_1 \upsilon_1 \frac{3\lambda_0}{(2\lambda_0+\lambda_1)} + \lambda_2 \upsilon_2 \frac{3\lambda_0}{(2\lambda_0+\lambda_2)}}{\upsilon_0 + \upsilon_1 \frac{3\lambda_0}{(2\lambda_0+\lambda_1)} + \upsilon_2 \frac{3\lambda_0}{(2\lambda_0+\lambda_2)}} \quad (1)$$

Later on (Eq.1) was generalized by Wang et.al [33] as shown by (Eq.2).

$$\lambda = \frac{\sum_{i=1}^{m} \lambda_i \upsilon_{i0} \frac{d_i \tilde{\lambda}}{(d_i-1)\tilde{\lambda}+\lambda_i}}{\sum_{i=1}^{m} \upsilon_{i0} \frac{d_i \tilde{\lambda}}{(d_i-1)\tilde{\lambda}+\lambda_i}} \quad (2)$$

Maxwell-Eucken (Eq.3) is obtained by assuming air and wet polymer as disperse and continuous phases respectively for above (Eq.2). Maxwell–Eucken (ME) model (Eq.3) can be used to describe an effective thermal conductivity of a two-component material with simple physical structures. (Eq.3) representing a two components system for effective thermal conductivity based on volume fraction and respective. Many effective thermal conductivity models require the naming of continuous and dispersed phases. Materials with exterior porosity, individual solid particles are surrounded by a gaseous matrix, and hence the gaseous component forms the continuous phase and the solid component forms the dispersed phase [34]. For external porosity, and are considered as continuous & dispersed phases respectively.

$$\lambda_{fab} = \frac{\lambda_a F_a + \lambda_{wet\ polymer} F_{wet\ polymer} \frac{3\lambda_a}{2\lambda_a+\lambda_{wet\ polymer}}}{F_a + F_{wet\ polymer} \frac{3\lambda_a}{2\lambda_a+\lambda_{wet\ polymer}}} \quad (3)$$

$F_{wet\ polymer}$ and $\lambda_{wet\ polymer}$ is calculated as per (Eqs.15-17).

2.1.2 Schuhmeister's modified model

Schuhmeister (Eq.4) summarized the relationship between the thermal conductivity of fabric and the fabric structural parameters by an empirical equation [21];

$$\lambda_{fab} = 0.67 \times \lambda_s + 0.33 \times \lambda_p \quad (4)$$

Where $$\lambda_s = \frac{\lambda_{wet\ polymer} \times \lambda_a}{\lambda_{wet\ polymer}\ F_a + \lambda_a\ F_{wet\ polymer}} \quad (5)$$

and $$\lambda_p = F_{wet\ polymer}\lambda_{wet\ polymer} + F_a\lambda_a \quad (6)$$

Where λ_{fab} is the thermal conductivity of fabric, $\lambda_{wet\ polymer}$ is the conductivity of wet fibers, λ_a is the conductivity of air, $F_{wet\ polymer}$ is the filling coefficient of the solid fiber, F_a is the filling coefficient of air in the insulation.

2.1.3 Militky's modified model

Militky (Eq.7) summarized the relationship between the thermal conductivity of fabric by an empirical equation [23];

$$\lambda_{fab} = \left(\frac{\lambda_s + \lambda_p}{2}\right) \quad (7)$$

Where λ_s and λ_p are calculated as per (Eqs.5-6) respectively.

Where λ_{fab} is the thermal conductivity of fabric, $\lambda_{wet\ polymer}$ is the conductivity of wet fibers, λ_a is the conductivity of air, $F_{wet\ polymer}$ is the filling coefficient of the solid fiber, F_a is the filling coefficient of air in the insulation.

2.2 Thermal absorptivity

Thermal absorptivity is mainly a surface-related property, it could be changed by any finishing treatment, like raising, brushing coating [35]. Hes as a pioneer of this newly used term "thermal absorptivity", in the area of textiles has many studies on his credit. As the thermal contact between the textile material and the human skin is transient, the fabric was assumed to be a semi-infinite body characterized by its thermal capacity. Hes proposed to use the thermal absorptivity in the (Eq.8) as a measure the of thermal contact feeling of textile materials. Thermal absorptivity neither depends on the temperature difference between the two bodies in contact nor on the time measurement [35].

$$b = \sqrt{\lambda \rho c} \quad (8)$$

Baczek & Hes observed 9 times higher thermal absorptivity of plaited knitted fabrics in the wet state [36]. Mangat's model for thermal absorptivity prediction is based on the contact area effect [5]. Oglakcioglu's contribution to thermal absorptivity covered the effect of moisture content [37], fibre composition [38] and fabric construction [39]. Up to now several researchers had analysed the effect of fabric structure, contact area [30], moisture content [37], extension [40][41], fibre composition, finishing (chemical/ mechanical) [42] on thermal absorptivity [36], but no study was found with the combined effect of moisture and extension. Faisal et al. used a special frame for extension and observed reduction in thermal absorptivity of compression socks at different extension levels [41]. Gupta also extended the compression circular knitted garments up to 60% and found a decrease in the thermal absorptivity [40]. Irrespective of other studies an embroidery hoop was used for simulation of real extension. Previous researchers have extended the fabric in one direction only. They have not considered the real situation of extension. Because elastic garments extended in both directions. So the motivation of this work is based on the following gaps;

- ❖ As the socks are extended in both directions at the same time during wearing. So the extension of socks should be simultaneous in both directions for thermal absorptivity measurement.
- ❖ No combined study found having both moisture and extension consequences on thermal absorptivity.

2.3 Relative water vapor permeability

So far researchers found that water vapor permeability could be affected by fibre type and structure, fibre composition [43], yarn diameter [44], fabric thickness, covering factor, porosity [45], fabric structure [39], chemical [46] and mechanical finishes. The work of Hes et al. [7] for total heat flow in the wet state has opened new directions. According to their theory, total relative cooling heat flow (q_{tot}) transferred through the boundary layer of the wet fabric surface is given by the sum of heat flow passing from the skin through the permeable fabric '$q_{fab,w}$' and heat flow '$q_{fab,surf}$' caused by temperature gradient between the skin and fabric surface, which is cooled by evaporating of water from the fabric surface as shown by (Eq.9) and (Fig.1).

$$q_{tot,w} = q_{fab,w} + q_{fab,surf} \quad (9)$$

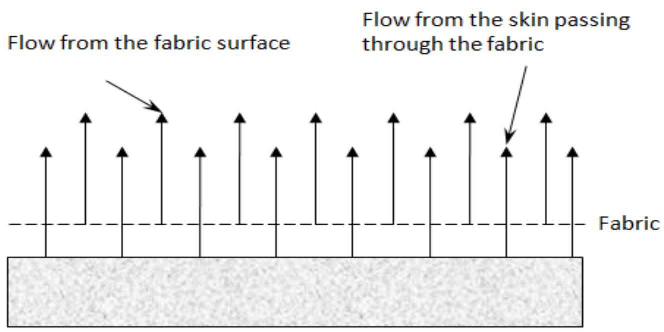


Figure 1. Cooling flow from the surface & through the fabric [7]

Gupta extended the compression circular knitted garments up to 60% and found 47% increase in the water vapor permeability [40]. Moisture content can also significantly change the water permeability [48][43]. But no study was found with the combined effect of moisture and extension. Likewise thermal absorptivity an embroidery hoop also used for simulation of real extension. Previous researchers have extended the fabric in one way only. They have not considered the real situation of extension. Because elastic garments extended in both directions. So the motivation of this work is based on the following gaps;

- ❖ As the socks are extended in both directions at the same time during wearing. So the extension of socks should be simultaneous in both directions for relative water vapor permeability measurement.
- ❖ No combined study found having both moisture and extension consequences on relative water vapor permeability.

2.4 Coefficient of friction

Blisters are caused by clothing friction on the skin. Their formation depends on the magnitude of the frictional forces and the number of times that an object touches across the skin [47]. The friction coefficient normally increases when epidermal moisture raises [48]. To avoid the blister occurrence, the sliding should take place either between the sock-shoe or between two layers of socks interfaces. This implies that friction between the sock-skin interface has to be higher than the other interfaces. "Activity-related blisters are mostly due to frictional shear forces" [49]. However, frictional shear forces do not appear to be adequate for a blister to arise. As per Reynolds et al., it is the combination of shear, pressure, and a moderate level of moisture [50]. Moisture accumulated within a shoe is mainly due to a high sweat rate. An athlete may have a sweat rate of nearly 3 litres per hour during a long run in a damp environment [51]. Additional shear force at sock fabric - plantar skin interface could have a negative impact on the range of movement and could even potentially lead to friction blisters [9], which would increase discomfort to the wearer [52]. Blisters are caused by the rubbing pressure between the skin of the foot and adjacent sock surfaces. When a runner's shoe strikes the ground, the shoe tends to undergo a rapid decrease in velocity whereas the foot and sock within the shoe be likely to continue forward at a fast speed until the shoe restricts the forward motion. Subsequently, there is an abrasive action occurs at the foot-sock and sock-shoe interfaces. Heat built up due to friction at these interfaces is the main cause of blisters [53]. So, both kinds are very important with respect to blisters or irritations. Many researchers have studied sock's friction at these interfaces such as sock-skin friction [54] & sock-material (shoes insole, floor covering, tile, etc.) friction [55]. Furthermore, it was well established that sock-insole friction should be lower than sock-skin to avoid friction blisters [56]. Factors recommended as changing the friction of fabrics are the fiber type [52], yarn density [57], orientation of the fabric structure [9][54], applied weight, and the moisture content [58]. The friction force is more related to the wetness of the skin than material or finishing treatment of the fabric [8][58]. Very fewer studies found on COF between sock-material (insole/shoes) interfaces in the wet state with the information of moisture content percentage.

4 *Materials and Methods*

4.1 Socks samples

All the plain (single jersey) socks samples as shown in (Table 1 & Fig.2) were knitted on the same machine (Lonati Goal GL544S, 144Needles, Diameter 4´´, 4Feed) settings by varying the main yarns to get the homogeneous samples with respect to specs and stretches for contrast comparison. "The yarn running at the surface of the sock is called the main yarn and the plaiting yarn (generally spandex covered polyamide or polyester filament yarn) runs inside the fabric providing stretch, elasticity, comfort and shape to the sock" [42]. After knitting, all the samples were processed for washing in the same machine bath followed by tumble drying and boarding.

Table 1. Sock samples specifications

Main yarn nominal count	Plaiting yarn	Fibre composition [%]	GSM [gm⁻²]	Thickness [mm]	Sock codes
29.525/1 tex 100% Cotton spun yarn	2.22/8.33/36/1 tex Polyester air covered Elastane (91:9) %	Cotton 80%, Polyester 18.20%, Elastane 1.8%	129.88	0.95	P1
29.525/1 tex 100% Viscose Spun yarn		Viscose 81.08%, Polyester 17.22 %, Elastane 1.70%	130.44	0.90	P2
29.525/1 tex 100% Spun Polyester		Polyester 98.38%, Elastane 1.62%	125.70	0.95	P3
11.11/36/2 tex 100% Nylon filament yarn		Nylon 70.83%, Polyester 26.54%, Elastane 2.63%	115.34	0.91	P4
8.4/25/2 tex 100% polypropylene filament yarn		Polyproplene 65.22%, Polyester 31.65%, Elastane 3.13%	108.92	0.82	P5
33.33/1 tex 100% Wool spun yarn		Wool 76.19%, Polyester 21.67%, Elastane 2.14%	133.69	1.16	P6
50/1 tex 100% Acrylic spun yarn		Acrylic 81.25%, Polyester 17.06%, Elastane 1.69%	166.89	1.20	P7

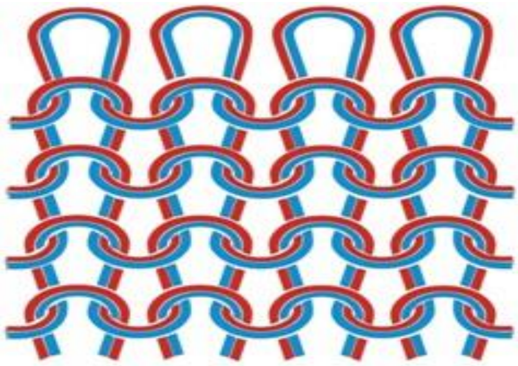


Figure 2. Knitting style of plain (single jersey) sock construction

For friction testing, an insole (commercially available) was arranged randomly. Specifications (mentioned on the label) of the insole are as under (Table 2);

Table 2. Insole sample specifications

	Salamander professional (melvo GmbH) Length = 30cm Top layer = Long terry cotton woven fabric Middle layer = Activated carbon Bottom layer= Latex foam

4.2 Volume socks porosity by model

Sock's structure is important due to several advantages. Physically, it presents properties of comfort such as high elasticity, conformity with the shape of the body, softer hands feel, and others. In general, heat & mass transmission rate is dependent mainly on the fabric geometrical parameters, namely, thickness and porosity [59]. Porosity (ε) is the volumetric ratio of the pores accessible by total volume [60]. The porosity of the fabrics can be calculated by air permeability, image processing, and geometrical modelling approaches [61]. Volume porosity of the socks was determined according to (Eq.10) [62][63].

$$\text{Porosity } (\varepsilon)\% = \left(\frac{\rho_0 - \rho}{\rho_0}\right) \times 100 \tag{10}$$

where ρ_0 is fibre density [kgm^{-3}] and ρ is fabric density [kgm^{-3}]

4.3 3D porosity of socks by micro-tomography scanning

3D porosity of the socks was investigated by using an x-ray computed micro-tomography SKYSCAN 1272 system. In this system, radiation is converted into an electrical signal between the x-ray source and the detector, the specimen revolves on a vertical axis. 2D images in several steps are taken during this rotary motion. Reconstruction software generates a 3D model of the actual specimen from these images [64]. Following are the common settings for all the tested samples: image pixel size –3.0μm, lower grey threshold−33, upper grey threshold −255, rotation step − 0.2°, rotation degrees −180 °, frame averaging − 3, exposure − 672 ms, voltage source − 50 kV, source current −200 uA.

4.4 Sample preparation for testing

For the extension simulation, the socks were loaded on a dummy leg (Salzmann MST Switzerland) [65] of medium size (24cm) as per specification of the standard method (RAL-GZ-387/1). Then worn socks are marked as per the testing template. After unloading, the socks were extended to the marked circle with the help of an embroidery hoop as shown in (Fig.3). Sock samples were tested for the thermal resistance & thermal absorptivity in the dry state (lab conditions moisture content). Then wet to the saturated level (100% moisture content) by BS EN ISO 105-X12 standard test method. The established technique for preparing a wet fabric of the known oven-dry fabric weight, then thoroughly wetted in distilled water. The wet pick-up brought to 100 ± 0.5% by putting wet testing fabric on a blotting paper. The evaporation of the moisture content below the specified level was avoided by using polyethylene bags. Furthermore, tested again for the up given tests under extension at different moisture levels.

(a) *(b)* *(c)*

Figure 3. Schematic illustration of (a) Circle marking, (b) Socks loading on dummy foot, and (c) Embroidery hoop respectively

4.5 Testing equipments/ methods

Type of equipments was selected for this research as per the situation of worn socks and limitations of the manikins. Socks wore inside shoes shown 1st order boundary conditions; the constant different temperatures on both surfaces of the fabric (like Alambeta). Socks were worn (calf area) partly under 3rd order boundary conditions; conduction inside = convection outside (Thermal foot model, Permetest). The condition is more clearly illustrated in (Fig.4). Furthermore, short testing time (almost keep the specific moisture content) distinct the Alambeta and Permetest from other skin models and manikins. So Alambeta and Permetest were selected especially for wet testing.

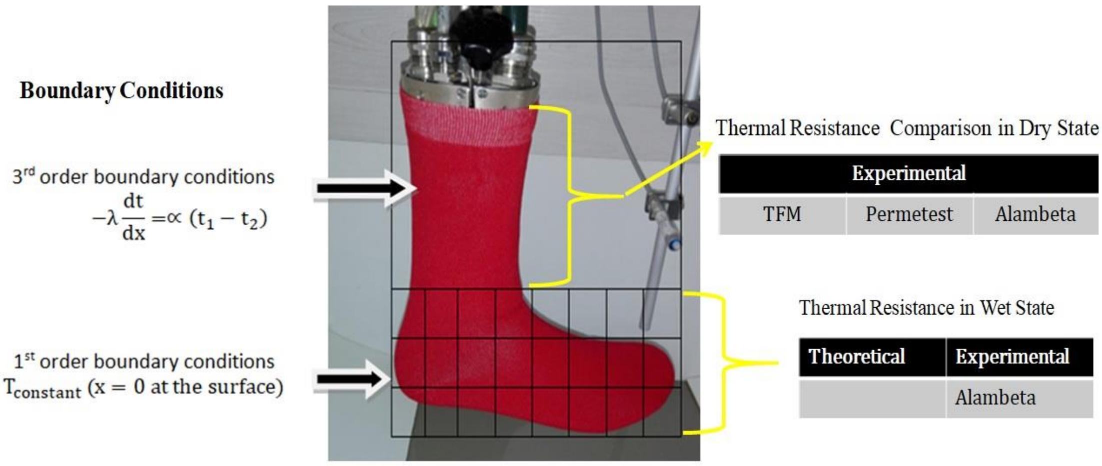


Figure 4. Worn sock situation inside the shoe

4.5.1 Alambeta (equivalent to ISO 8301)

The thermal resistance (Rct) and thermal absorptivity (b) of the developed samples were measured by Alambeta tester [35], which provides a fast measurement of both steady-state and transient-state thermal properties. This instrument simulates the heat flow q [Wm^{-2}] from the human skin to the fabric during a short initial contact in the absence of body movement and external wind flow. The measuring head drops down, touches the fabrics, and the heat flow levels are processed and the thermo-physical properties of the measured specimen are evaluated. The measurement lasts for several minutes only. Thus, reliable measurements on wet fabrics are possible, since the sample moisture during the measurement keeps almost constant. As mentioned earlier, socks are worn inside the shoes under first-order boundary conditions, and Alambeta testing corresponded well to the use of socks inside a shoe (boundary conditions of first-order).

4.5.2 Permetest

The relative water vapour permeability and Rct [m^2KW^{-1}] were measured by using Permetest. The Permetest [66] instrument is the so-called skin model that simulates dry and wet human skin and it serves for the determination of water vapour and thermal resistance of fabrics. Common standard measuring instruments mostly do not provide for a reliable measurement of water vapour permeability for wet fabrics due to the time-consuming measurement. Permetest is the equipment which provides a faster measurement of the water vapour permeability of fabrics, especially, in the wet state. Results of measurements are expressed in the units defined in the ISO Standard 11092. Thermal resistance Rct is measured as per below (Eqs.11-13).

$$R_{ct0} = \frac{(ts-ta)\times A}{P} \tag{11}$$

$$R_{ctn} = \frac{(ts-ta)\times A}{P} \tag{12}$$

$$R_{ct} = R_{ctn} - R_{ct0} \tag{13}$$

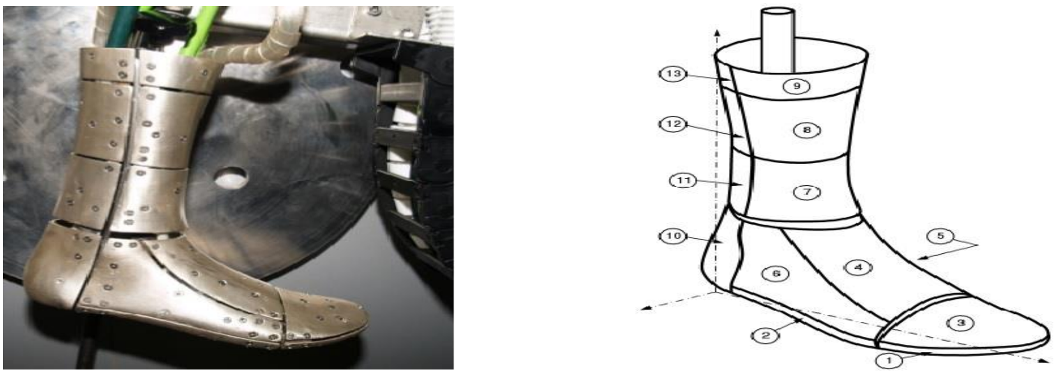
Where, t_s, t_a are skin and ambient temperatures respectively. A represented area [m^2] and P is the transmitted power [W]. R_{ct0} and R_{ctn} are the thermal resistance values without and with a sample. Relative water vapour permeability (RWVP) is a non-standardized but practical parameter. It is given by the following relationship (Eq.14):

$$RWVP\ (\%) = 100\left(\frac{q_s}{q_0}\right) \tag{14}$$

q_s, q_0 are heat flow with and without sample respectively.

4.5.3 Thermal foot model

Thermal foot model (TFM) is a part of the “thermal sweating foot manikin system”. It consists of 13 silver alloy surface segments, stainless steel supporting structure, shock absorbers, heating subsystem, and sweating subsystem. TFM is intended to test the thermal resistance and evaporation resistance of footwear. Geometrically it resembles a human foot with several geometrical modifications. The size of the TFM was tuned to fit into the footwear of standard 42 EU size. The heating subsystem was connected by highly flexible cables to thermal manikin controller (TMC). The sweating subsystem was connected to the water dispensing unit (DU). For more detail see (appendix 1). At the moment water dispensing was functional as per the gravimetric method. Both TMC and DU were controlled programmatically by means of MANICON computer program on a standard PC. (Fig.5a) depicts an assembled FM, attached to Gait Simulator. (Fig.5b) is a general layout of individually controlled surface segments. The thermal resistance of the sock is measured as per the above (Eqs.11-13).



(a) (b)

Figure 5.(a) Assembled foot manikin (b) The layout of surface segments [67]

4.5.4 Averaging thermal conductivity & filling coefficient calculations

By assuming that the fabric density is changing by wetting, then wetting causes the change of filling coefficient, porosity and thermal conductivity of fabrics. On the basis of these assumptions following three equations are developed that will be applied to find the fabric density, filling coefficient and thermal conductivity for different moisture levels. An average thermal conductivity for different fibres (within socks) at different moisture levels will be calculated as per (Eq.15).

$$\text{Average Thermal Conductivity } (\lambda_{\text{wet Polymer}}) = \left(\frac{F_w.\lambda_w + F_{fib1}.\lambda_{fib1} + F_{fib2}.\lambda_{fib2} + \cdots}{F_w + F_{fib1} + F_{fib2} + \cdots}\right) \quad (15)$$

F_w = Water filling coefficient, F_{fib1}= 1st fibre filling coefficient,
F_{fib2}= 2nd fibre filling coefficient, λ_w= Water thermal conductivity,
λ_{fib1}= 1st fibre thermal conductivity, λ_{fib2}= 2nd fibre thermal conductivity

Filling coefficients for water, fibre, wet polymer, and the air is calculated as per below steps given in Table 3;

Table 3. Filling coefficients

Measurement	F_w = Water filling coefficient	F_{fib} = Fibre filling coefficient
Moisture content	%	%
Mass	gram	gram
Area	m²	m²
Areal density	gram/m²	gram/m²
Volumetric density	Areal density/ Fabric thickness [kgm^{-3}]	Areal density/ Fabric thickness [kgm^{-3}]
Filling coefficient	Volumetric density / Fibre density	Volumetric density / Fibre density

Air filling coefficient (F_a) is calculated as per below (Eq.16);

$$\text{Air filling coefficient } (F_a) = 1 - (F_w + F_{fib}) \quad (16)$$

Filling coefficient for wet polymer will be calculated as per (Eq.17). This value will be used as input in all above models for measurement of thermal resistance in wet states.

$$\text{Wet Polymer filling coefficient } \left(F_{\text{wet polymer}}\right) = F_w + F_{fib} \quad (17)$$

The output of (Eqs.15-17) is used as input in the above models. The thermal conductivity of water and air is taken as 0.60, 0.026 [$Wm^{-1}K^{-1}$] while the density of water is 1000 [Kgm^{-3}]. Different values were found for the thermal conductivity of textile fibres. However, the following values of density [68] and thermal conductivity have been taken for different fibres in this study are given below in the below Table 4.

Table 4. Different fibres properties

Fibre name	Density [Kgm^{-3}]	Thermal conductivity [$Wm^{-1}K^{-1}$]
Cotton	1540	0.50 [69]
Viscose	1530	0.50 [22][68][69]
Polyester	1360	0.40 [68]
Polyamide	1140	0.30 [68][69][70]
Polypropylene	900	0.20 [68][69]
Wool	1310	0.50 [22]
Acrylic	1150	0.29 [71]

4.5.5 Validation of the models

Validation of the theoretical models is done by comparison of results (x) with results obtained by experiments (y) for a set of parallel determinations. If both methods (theoretical & experimental) lead to same results, the dependence of y on x is linear ($y = \beta_1 x + \beta_2$) with zero intercept $\beta_2 = 0$ and unit slope $\beta_1 = 1$. This validation is done by the joint confidence region for intercept and slope because estimators are correlated. Assumptions for this composite inference will be as under i.e.

1. Null hypothesis H_0: $\beta_2 = 0$ and $\beta_1 = 1$
2. Alternative hypothesis H_1: $\beta_2 \neq 0$ and $\beta_1 \neq 1$

3. Level of significance: $\propto = 0.05$

4. Test statistics:

$$F_1 = \frac{(RSC_1 - RSC)(n-m)}{RSCq} \quad (18)$$

5. Critical region:

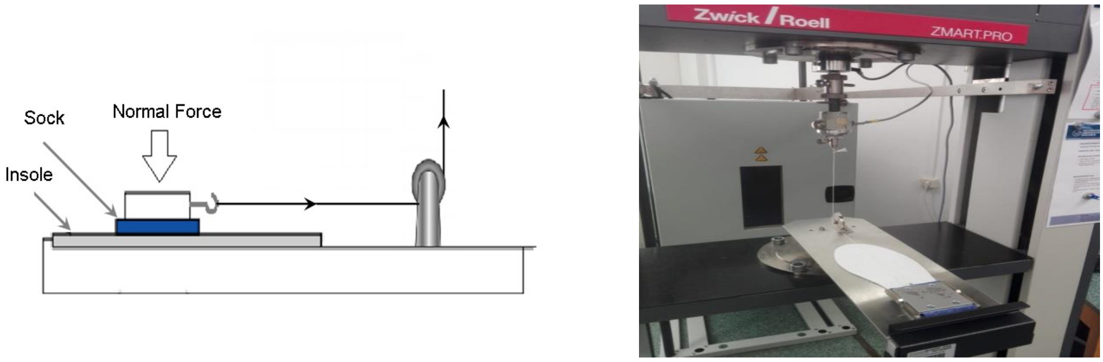
   Check the value from table for Fisher-Snedecor F-distribution $F_{0.95}$ (m, n-m)

6. Conclusion:

   If the calculated value (Eq.18) is less than the critical value then accept the null hypothesis H_0: $\beta_2 = 0$ and $\beta_1 = 1$. It means both intercept and slope isn't significantly different from 0 and 1 respectively at a 95% confidence level. A simultaneous test of the composite hypothesis confirmed that a new laboratory method (by theoretical model) is in agreement with the results of a standard one (experimental). And if the calculated value is higher than the critical then alternative hypothesis H_1: $\beta_2 \neq 0$ and $\beta_1 \neq 1$ will be accepted with the conclusion that theoretical model results aren't in agreement with the experimental results [72].

4.5.6 Frictional characteristics of socks in wet conditions

Clothing comfort is an intricate theory affected by different causes i.e. thermophysiological, sensorial, and ergonomic. Thermo-physiological relates to heat and mass transfer, sensorial is a tactile property related to skin feel and ergonomic comfort links to the garment fit and an affinity to stick the skin [73]. Various researchers investigated the effect of humidity on the coefficient of friction between skin-socks & socks-textile interfaces and reported an increase in the coefficient of friction with higher humidity [52]. Friction between another interface (sock-insole) is also very critical to design (socks/ shoes), blister formation, postural balance and friction ratio (between sock-skin & sock-insole interfaces). The purpose of the current study was to assess the effect of different levels of moisture content, influencing the sock-insole frictional performance on the plain knitted socks. All the plain knitted socks have been used for the characterization of friction properties at different moisture levels. The frictional property of the sock-insole interface was determined by using a horizontal plate method (ASTM D1894) where a sled of known weight (200g) connected with a tensile testing machine (Zwick/ Roell ZMART.PRO). This apparatus (Fig.6) is based on the sliding type of movement and can characterize both static and dynamic friction contacts under a variety of test conditions [74][75].



(a) *(b)*

Figure 6. Horizontal plate friction analyzer (a) Drawing (b) Real situation

The contact area of the sock sample with the insole is (6.4×6.4) cm². The load cell of 5N was selected with a pretension of 0.25N and 100mm/min speed to pretension. During the friction test, the insole remained stationary, while the sock (clamped inside the sled) was submitted to a horizontal movement. The friction force between the sock-insole interface was measured by a force sensor and coefficients of friction (μ) were calculated according to (Eq.19).

$$\mu = \frac{F}{N} \tag{19}$$

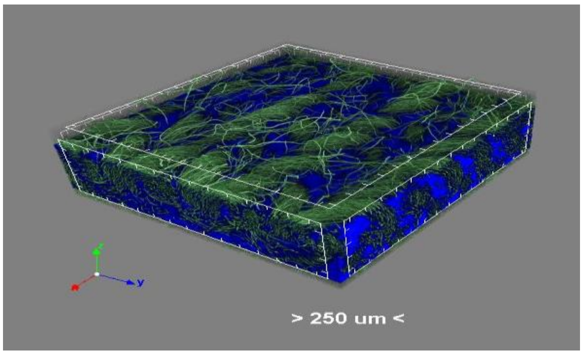
Although, friction should be characterized under an extension to simulate the real condition, along with the load that produces equivalent normal force to the average human body weight. But it was not feasible on the above-mentioned machine until unless some modification was done through mechanical work. The bodyweight factor could be compensated by the frictional force conversion into the coefficient of friction (COF). Secondly, the aim of the study is the effect of the moisture content on the sock's frictional properties.

5 *Results and discussions*

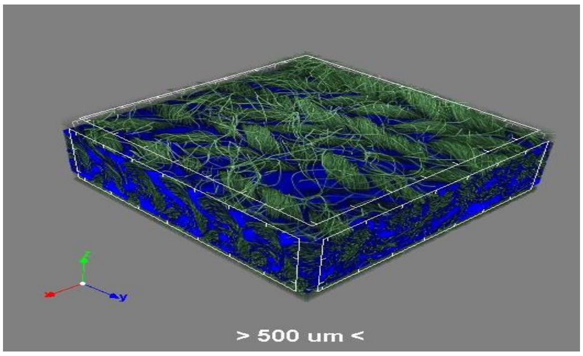
5.1 Socks porosity

5.1.1 Volume porosity of socks by model & micro-tomography (MCT)

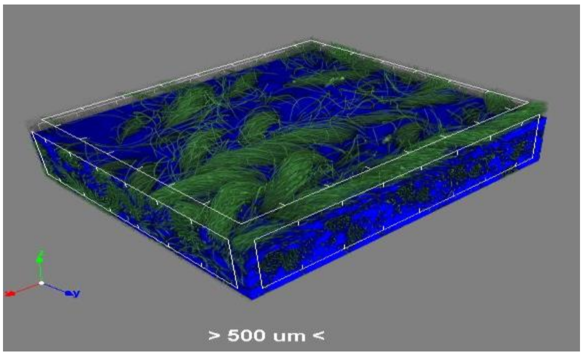
Images of all the tested socks scanned by micro-tomography scanner (SkyScan 1272) as 2D and converted into 3D by using NRecon. A sample size of 5x5 mm has been used for scanning these images. For porosity quantification, distribution of the pores, and pore thickness, above images were analyzed by using another software recommended by the manufacturer (BRUKER) is CTAn. The color coded images (Fig.7) were generated by CTVox by using the data provided by CTAn. The measurement of the 3D pore thickness referred to as "sphere-fitting" and this thickness considered as the diameter of the largest enclosed sphere [76].



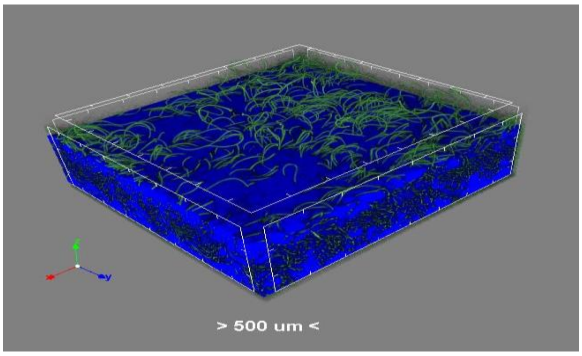
P1



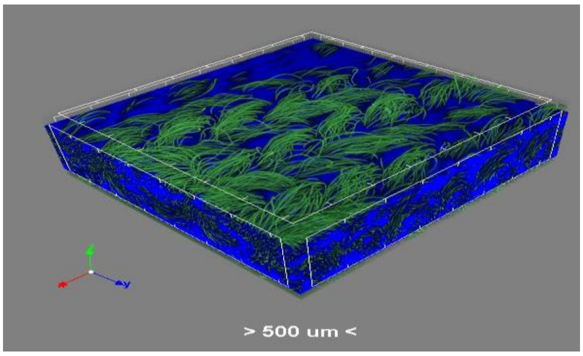
P2



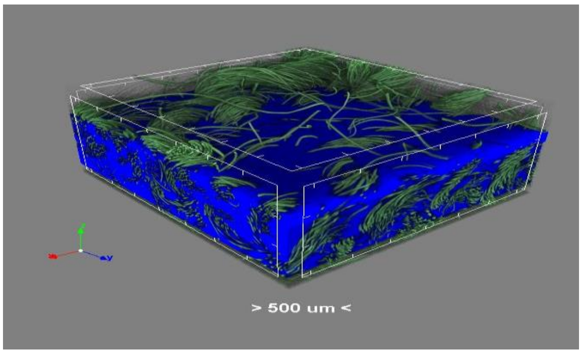
P3



P4

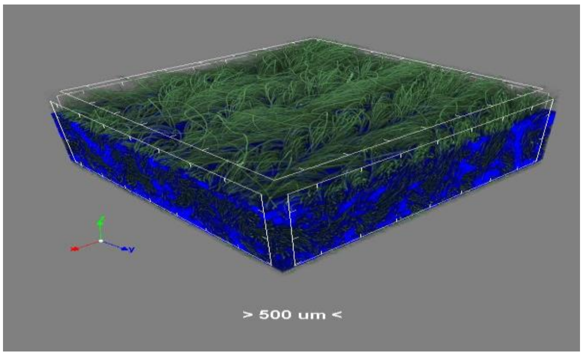


P5



P6

Figure 7. Color coded images by CTVox



P7

Figure 7. Color coded images by CTVox

The results of the volume porosity demonstrated that extended socks have higher porosity (Fig.8). This increase in the porosity also reported by Abdolmaleki et al. at different extension levels for loose knitted fabrics [77]. Porosity falls between 78% to 90% range without and with extension respectively. Guidoin et al. stated that knitted fabrics porosity lies between 67%-84%

and even 90% is not uncommon [63]. Extension causes to increase the pore size (space between loops) of the fabric and decrease the fabric thickness. It leads to a decrease in the volume of the fibre (solid part) and increases the volume of air corresponds to porosity. Porosity measured by micro-tomography (Fig.8) is in agreement with theoretical porosity (without extension) at a 95% confidence level for all the socks. As the thermal resistance model's prediction in the next sections is based on this porosity model. This comparison is logical and it further validated that the used model for the calculation of porosity is correct. The difference is between (0.14 - 4.3715%) for all the socks except P1. 7.4256% lower porosity is measured by micro-tomography with respect to the predicted value. That is close to the difference observed by Doczyova et al. i.e. 6% during porosity comparison of knitted structures [78].

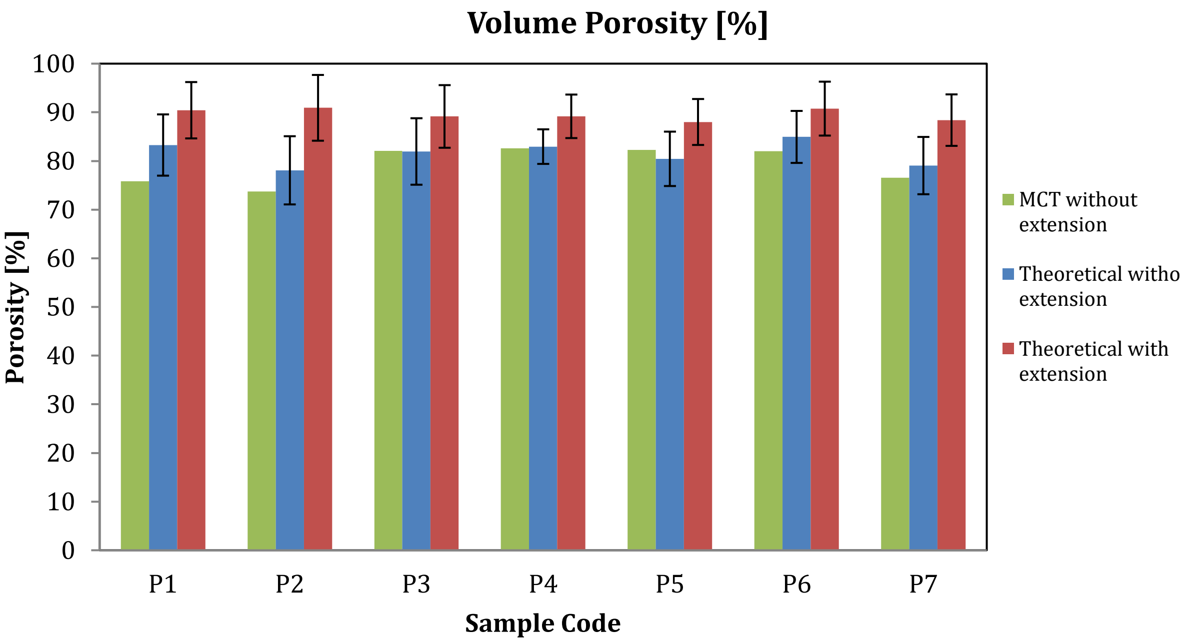


Figure 8. Volume porosity (micro-tomography vs theoretical)

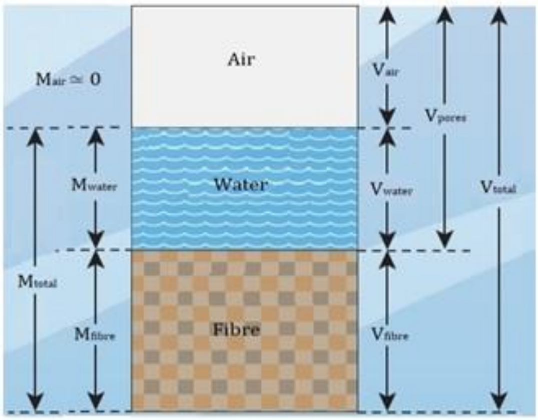
5.2 Effect of moisture content on thermal resistance

Figures 10, 12, 14, 16, 18, 20 and 22 clearly demonstrate that as the moisture (%) increases, the thermal resistance decreases irrespective of sock fibre composition. That is in compliance with the previous researchers [37][14][15][16][17][79]. For all the models the input thermal conductivity and filling coefficients were measured in wet polymer at different moisture levels. The correlation between experimental and predicted models was checked by coefficient of determination (R^2). The values of coefficient of determination (Figures 11, 13, 15, 17, 19, 21 and 23) for all the three modified models (ME-2, Schuhmeister and Militky) showed that these models could make reasonable predictions of thermal resistance in the dry, as well as the wet condition also at different moisture levels for all the major fibre blends being used for socks. Coefficient of determination (R^2) is fall between 0.7691-0.9535 for all the samples.

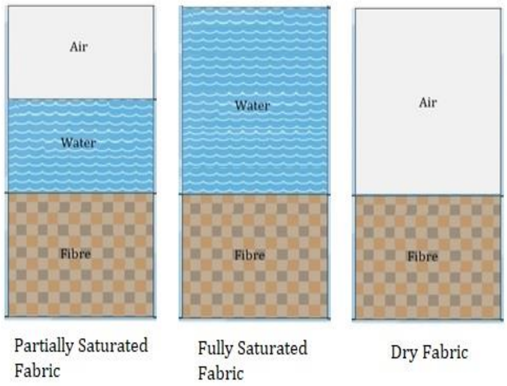
5.3 Assumptions for theoretical models

All the theoretical models for thermal resistance prediction are used by feeding the thermal conductivity ($\lambda_{\text{wet polymer}}$) and the filling coefficient ($F_{\text{wet polymer}}$) of wet polymer instead dry.

$F_{wet\ polymer}$ and $\lambda_{wet\ polymer}$ is calculated as per (Eqs.15-17). After this amendment, these models can also predict thermal resistance for wet fabrics. (Fig.9) demonstrated the volume fraction of air, water, and fibre.



(a)



(b)

Figure 9. Schematic presentation of (a) Segmental mass & volume, and (b) Volumetric change during wetting

Following are the assumption assumed for the development of theoretical models for the prediction of thermal resistance in the wet state;

- Fabric thickness assumed as constant
- No Free convection (as Rayleigh Number < 1000)
- The constant different temperature on both surfaces of the fabric **1st order boundary conditions**
- To simplify the model, fibre filling coefficient is assumed as **constant**
- Air and water filling coefficients are **variable**
- Fibre (polymer) and water filling coefficients are **combined as wet polymer** filling coefficient
- Thermal conductivity of wet polymer (water and fibres) are combined as per their **volume**
- **No dimensional changes** occurred at different moisture levels as tested in **extended state**
- Fabric areal density and thickness measured in the extended state
- Alambeta's thickness is considered

5.3.1 Effect of moisture content on cotton socks (P1)

The predicted and experimental thermal resistance of P1 (cotton 80%, polyester 18.20%, elastane 1.8%) at various moisture levels is given in (Fig.10). All three Maxwell modified Militky modified and Schuhmeister modified models have the best prediction at different moisture levels for the P1 sample. ME-2 modified, Militky modified, and Schuhmeister modified have R^2 values, i.e. 0.8911, 0.8851, and 0.8754 respectively as shown in (Fig.11). The thermal resistance is decreasing with the increase of moisture level (Fig.10). About 50% reduction in the thermal resistance is observed at 30% moisture content. This reduction is in accord with Naka and Kamata's study and close to the value reported by Mangat i.e. 70% [17][15]. Kanat et. al also observed a 50% reduction between 25-30% moisture content for single jersey cotton knitted fabrics in loose as well as tight state [79]. Overall Schuhmeister has the highest prediction due to 67% consideration of thermal resistance in series followed by the Militky modified model. It means as the portion of series consideration decreases thermal resistance decreases. In line with previous investigations of fibre alignment in series having 2-3 times higher thermal resistance than parallel [31][80].The findings are in accordance with Wang et. al [33] work. They have predicted the thermal conductivity with respect to porosity by using different combinations and models i.e. ME-1, ME-2, series, parallel, EMT, series+ parallel, ME-1+ME-2, etc. Reddy and Karthikeyan [81] also have the same findings during their study for predicting the thermal conductivity of frozen and unfrozen food materials.

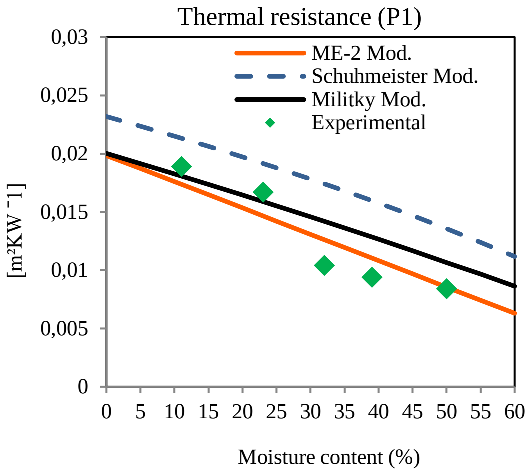


Figure 10. Predicted & experimental thermal resistance: P1 (cotton 80%, polyester 18.20%, elastane 1.8%)

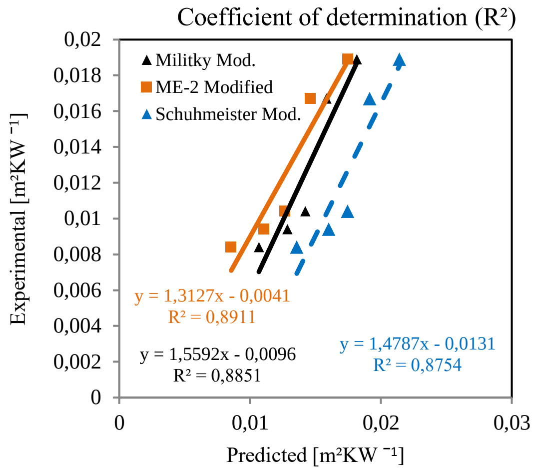


Figure 11. Coefficient of determination predicted & experimental thermal resistance: P1 (cotton 80%, polyester 18.20%, elastane 1.8%)

Validation of the theoretical models is done by comparison of results (x) with results obtained by experiments (y) for a set of parallel determinations. This validation is done by joint confidence region. After calculation and substitution in to (Eq.18), F1 values are 0.7039, 3.3266 and 16.3287 for ME-2, Militky and Schuhmeister modified models respectively against critical value $F_{0.95}$ (2, 3) = 9.5521. So the null hypothesis H_0 cannot be rejected for ME-2 & Militky modified models. It means the predicted thermal resistance with the ME-2 and Militky modified model isn't significantly different than the experimental results. Whereas the Schuhmeister modified is significantly different than the experimental results as evident by the null hypothesis rejection.

5.3.2 Effect of moisture content on viscose socks (P2)

In the case of P2 sock (viscose 81.08%, polyester 17.22% & elastane 1.77%), Militky modified model has the best prediction at 11.45%, and 19.50% moisture levels as shown in (Fig.12). ME-2 modified has a better thermal resistance prediction at 30.30, 40.17% and 49.80% moisture levels. All three models have a reasonable prediction of thermal resistance with $R^2 >$ 0.94 as shown in (Fig.13). Similar to the P1 sample a rapid decline in the thermal resistance with the increased moisture content is also observed, between 20% to 30% moisture content. This reduction is in agreement with Naka and Kamata's study and close to the value reported by Mangat i.e. 70% [17][15]. Schuhmeister modified model has the highest prediction followed by Militky modified and ME-2 modified at all the moisture levels. Over again lowest to the highest prediction of thermal resistance order by different models has verified the findings of Finck [80], Bogaty et. al [31], Wang et. al [33] & Reddy [81]. From these studies, it has been established that series alignment has predicted the highest thermal resistance followed by ME-2, combinations of (ME-2, ME-1, EMT, series, and parallel), EMT, ME-1, and parallel.

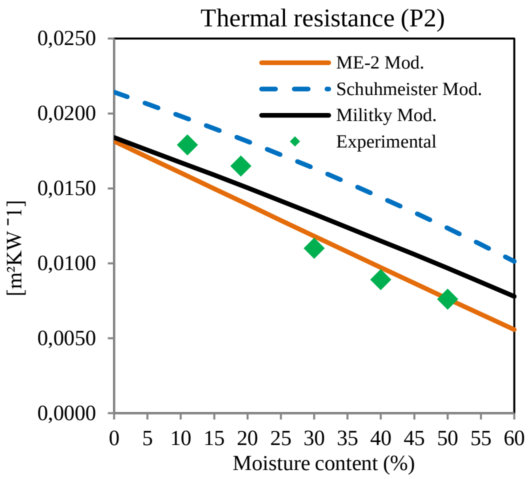


Figure 12. Predicted & experimental thermal resistance: P2 (viscose 81.08%, polyester 17.22% & elastane 1.77%)

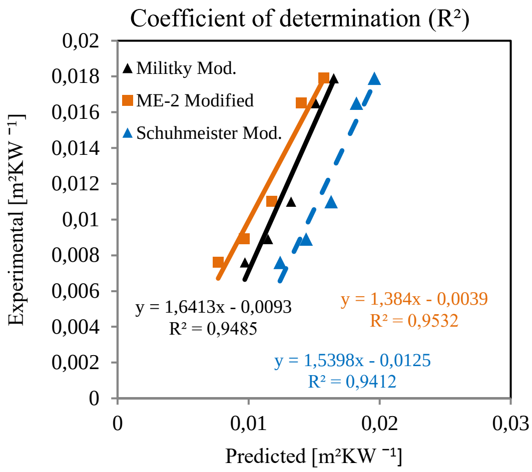


Figure 13. Coefficient of determination predicted & experimental thermal resistance: P2 (viscose 81.08%, polyester 17.22% & elastane 1.77%)

The value of composite confidence region for slope and intercept at 95% confidence level validated all the theoretical models except Schuhmeister modified model as the calculated value F_1=24.6719 is higher than the critical value $F_{0.95}$ (2, 3) = 9.5521. It means the thermal resistance prediction with Schuhmeister modified model is not significantly correct with respect to experimental results. Null hypothesis H_0 is accepted, ME-2 modified model is validated as having lower F_1 i.e. 3.0476 than the critical value 9.5521. In case of Militky modified model, (F_1 =3.0476) is lower than the quantile of the Fisher-Snedecor F-distribution $F_{0.95}$ (2, 3) = 9.5521, so the null hypothesis H_0 cannot be rejected.

5.3.3 Effect of moisture content on polyester socks (P3)

(Fig.14) depicts theoretical and experimental thermal resistances of P3 socks (polyester 98.38% & elastane 1.62%) at various moisture levels. ME-2 modified, Militky modified and Schuhmeister modified models have R^2 values 0.7999, 0.7876, and 0.7671 respectively (Fig.15). The drop off in the thermal resistance is slower and uniform between 5 % to 10% and 20% to 50% moisture content levels. But this decline (42% reduction) is fast between 10% to 20% moisture content as evident from experimental green square legends (Fig.14). This is in concurrence to Bogusławska and Hes work who reported a 50% reduction in the thermal resistance between 10 to 20% moisture content in different fabrics [7]. Kanat et. al have reported a 30-35% reduction at 25% moisture level for single jersey polyester knitted fabrics [79]. Unlike P1 and P2, 50% of the thermal resistance reduction in P3 is observed at 50% moisture content due to the hydrophobic nature of polyester. Once more Schuhmeister modified model has a higher prediction at all the moisture levels except 5% and 10% moisture content. It has predicted 0.5 to 2 times higher thermal resistance. It is in accord with Mao and Russel's study [82]. They have observed 0.5 to 3 times lower thermal conductivity prediction for 100% polyester spacer fabric with Schuhmeister's model. They haven't incorporated moisture content. Even then their predictions are very high with respect to experiments. Lowest to the highest prediction of thermal resistance sequence with these models are in line with the findings of previous researchers [80][31][33][81].

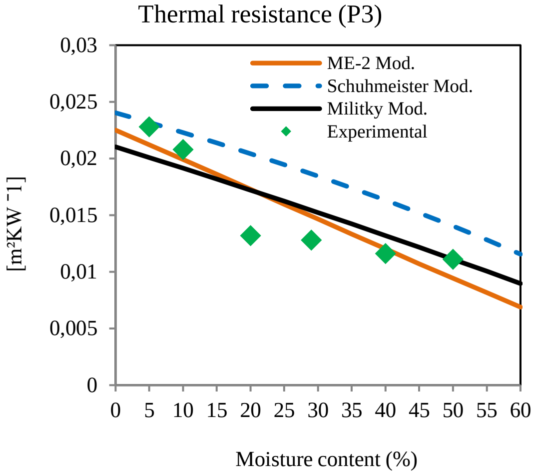


Figure 14. Predicted & experimental thermal resistance: P3 (polyester 98.38% & elastane 1.62%)

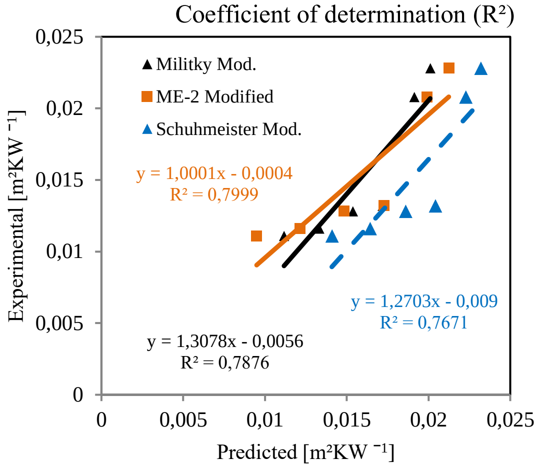


Figure 15. Coefficient of determination predicted & experimental thermal resistance: P3 (polyester 98.38% & elastane 1.62%)

The constructed confidence region for slope and intercept at 95% confidence level validated all the theoretical models. All the models have lower F_1 values than the tabulated values (critical region). So the null hypothesis couldn't be rejected for these models. It means the intercepts (β_2) and slopes (β_1) aren't significantly different from zero and one respectively. So the thermal resistance prediction with all three modified models is not significantly different with respect to experimental results for sample P3. Calculated values of F_1 also justify the ME-2 modified model has top prediction among all others followed by Militky modified and Schuhmeister modified. On the nutshell ME-2 modified model has the better forecast for sample P3 than both other models i.e. Militky modified and Schuhmeister modified. Test statistics (calculated F_1) values are 0.2369, 1.1055 and 6.8867 for ME-2, Militky & Schuhmeister modified models respectively against the critical value of the Fisher-Snedecor F-distribution $F_{0.95}(2, 4) = 6.9443$. So the null hypothesis H_0 cannot be rejected f. It means the predicted thermal resistance with these models isn't significantly different than the experimental results.

5.3.4 Effect of moisture content on polyamide socks (P4)

ME-2 modified has the overall top thermal resistance prediction in general and at 5.17%, 10.01%, 20.51%, 40.06% and 49.93% moisture levels specifically for P4 (nylon 70%, polyester 26.54% & elastane 2.63%) as shown in (Fig.16). This is also evident by the highest $R^2 = 0.9446$ (Fig.17). Militky modified prediction is on second number with ($R^2 = 0.9416$) as shown in (Fig.17). A rapid decline in the thermal resistance similar to P1, P2, and P3 between 20-30% moisture content is detected for the P4 sample as well. In the case of P4, a 50% reduction in the thermal resistance is observed at a 40% moisture level. Schuhmeister modified has better prediction till 20% moisture content. However, it didn't follow the experimental footprints as Militky modified and ME-2 modified models.

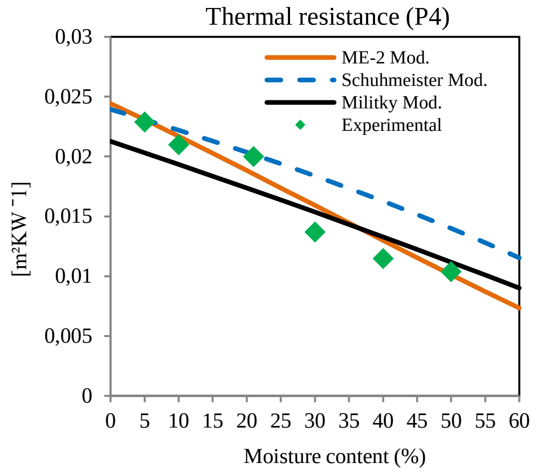


Figure 16. Predicted & experimental thermal resistance: P4 (polyamide nylon 70%, polyester 26.54% & elastane 2.63%)

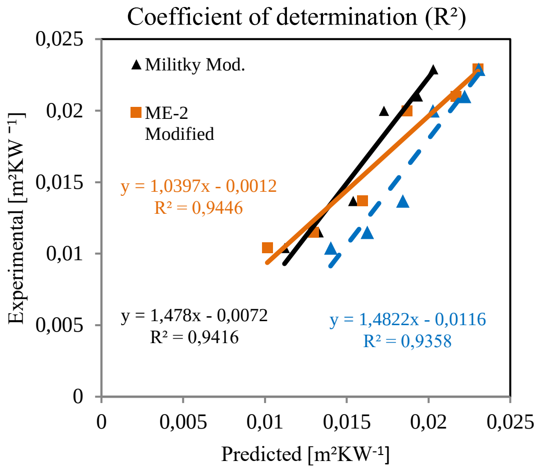
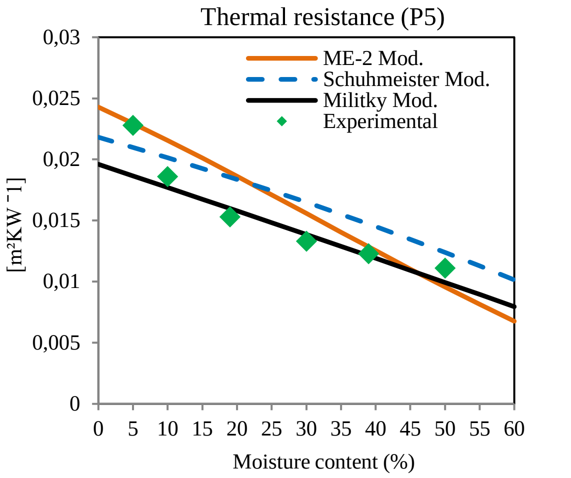


Figure 17. Coefficient of determination predicted & experimental thermal resistance: P4 (polyamide nylon 70%, polyester 26.54% & elastane 2.63%)

Null hypothesis acceptance (F_1 calculated values i.e. 0.7963, 4.3633 and 5.4464 are lesser than the critical value of the Fisher-Snedecor F-distribution $F_{0.95}$ (2, 4) = 6.9443) further provide strong evidence for the validity of the ME-2 Militky and Schuhmeister modified models against the assumptions i.e. H_0: $\beta_2 = 0$ and $\beta_1 = 1$ at 95% confidence level. It means their structured confidence region isn't significantly different from "0" and "1" for intercept & slope respectively. It means the modified model's prediction isn't significantly different from experimental results.

5.3.5 Effect of moisture content on polypropylene socks (P5)

In (Fig.18) for P5 (polypropylene 65.22%, polyester 31.65% & elastane 3.13%) socks Militky modified prediction is the best with respect to ME-2 modified model at 10.21%, 19.13%, 29.99%, 38.50 and 50.22%. ME-2 modified has the best forecast at 5.05%, 38.50% and 50.22% moisture contents. The coefficient of determination values (R^2) 0.867, 0.8643, and 0.8472 also have the same sequence as shown in (Fig.19). P5 curve is like P3, i.e. after the sudden decline, there is some stability in the drop. Similar to P3 it has 50% thermal resistance fall at 50% moisture content.



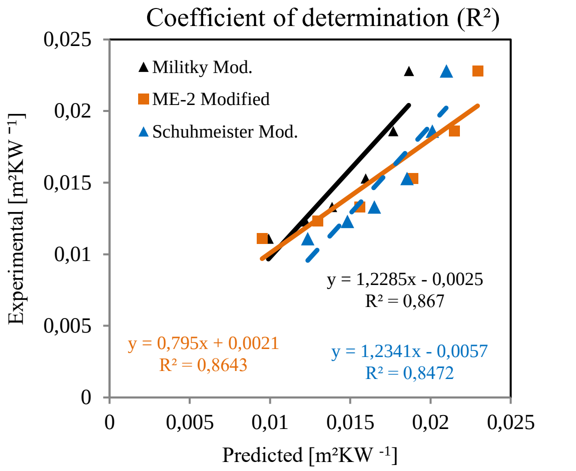


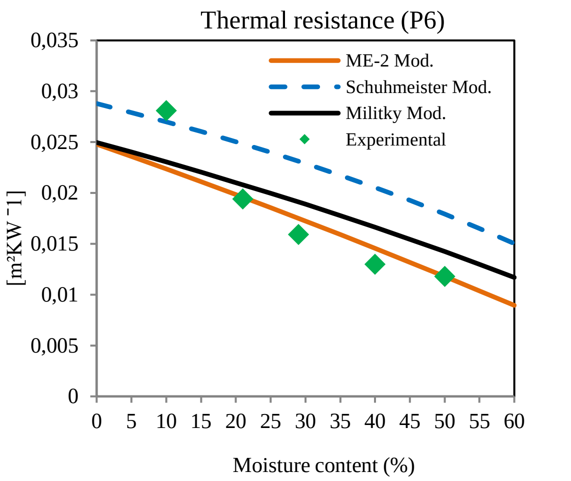
Figure 18. Predicted & experimental thermal resistance: P5 (polypropylene 65.22%, polyester 31.65% & elastane 3.13%)

Figure 19. Coefficient of determination predicted & experimental thermal resistance: P5 (polypropylene 65.22%, polyester 31.65% & elastane 3.13%)

F_1 values i.e. 2.8625, 1.4727 and 3.2226 (for ME-2, Militky and Schuhmeister models respectively) are smaller than the critical value i.e. $F_{0.95}(2, 4) = 6.9443$. So the null hypothesis i.e. H_0: $\beta_2 = 0$ and $\beta_1 = 1$ for all these models couldn't be rejected. It validates that ME-2 modified, Militky modified and Schuhmeister modified models prediction isn't significantly different from experimental results.

5.3.6 Effect of moisture content on wool socks (P6)

(Fig.20) shows the effect of moisture content (%) on the thermal resistance of P6 socks (wool 76.19%, 21.67% polyester & elastane 2.14%). All the models have an appropriate prediction of thermal resistance as evident in (Fig.21). Both ME-2 and Militky models have a better prediction at 21.30%, 28.90%, 40.38% and 49.90% moisture levels. But this forecast is not so close at 10% moisture level. This trend is also manifested in (Fig.20). As well as the coefficient of determination is concerned, ME-2 modified, Militky modified and Schuhmeister modified models have 0.882, 0.8723 and 0.8566 in that order as shown in (Fig.21). Similar to the above samples P6 has also half a thermal resistance with 30% moisture content.



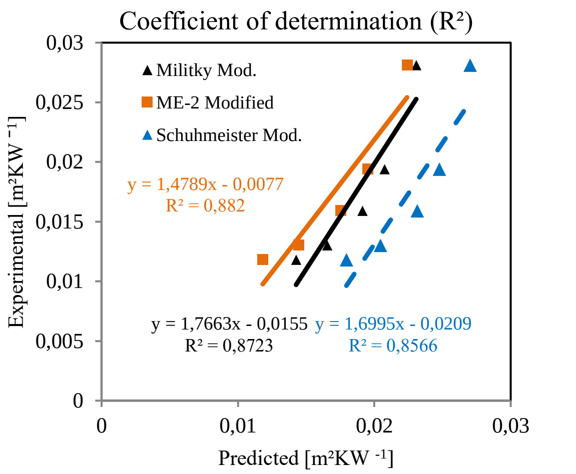


Figure 20. Predicted & experimental thermal resistance: P6 (wool 76.19%, 21.67% polyester & elastane 2.14%)

Figure 21. Coefficient of determination predicted & experimental thermal resistance: P6 (wool 76.19%, 21.67% polyester & elastane 2.14%)

Hypothesized results for intercept and slope assuming them as equal to zero and one also validated that the suggested models have not significantly different results at a 95% confidence level. Because the F1 values i.e. 1.2677, 2.3522 and 9.2379 for ME-2, Militky and Schuhmeister modified models are smaller than the critical value i.e. 9.5521 for $F_{0.95}$ (2, 3). So the null hypothesis couldn't be rejected. It concluded that predicted (theoretical) results are in agreement with the experimental results.

5.3.7 Effect of moisture content on acrylic socks (P7)

(Fig.22) shows the effect of moisture content (%) on the thermal resistance of P7 sock (acrylic 81.25%, 17.06% polyester & elastane 1.69%). All the models have the apposite prediction of thermal resistance as evident in (Fig.22 and Fig.23). (Fig.22) shows the coefficient of the determination between the theoretical (predicted) and experimental thermal resistance. All the models have good conformity with the experimental thermal resistance, i.e. 0.9051 and 0.8988 for ME-2 modified and Militky modified models, respectively.

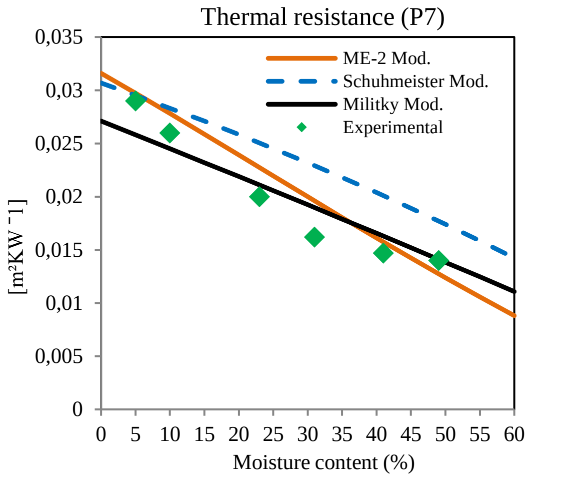


Figure 22. Predicted & experimental thermal resistance: P7 (acrylic 81.25%, 17.06% polyester & elastane 1.69%)

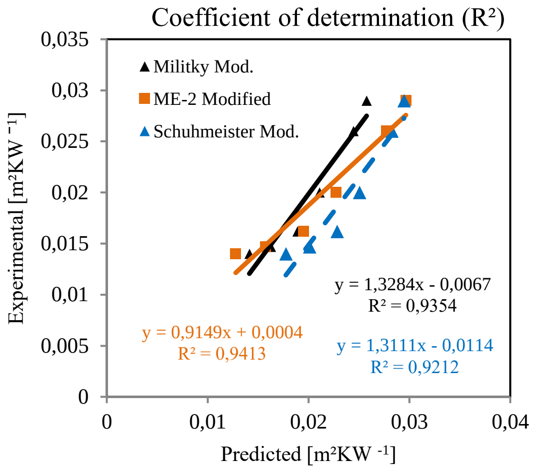


Figure 23. Coefficient of determination predicted & experimental thermal tesistance: P7 (acrylic 81.25%, 17.06% polyester & elastane 1.69%)

F1 values for ME-2 and Militky modified models i.e. 3.8301, 3.3563 respectively are lesser than the quantile of the Fisher-Snedecor F-distribution $F_{0.95}$ (2, 4) = 6.9443, so the null hypothesis H_0 cannot be rejected. It means the predicted thermal resistance with the ME-2 and Militky modified models isn't significantly different than the experimental results. However this value (F1 = 17.0908) is greater than the critical value (6.9443). It concluded that the thermal resistance predicted by Schuhmeister modified model isn't in agreement with the experimental values for P7 sample.

5.4 Effect of moisture content on thermal absorptivity

(Fig.24) demonstrated that as the moisture (%) increases, the thermal absorptivity also increases irrespective of sock fibre composition. That is in compliance with the previous researchers [83][84][37]. Baczek & Hes observed 9 times higher thermal absorptivity of plaited knitted fabrics in the wet state [36]. P5 sock has the lowest thermal absorptivity under dry and wet conditions (at 10%, 20%, 30%, 40% & 50% moisture content) followed by P3 (composed of 100% polyester) socks. Even at 50% moisture content P5 socks have the thermal absorptivity <300. So these socks will have a higher feeling of dryness than any other socks due to the composition of hydrophobic fibres of polypropylene and polyester. At 10% moisture content all the socks P3, P4, P5, P6, and P7 have the thermal absorptivity between (100-110 $Ws^{½}$ $m^{-2}K^{-1}$) apart from P1 and P2 socks. P1& P2 socks have 134 and 130 $Ws^{½}$ m^{-2} K^{-1} respectively. At 20% moisture content this range is between (143-171 $Ws^{½}$ $m^{-2}K^{-1}$). P5 has the lowest value followed by P3, P7, P4, P1, P6, and P2. At 30% humidity level the rise of thermal absorptivity is more significant, i.e. 47.95%, 52%, 61.78, 63.03 and 66.66% for P2, P4, P7, P6, and P1 socks. This increase is also observed in P5 and P3 socks, but to a lower extent, i.e. 38.46% and 34.64%, respectively.

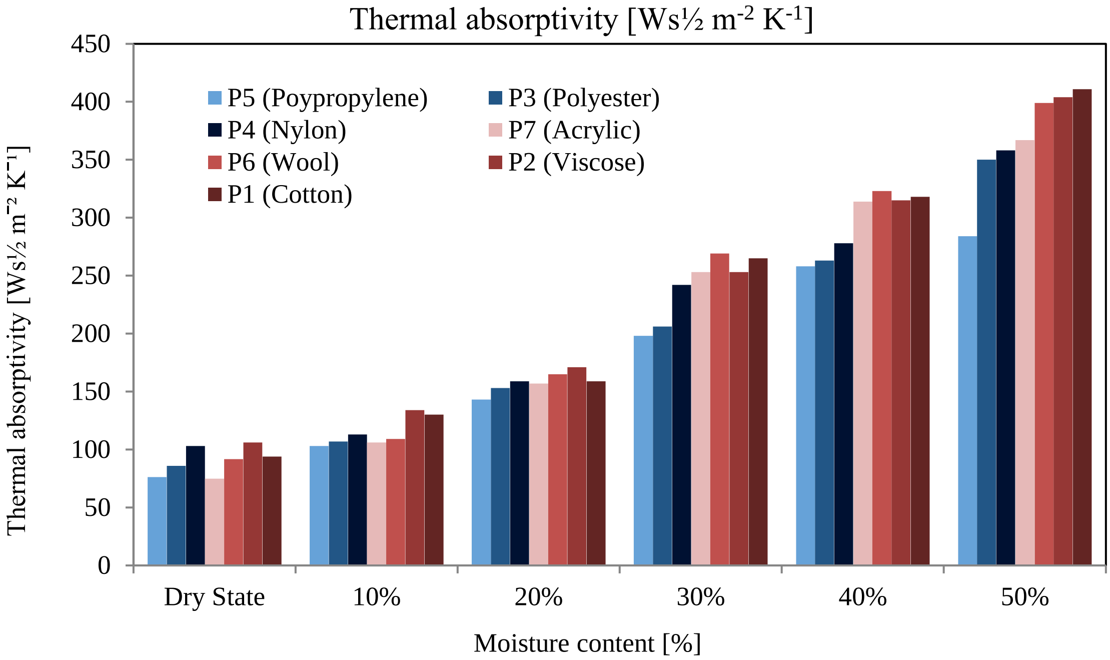


Figure 24. Effect of moisture content on thermal absorptivity

5.5 Effect of moisture content on RWVP

(Fig.25) shows that the increasing moisture content in fabrics leads to increasing their ability to transport water vapour. Same behaviour was also observed by Hes [7], Lenfeldova [85] and Baczek [86] . Higher RWVP (%) leads to a higher cooling effect. As moisture content and water condensation in the fabric increased, it causes to increase water vapour permeability through the fabric [87]. P6 and P7 will be the warmest socks with a lower RWVP (%). The presented results show that the addition of hydrophobic fibres affects the water vapor transportability of hydrophilic fabrics. Relative water vapour permeability increases almost 100% with 50% moisture content. The study by Hes showed the same results without any air gap [88]. Most of the socks, i.e. P5 (polypropylene 65.22%, polyester 31.65%, elastane 3.13%), P4 (nylon 70.83%, polyester 26.54%, elastane 2.63%), P3 (polyester 98.38%, elastane 1.62%) are composed of synthetic fibres and have a higher relative water vapour permeability. P6 (wool 76.19%, polyester 21.6.7%, elastane 2.14%) has the lowest RWVP at the dry and wet state (10%, 20% & 30% moisture content) followed by P2 (viscose 81.08%, polyester 17.22 %) and P7 (acrylic 81.25%, polyester 17.06%, elastane 1.69%) in the dry state, at 10%, and

20% moisture content. At 40% and 50% moisture level P7 has the lowest RWVP among all the socks, slightly different to P6.

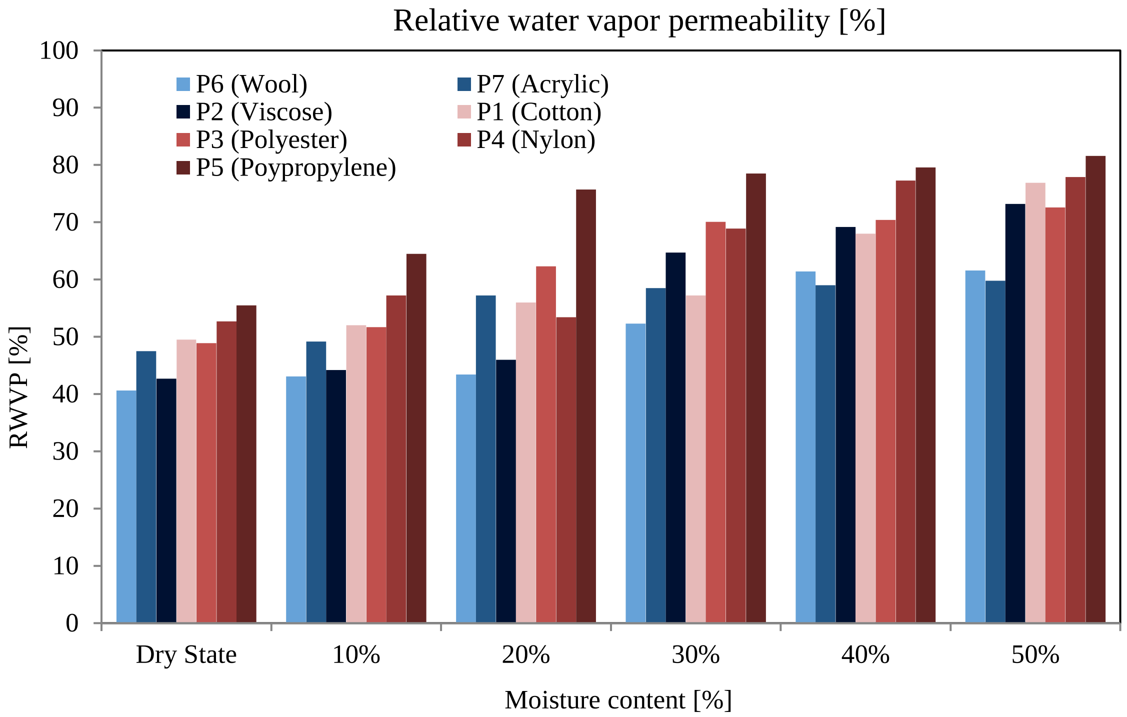


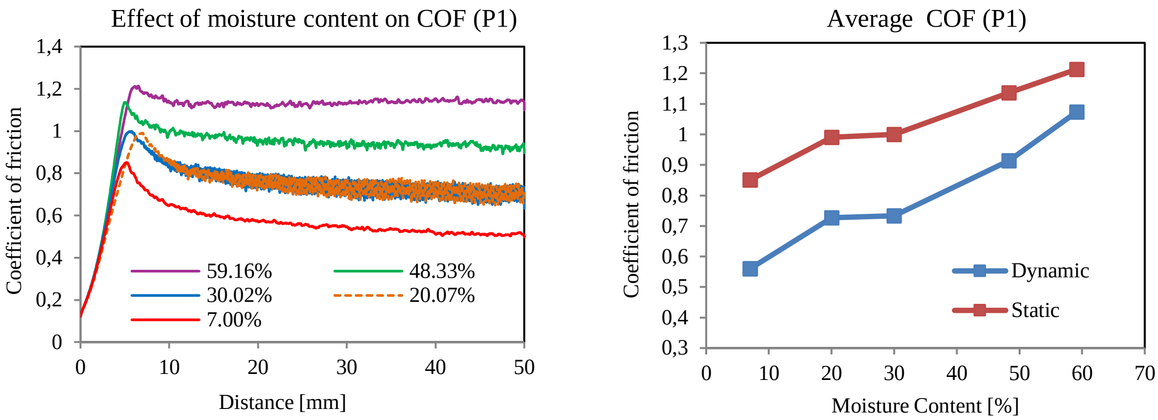
Figure 25. Effect of moisture content on RWVP

Hydrophilic fibres composed socks like wool and cotton owing to bond with water molecules. Therefore, they have poor moisture transportation. On the other hand, synthetic fibers such as polyester, polypropylene, and nylon have an advantage of liquid transport and release by capillary wicking. It is in accordance with previous studies [84][89]. Swelling can also set up internal stresses that may affect the sorption process. This could increase the adsorption hysteresis with the increase of hydrophilic fibres [90]. There is an inverse relation between the diffusion fibre volume fraction and the flatness of fibre cross section, also reported in the literature [91]. A higher fabric thickness can also decrease RWVP significantly [92]. P7 sample has the highest thickness followed by P6, P1, P3, P4, P2 and P5. RWVP is affected by the thickness at all moisture levels.

5.6 Effect of moisture content on coefficient of friction

Results for the sock-insole static and dynamic coefficients of friction (COF) at different water content for all the seven socks are shown in (Figures 26-32). (Fig.47) shows the graphs for COF at different moisture levels for P1 sock. The results demonstrated that as the moisture content increases, it causes to increase the coefficient of friction. That is in accord with the previous studies [52][58]. Bertaux et al. reported an 83.87% increase in sock-skin static COF from 0.31 to 0.57 (dry to wet state) by the addition of 5.58g of water having cotton/polyamide at toes and waist area [52]. There is a continuous increase in the friction with the increase of moisture content except between 20-30%. Hes et al. observed the same increase in static and dynamic friction in a wet state for cotton elastic knitted fabrics [93]. Tasron et al. reported 0.33

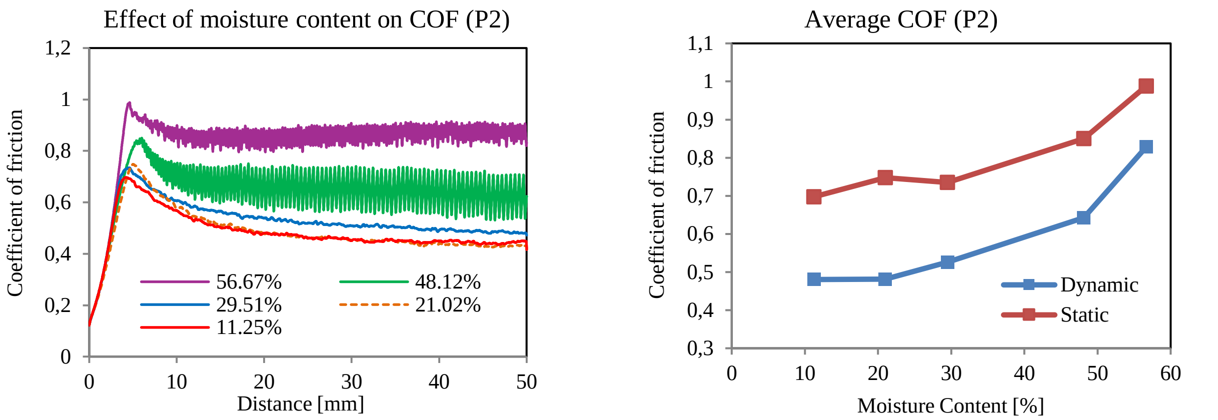
± 0.07, 0.67± 0.08 & 0.74 ± 0.08 dynamic COF values for cotton plain knitted socks in dry, low moisture and high moisture content respectively [94].



(a) *(b)*

Figure 26. (a) Effect of moisture content on coefficient of friction (b) Average COF at different moisture levels (P1)

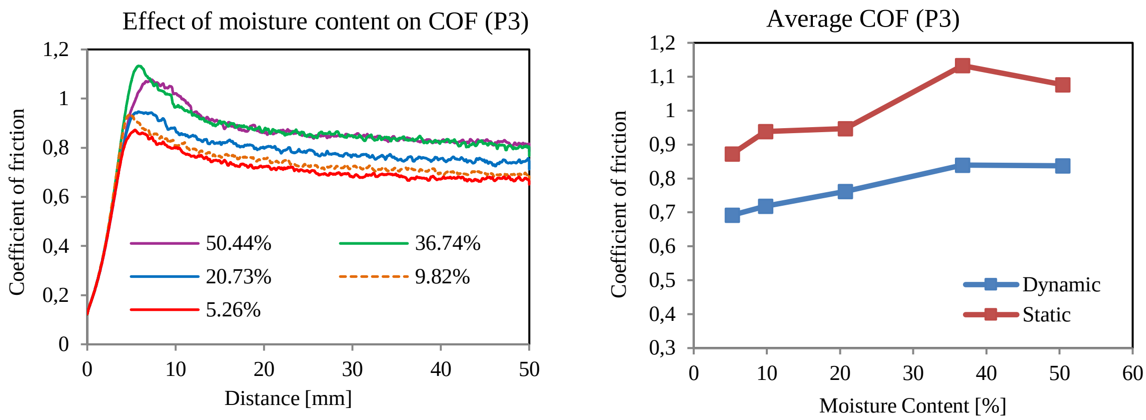
(Fig.27) shows the graphs for COF at different moisture levels for P2 sock. Similar to P1 sock, as the moisture content increases, it causes to increase the coefficient of friction. There is a continuous increase in friction with the increase of moisture content. Viscose has lower insole-sock frictional force or COF with respect to P1 (cotton rich sock) at the nearer moisture levels due to its smooth glossy surface [95].



(a) *(b)*

Figure 27. (a) Effect of moisture content on coefficient of friction (b) Average COF at different moisture levels (P2)

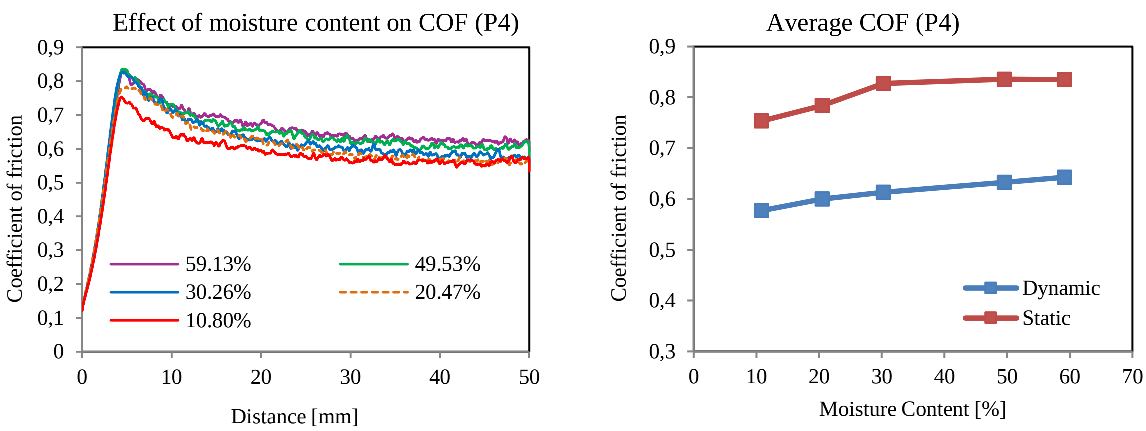
(Fig.28) shows the COF at different moisture levels for P3 sock. Even though there is a continuous increase in the friction with the increase of the moisture content. But unlike with P1 & P2 socks, the increment in the friction isn’t so rapid. That is manifested especially by the blue line slope representing dynamic COF as shown by (Fig.28b). Dynamic COF almost has the same values between 36.74-56.44% moisture levels. Here a decline is observed for static COF between this range. The dynamic COF slope is more uniform than the static COF slope with respect to different moisture levels. Previously, Rotaru et al. measured the dynamic friction between human skin and knitted bed sheets consisting of 50% cotton and 50% polyester and reported 0.50 and 0.90 in the dry, wet state respectively [96]. Both dynamic and static COF is lower than the P1 sample. Varadaraju and Srinivasan have also found that polyester inner layer fabric has a lower COF value than a cotton inner layer in the wet state [97].



(a) *(b)*

Figure 28. (a) Effect of moisture content on coefficient of friction (b) Average COF at different moisture levels (P3)

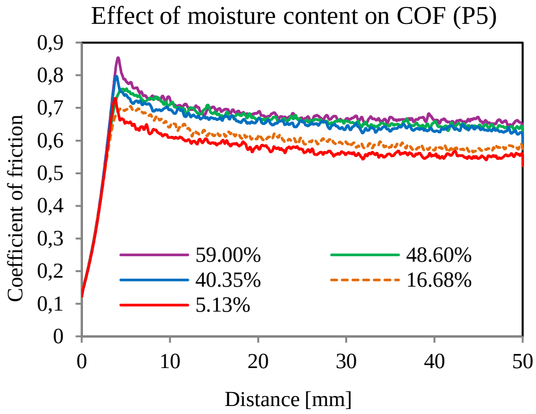
COF at different moisture levels for P4 sock is illustrated by (Fig.29a and Fig.29b). Similar to P3 sock, there is a continuous increase in the friction (both static & dynamic) with the increase of the moisture content. Bertaux et al. observed dynamic COF (sock-skin interface) values are 0.495, 0.475 for two different wet socks at heel and waist consist of polyamide after 40 min of exercise [52]. The increment in the friction isn't so higher and rapid. Only 10.82 to 11.50% increase in static and dynamic COF is observed between 10.80% to 59.13% moisture content. It is the 2nd lowest increase observed after P7 sock. The results of dynamic COF for P4 socks are in line with Tasron et al. work. As average dynamic COF falls between 0.57 to 0.64 at 10.80% to 59.13% moisture level. Earlier, Tasron et al. reported 0.44 ± 0.1, 0.61± 0.08 & 0.69 ± 0.07 dynamic COF values for polyamide plain knitted socks in dry, low moisture and high moisture content respectively [94]. Similar results have been observed by Ke et al. They have measured the dynamic COF between human skin and five different polyamide rich medical compression stockings in dry/ wet states and observed that the COF range is 0.31-0.60 for 1x1 jersey structures in the wet state [98]. But they haven't mentioned the moisture content value.



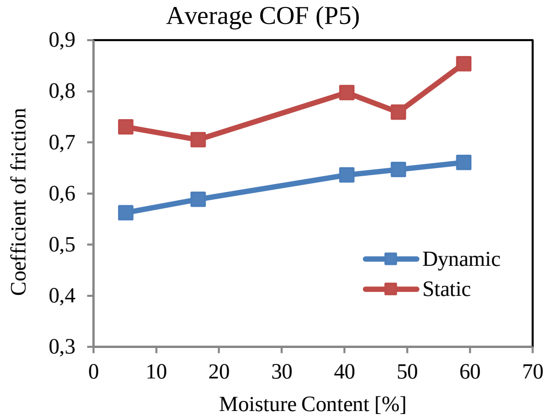
(a) *(b)*

Figure 29. (a) Effect of moisture content on coefficient of friction (b) Average COF at different moisture levels (P4)

COF for P5 sock is showed by (Fig.30a and Fig.30b) in that order. Similar to P3 and P4 socks, there is a continuous increase in the dynamic friction with the increase of the moisture content. The increase isn't so higher and rapid. Merely 16.97% to 17.46% increase in static and dynamic COF is observed between 5.13% to 59% moisture content. It is the 3rd lowest increase observed after P4 and P7 socks. That is manifested by their slopes as shown by (Fig.51b). Bertaux et al. observed dynamic COF (sock-skin interface) value is 0.52 for wet sock's toe consist of polypropylene after 40 min of exercise [52].



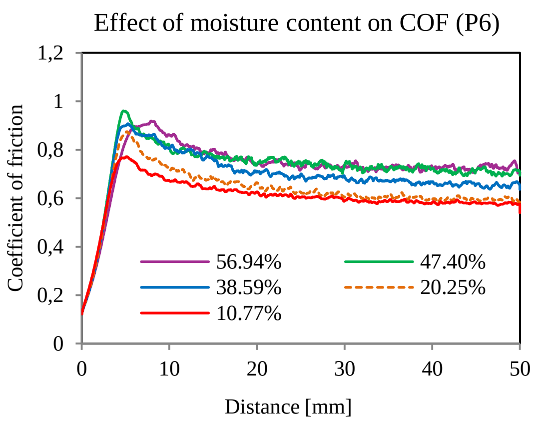
(a)



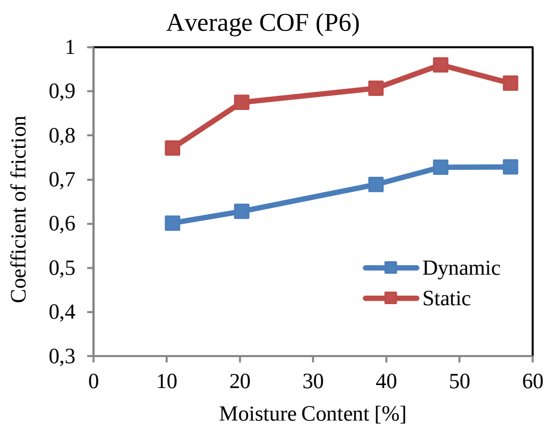
(b)

Figure 30. (a) Effect of moisture content on coefficient of friction (b) Average COF at different moisture levels (P5)

COF at different moisture levels for P6 sock has been shown by (Fig.31a and Fig.31b. The results demonstrated that as the moisture content increases, it causes to increase in the coefficient of friction following Amber et al. work [10]. There is a uniform increase in the friction with the increase of moisture content. Unlike other hygroscopic fibre containing socks i.e. P1 (cotton rich) and P2 (viscose rich), P6 has not shown a rapid increase in dynamic friction with the increase of the moisture content. 20% increase in dynamic COF observed between (10.77% to 47.40%) moisture content range, whereas about dynamic COF raised to about 25% among the same moisture range. Minimum dynamic COF (0.60) is observed at 10.77% moisture content. This could be considered as a dry state for wool fibres as 16% moisture regain is known for wool fibre in standard atmospheric conditions. This value is close to the result reported by Sanders et al. They have observed dynamic COF range is 0.60 to 0.79 between wool socks and different materials (insoles) interfaces in the dry state.



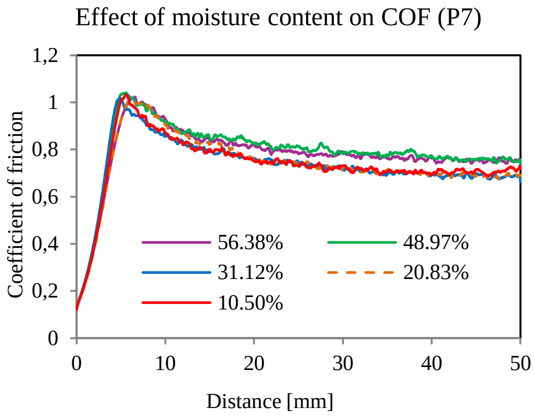
(a)

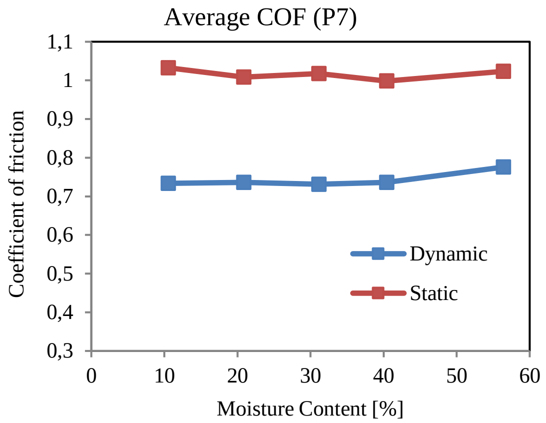


(b)

Figure 31. (a) Effect of moisture content on coefficient of friction (b) Average COF at different moisture levels (P6)

The graphs for COF (Fig.32a & Fig.32b) at different moisture levels for P7 sock. Unlike with all the above socks, P7 has not shown a significant increase in static or dynamic friction with the increase of the moisture content. Arai et al. have observed the same kind of results on measuring the static COF for water-absorbing acrylic (Kanebo Lumiza) knitted fabrics at different moisture levels [99]. (Fig.32 b) illustrates that there is no change in the dynamic COF till 40% moisture level and a slight rise of 5.67% at 56.38% moisture level. While static COF has shown a slight decrease trend with the increase of the moisture. But it is not significant. In an earlier study, the effect of wetting on the frictional behavior of acrylic and polypropylene multifilament yarns was examined by El-Mogahzy [100]. The results show that the coefficient of friction increased with wetting. But the change in the value of the friction is not significant. Suchatlampong et al. also reported a decline or no change in the value of the friction coefficient when tested acrylic liners against aluminium plate and silicone impression material [101].





(a) *(b)*

Figure 32. (a) Effect of moisture content on coefficient of friction (b) Average COF at different moisture levels (P7)

5.7 Thermal resistance comparison among different skin models

Thermal resistance study in the wet state should be planned on TFM with aspect to the real simulation of extension and foot geometry. It was tried, but couldn't succeed due to the equipment limitations. The thermal foot model is closer to the real simulation of the worn sock but due to a longer period of measurement (about 1hour) and 35˚C temperature of the thermal foot plus free convection of 1ms^{-1} dries the sample or changes the moisture content. The second choice may be Permetest. Although Permetest has a short time of testing, free convection existence here also leads to continuous evaporation of the moisture from the fabric. Finally, Alambeta was selected for thermal resistance testing in the wet state. The comparison is done in the dry state to indirectly prove that if the results of thermal resistance on the selected skin model (Alambeta) are in good agreement in the dry state. They will have also good conformity in the wet state as well. For a real simulation of the extension like the thermal FM, socks were loaded on a dummy leg and marked with a circle of 12.2cm diameter with the help of a paper card (Fig.3). Then socks were slashed and extended on an embroidery hoop to the marked circle. Finally, these samples were tested on Alambeta and Permetest for Rct under the dry condition. (Fig.33) shows the comparisons of thermal resistance, between TFM and Alambeta. Although thermal resistance measured by TFM is higher for all the samples, however the error bars at 95% confidence interval demonstrated that these results from two different skin models are comparable between (0~0.25 ms^{-1}) air velocity. These results are in line with the previous researchers. Mansoor et al. observed the coefficient of determination value is 0.55 while comparing the thermal resistance of terry knitted socks measured by Alambeta and TFM [84]. Abdelhamid et al. also reported good agreement of thermal resistance measured by Alambeta and TFM for woven compression bandages [102].

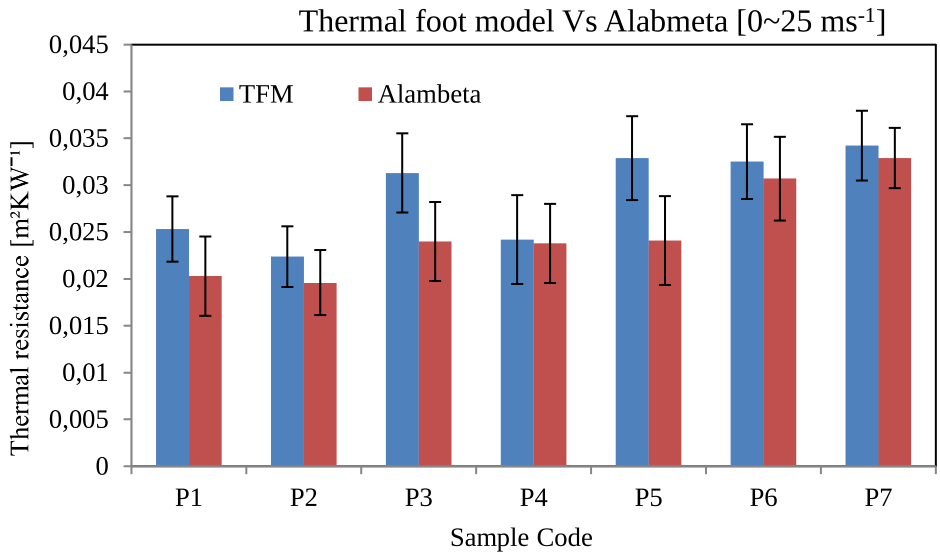


Figure 33. Thermal resistance comparison (TFM Vs Alambeta)

(Fig.34) shows the comparison of thermal resistance, between TFM and Permetest. The error bars at a 95% confidence interval verified that these results from two different skin models are comparable at 1ms^{-1} air velocity. These results are aligned with the previous researchers. Mansoor et al. observed the coefficient of determination value is 0.64 while comparing the thermal resistance of terry knitted socks measured by Permetest and TFM [84].

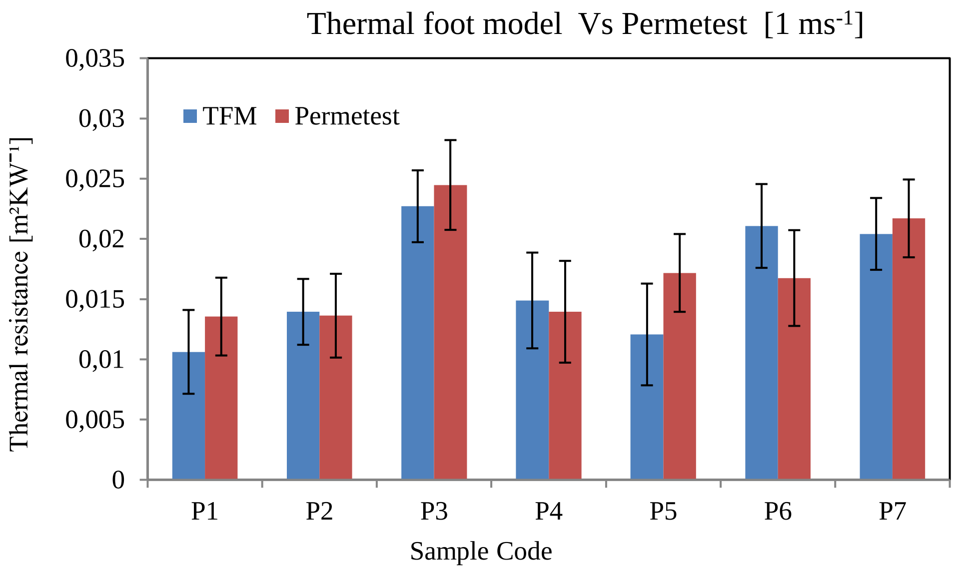


Figure 34. Thermal resistance comparison (TFM Vs Permestest)

6 Conclusion

A semi-empirical approach was used to model the Thermal resistance prediction of plain knitted socks in the wet state. The aim was to modify/ develop the aforementioned thermal resistance models with acceptable degrees of accuracy from simple inputs of fabric (socks) geometrical parameters such as fibre composition, areal density, and thickness. These parameters were first derived and then used as predictors for the thermal resistance prediction. This work focuses on the thermal resistance prediction of socks in the wet state followed by some other comfort parameters such as thermal absorptivity, relative water vapour permeability and sock-insole interface friction. Although both theoretical porosity (for yarn and socks) and experimental (socks) were calculated but thermal resistance prediction is based on theoretical results. Validation of the models has been done through the coefficient of determination (R^2) and inference statistics i.e. hypothesizing slope =1 & intercept = 0 at 95% confidence interval. By adopting this new approach of feeding the wet polymer filling coefficient and the thermal conductivity instead of dry polymers different models can provide a justified prediction of thermal resistance under wet conditions as well. All the models (Militky modified, ME-2 modified & Schuhmeister modified) have a coefficient of determination, i.e. R^2 range in between 0.76~0.95 for all the sock samples at different moisture levels. As well as the validation through hypothesis i.e. slope =1 & intercept =0, Schuhmeister's modified model couldn't qualify for P2 and P4 socks. A higher value of moisture causes to decrease the thermal resistance. 50% reduction in thermal resistance occurs at 30% moisture content in all the samples, except P3 (polyester), P4 (nylon) and P5 (polypropylene) socks. Thermal absorptivity increases by increasing moisture content. It may provide an indication of dry to cool, cold and wet feelings. The results of this study show that the thermal absorptivity values of dry fabrics range from 79.7 to 180 [$Ws^{1/2}m^{-2}K^{-1}$]. When the fabric is getting wet, as the thermal conductivity of water is much higher than that of fibre and there is the air entrapped in the textile structure, these values increase. In the case of plain socks, only P5 sock has the thermal absorptivity < 300 at 50% moisture level. P1 (>80% cotton) and P2 (>80%viscose) have the highest thermal absorptivity. Relative water vapour permeability (RWVP) of the most synthetic fibres is higher, except P7 composed of (>80% acrylic). P7 has the worsened RWVP due to its highest thickness and GSM among all the socks. Socks theoretical porosity falls between 74% to 90% range without and with extension respectively. Extension causes to increase the pore size (space between loops) of the fabric and decrease the fabric thickness. It leads to a decrease in the volume of the fibre (solid part) and increases the volume of air corresponds to porosity. Volume porosity and pore size distribution for socks has been measured by micro-tomography also. It is in agreement with the theoretical volume porosity.

Extended socks have a lower thermal resistance. This is mainly due to the thickness reduction with extension. Thickness is one of the major factors that affect the thermal insulation. Most of the socks haven't close thermal resistance even at 95% confidence level. As socks extended, the number of contact points decreased. It results in a lower value of thermal absorptivity. So this condition is the stimulus for characterizing the socks in an extended state. The thermal resistance measured in the dry and extended state by Alambeta and Permetest is comparable with Rct measured by the thermal Foot Model at a 95% confidence interval.

The results of the frictional characterization between the sock-insole interface as expected has positive correlation with the humidity levels. A comparatively higher COF observed for plain knitted socks with respect to previous studies probably due to the long terry of the insole fabric and testing without extension. Sock-insole interface is also very critical with respect to design (socks/ shoes), blister formation, postural balance and friction ratio (between sock-skin & sock-insole interfaces). A uniform and slight increase is observed in dynamic COF except for P1 (cotton based sock) and P2 (viscose rich sock). Whereas static COF has uneven and rapid risen except P7 (acrylic rich sock).

Working on this dissertation has uncovered many worthy avenues for future investigations. The inquisitive readers will no doubt have ideas of their own, but there are some suggestions for research of possible interest:

- ❖ This study was conducted by assuming thickness and GSM as constant. A separate study could be planned to identify the effect of swelling on the thickness, especially in hydrophilic fabrics.
- ❖ Future studies could be planned for examining other types of fabrics and mathematical models by adopting this approach.
- ❖ Shoes could be added with the addition of more boundary conditions
- ❖ COF between the sock-skin interface for the same samples

7 References

[1] Fogarty AL, Barlett R, Ventenat V, et al. Regional foot sweat rates during a 65-minute uphill. 2006; 2006–2007.

[2] Taylor NAS, Caldwell JN, Mekjavic IB. The sweating foot: local differences in sweat secretion during exercise-induced hyperthermia. *Aviat Space Environ Med* 2006; 77: 1020–1027.

[3] Küklane K. Footwear for cold weather conditions. *Handb Footwear Des Manuf* 2013; 283–317.

[4] Kuklane K, Gavhed D, Fredriksson K. A field study in dairy farms: thermal condition of feet. *Int J Ind Ergon* 2001; 27: 367–373.

[5] Mangat AE, Hes L, Bajzik V, et al. Thermal absorptivity model of knitted rib fabric and its experimental verification. *Autex Res J* 2018; 18: 20–27.

[6] Hes L. An indirect method for fast evaluation of surface moisture absorptivity of shirt and underwear fabrics. *Vlakna a Text* 2000; 7: 178–185.

[7] Bogusławska-Baczek M, Hes L. Effective water vapour permeability of wet wool fabric and blended fabrics. *Fibres Text East Eur* 2013; 97: 67–71.

[8] Tasron DN, Thurston TJ, Carré MJ. Frictional behaviour of running sock textiles against plantar skin. *Procedia Eng* 2015; 112: 110–115.

[9] Baussan E, Bueno MA, Rossi RM, et al. Analysis of current running sock structures with regard to blister prevention. *Text Res J* 2013; 83: 836–848.

[10] Van Amber RR, Lowe BJ, Niven BE, et al. The effect of fiber type, yarn structure and fabric structure on the frictional characteristics of sock fabrics. *Text Res J* 2015; 85: 115–127.

[11] Kuklane K. Protection of feet in cold exposure. *Ind Health* 2009; 47: 242–253.

[12] West AM, Tarrier J, Hodder S, et al. Sweat distribution and perceived wetness across the human foot: the effect of shoes and exercise intensity. *Ergonomics* 2019; 62: 1450–1461.

[13] Young AJ, Roberts DE, Scott DP, et al. *Sustaining health and performance in the cold: A pocket guide to environmental medicine aspects of cold-weather operations*. Army Research Inst of Environmental Medicine Natick Ma, 1992.
[14] Mangat MM, Hes L. Thermal resistance of denim fabric under dynamic moist conditions and its investigational confirmation. *Fibres Text East Eur* 2014; 22: 101–105.
[15] Mangat MM, Hes L, Bajzík V. Thermal resistance models of selected fabrics in wet state and their experimental verification. *Text Res J* 2015; 85: 200–210.
[16] Hollies RS, Bogaty H. Some thermal properties of fabrics: part II: the influence of water content. *Text Res J* 1965; 35: 187–190.
[17] Naka S, Kamata Y. Thermal conductivity of wet fabrics. *J Text Mach Soc Japan* 1977; 23: 114–119.
[18] Dias T, Delkumburewatte GB. The influence of moisture content on the thermal conductivity of a knitted structure. *Meas Sci Technol* 2007; 18: 1304.
[19] Fricke H. A mathematical treatment of the electric conductivity and capacity of disperse systems I. The electric conductivity of a suspension of homogeneous spheroids. *Phys Rev* 1924; 24: 575.
[20] Wei J, Xu S, Liu H, et al. Simplified model for predicting fabric thermal resistance according to its microstructural parameters. *Fibres Text East Eur* 2015; 23: 57–60.
[21] Schuhmeister J. Ber. *K Akad Wien (Math-Naturw Klasse)* 1877; 76: 283.
[22] Baxter S t. The thermal conductivity of textiles. *Proc Phys Soc* 1946; 58: 105.
[23] Militký J, Becker C. Selected topics of textile and material Science. *Sel Top Text Mater Sci* 2011; 404.
[24] Maxwell JC. *A treatise on electricity and magnetism*. Dover, 1954.
[25] Eucken A. Allgemeine gesetzmäßigkeiten für das wärmeleitvermögen verschiedener stoffarten und aggregatzustände. *Forsch auf dem Gebiet des Ingenieurwesens A* 1940; 11: 6–20.
[26] Howard E, Oakley N. The design and function of military footwear: a review following experiences in the South Atlantic. *Ergonomics* 1984; 27: 631–637.
[27] Li Y. The science of clothing comfort. *Text Prog* 2001; 31: 1–135.
[28] Cleland AC. *Food refrigeration processes*. Elsevier applied science, 1990.
[29] Cleland AC, Earle RL. A comparison of analytical and numerical methods of predicting the freezing times of foods. *J Food Sci* 1977; 42: 1390–1395.
[30] Das A, Alagirusamy R, Kumar P. Study of heat transfer through multilayer clothing assemblies: a theoretical prediction. *Autex Res J* 2011; 11: 54–60.
[31] Bogaty H, Hollies NRS, Harris M. Some thermal properties of fabrics: part I: The effect of fiber arrangement. *Text Res J* 1957; 27: 445–449.
[32] Brailsford AD, Major KG. The thermal conductivity of aggregates of several phases, including porous materials. *Br J Appl Phys* 1964; 15: 313.
[33] Wang J, Carson JK, North MF, et al. A new approach to modelling the effective thermal conductivity of heterogeneous materials. *Int J Heat Mass Transf* 2006; 49: 3075–3083.
[34] Carson JK. Prediction of the thermal conductivity of porous foods: a thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Food Engineering, Massey University, Palmerston North, New Zealand, 2002.
[35] Hes L, Dolezal I. New method and equipment for measuring thermal properties of textiles. *Sen'i Kikai Gakkaishi (Journal Text Mach Soc Japan)* 1989; 42: T124–T128.
[36] Bogusławska-Bączek M, Hes L. Thermophysiological Properties of Dry and Wet Functional Sportswear Made of Synthetic Fibres. *Tekstilec* 2017; 60: 331–338.
[37] Oglakcioglu N, Marmarali A. Thermal comfort properties of cotton knitted fabrics in

dry and wet states. *Tekst ve Konfeksiyon* 2010; 20: 213–217.
[38] Oglakcioglu N, Celik P, Ute TB, et al. Thermal comfort properties of angora rabbit/cotton fiber blended knitted fabrics. *Text Res J* 2009; 79: 888–894.
[39] Oğlakcioğlu N, Marmarali A. Thermal comfort properties of some knitted structures. *Fibres Text East Eur* 2007; 15: 64–65.
[40] Gupta D, Chattopadhyay R, Bera M. Comfort properties of pressure garments in extended state. *Ind J Fibre Text Res* 2011; 36: 415–421.
[41] Siddique HF, Mazari AA, Havelka A, et al. Analysis of thermal properties affected by different extension levels of compression socks. *Vlakna a Text* 2019; 26: 64–68.
[42] Mansoor T, Hes L, Skenderi Z, et al. Effect of preheat setting process on heat, mass and air transfer in plain socks. *J Text Inst* 2019; 110: 159–170.
[43] Hes L, Bogusławska-Baczek M, Geraldes MJ. Thermal comfort of bedsheets under real conditions of use. *J Nat Fibers* 2014; 11: 312–321.
[44] Jhanji Y, Gupta D, Kothari VK. Comfort properties of plated knitted fabrics with varying fibre type. *Indian J Fibre Text Res* 2015; 40: 11–18.
[45] Oğlakcioğlu N, Sari B, Üte TB, et al. A novel medical bandage with enhanced clothing comfort. In: *IOP Conference Series: Materials Science and Engineering*. IOP Publishing, 2016, p. 12021.
[46] Sampath MB, Senthilkumar M. Effect of moisture management finish on comfort characteristics of microdenier polyester knitted fabrics. *J Ind Text* 2009; 39: 163–173.
[47] Knapik JJ, Reynolds KL, Duplantis KL, et al. Friction blisters. *Sport Med* 1995; 20: 136–147.
[48] Gerhardt L-C, Strässle V, Lenz A, et al. Influence of epidermal hydration on the friction of human skin against textiles. *J R Soc Interface* 2008; 5: 1317–1328.
[49] Knapik JJ, Reynolds K, Barson J. Influence of an antiperspirant on foot blister incidence during cross-country hiking. *J Am Acad Dermatol* 1998; 39: 202–206.
[50] Reynolds K, Darrigrand A, Roberts D, et al. Effects of an antiperspirant with emollients on foot-sweat accumulation and blister formation while walking in the heat. *J Am Acad Dermatol* 1995; 33: 626–630.
[51] Costill DL. Sweating: its composition and effects on body fluids. *Ann N Y Acad Sci* 1977; 301: 160–174.
[52] Bertaux E, Derler S, Rossi RM, et al. Textile, physiological, and sensorial parameters in sock comfort. *Text Res J* 2010; 80: 1803–1810.
[53] Hursh DF, Johnston JB. *Anti-friction two-ply athletic sock*. Google Patents, 1989.
[54] Baussan E, Bueno MA, Rossi RM, et al. Experiments and modelling of skin-knitted fabric friction. *Wear* 2010; 268: 1103–1110.
[55] Sanders JE, Greve JM, Mitchell SB, et al. Material properties of commonly-used interface materials and their static coefficients of friction with skin and socks. *J Rehabil Res Dev* 1998; 35: 161–176.
[56] Dai X-Q, Li Y, Zhang M, et al. Effect of sock on biomechanical responses of foot during walking. *Clin Biomech* 2006; 21: 314–321.
[57] Jeddi AAA, Shams S, Nosraty H, et al. Relations between fabric structure and friction: Part i: Woven fabrics. *J Text Inst* 2003; 94: 223–234.
[58] Kenins P. Influence of fiber type and moisture on measured fabric-to-skin friction. *Text Res J* 1994; 64: 722–728.
[59] Yoon HN, Buckley A. Improved comfort polyester: Part I: Transport properties and thermal comfort of polyester/cotton blend fabrics. *Text Res J* 1984; 54: 289–298.
[60] Bories S, Mojtabi A, Prat M, et al. *Transferts de chaleur dans les milieux poreux*. Ed. Techniques Ingénieur, 1995.
[61] Dubois A. *Porosite des tissus: correlations entre les methodes de determination de la*

permeabilite a l'air. Eurédia, 1999.
[62] Hsieh Y-L. Liquid transport in fabric structures. *Text Res J* 1995; 65: 299–307.
[63] Guidoin R, King M, Marceau D, et al. Textile arterial prostheses: Is water permeability equivalent to porosity? *J Biomed Mater Res* 1987; 21: 65–87.
[64] Dyck V. Desktop X-ray microscopy and microtomography. *J Microsc* 1998; 191: 151–158.
[65] *Pressure measuring device for medical compression and support stockings (Salzman, Group Switzerland)*, https://www.swisslastic.ch/files/Druckmessgeraete/MST-MK V-EN_SP_JP_CN-2014-4p.pdf.
[66] Hes L, Dolezal I. A new computer-controlled skin model for fast determination of water vapour and thermal resistance of fabrics. In: *7th Asian Textile Conference, New Delhi*. 2003.
[67] Gorica S. *Foot Manikin Technical Specifications*. 2010.
[68] Wiley-VCH (ed). *Ullmann's Fibers, 2 Volumes*. Wiley, https://books.google.cz/books?id=R9c8wgEACAAJ (2008).
[69] Bobeth W. Thermisches Verhalten. In: *Textile Faserstoffe*. Springer, 1993, pp. 253–284.
[70] Geschke D. *Physical Properties of Polymers Handbook*. Springer New York. Epub ahead of print 1997. DOI: 10.1524/zpch.1997.199.part_1.128.
[71] Haghi AK. Thermal analysis of drying process: A theoretical approach. *J Therm Anal Calorim* 2003; 74: 827–842.
[72] Meloun M, Militky J. *Statistical data analysis: A practical guide*. Woodhead Publishing, Limited, 2011. Epub ahead of print 2011. DOI: 10.1533/9780857097200.
[73] Fan J. Physiological comfort of fabrics and garments. *Eng Appar Fabr Garments* 2009; 1: 201–250.
[74] Dreby EC. A friction meter for determining the coefficient of kinetic friction of fabrics. *J Res Natl Bur Stand (1934)* 1943; 31: 237–246.
[75] D1894. Standard test method for static and kinetic coefficients of friction of plastic film and sheeting. *Astm* 2014; 08: 1–8.
[76] Visualization of local thickness in 3D (Bruker Micro CT Academ). 2014; 1: 2–3.
[77] Abdolmaleki S, Jeddi AAA, Amani M. Estimation on the 3D porosity of plain knitted fabric under uniaxial extension. *Fibers Polym* 2012; 13: 535–541.
[78] Doczyova K, Glombikova V, Komarkova P. Application of microtomography in textile metrology. *Tekstilec*; 57.
[79] Kanat Z, ÖZDİL N, Marmarali A. Prediction of thermal resistance of the knitted fabrics in wet state by using multiple regression analysis. *J Text Apparel/Tekstil ve Konfeksiyon*; 24.
[80] Finck JL. Mechanism of heat flow in fibrous materials. *Bur Stand J Res* 1930; 5: 973–984.
[81] Reddy KS, Karthikeyan P. Combinatory models for predicting the effective thermal conductivity of frozen and unfrozen food materials. *Adv Mech Eng* 2010; 2: 901376.
[82] Mao N, Russell SJ. The thermal insulation properties of spacer fabrics with a mechanically integrated wool fiber surface. *Text Res J* 2007; 77: 914–922.
[83] Supuren G, Oglakcioglu N, Ozdil N, et al. Moisture management and thermal absorptivity properties of double-face knitted fabrics. *Text Res J* 2011; 81: 1320–1330.
[84] Mansoor T, Hes L, Bajzik V, et al. Effect of moisture content on thermophysiological properties of terry knitted socks followed by thermal resistance comparison among different skin models. In: *Fiber Society's Fall 2018 Technical Meeting and Conference: Advanced, Smart, and Sustainable Fibers, Materials, and Textiles*. Fiber Society, 2018.

[85] Lenfeldova I, Hes L. Dependence of water vapor permeability of knitted samples on their wetting level. In: *Book of Abstracts*, p. 141.
[86] Baczek MB, Hes L. The effect of moisture on thermal resistance and water vapour permeability of Nomex fabrics. *J Mater Sci Eng A* 2011; 1: 358.
[87] Adler MM, Walsh WK. Mechanisms of transient moisture transport between fabrics. *Text Res J* 1984; 54: 334–343.
[88] Hes L, de Araujo M. Simulation of the Effect of Air Gaps between the Skin and a Wet Fabric on Resulting Cooling Flow. *Text Res J* 2010; 80: 1488–1497.
[89] Bivainyte A, Mikučioniene D. Influence of shrinkage on air and water vapour permeability of double-layered weft knitted fabrics. *Medziagotyra* 2012; 18: 271–274.
[90] Chatterjee PK. *Textile Science and Technology*. 1994. Epub ahead of print 1994. DOI: 10.1016/B978-0-444-88224-0.50001-1.
[91] Woo SS, Shalev I, Barker RL. Heat and moisture transfer through nonwoven fabrics: Part I: Heat transfer. *Text Res J* 1994; 64: 149–162.
[92] Li Y, Zhu Q, Yeung KW. Influence of thickness and porosity on coupled heat and liquid moisture transfer in porous textiles. *Text Res J* 2002; 72: 435–446.
[93] Lubos H, Marmarali A, Oezdil N, et al. The effect of moisture on friction coefficient of elastic knitted fabrics. *Tekst ve Konfeksiyon* 2008; 18: 206–210.
[94] Tasron D, Nasir SH, Troynikov O, et al. Thermo-physiological comfort and frictional characteristics of running socks in different moisture conditions. In: *Proceedings of the 9th Conference of the Textile Bioengineering and Informatics Symposium*. 2016.
[95] Kozłowski RM, Mackiewicz-Talarczyk M, Wielgusz K, et al. Bast fibres: flax. In: *Handbook of Natural Fibres*. Elsevier, 2020, pp. 93–162.
[96] Rotaru G-M, Pille D, Lehmeier FK, et al. Friction between human skin and medical textiles for decubitus prevention. *Tribol Int* 2013; 65: 91–96.
[97] Varadaraju R, Srinivasan J. Design of polyester-elastane-cotton plated knitted components for hot and dry environment. *Int J Cloth Sci Technol* 2018; 30: 657–667.
[98] Ke W, Rotaru G-M, Hu JY, et al. In vivo measurement of the friction between human skin and different medical compression stockings. *Tribol Lett* 2015; 60: 4.
[99] Arai K. Wearing comfort of water absobent acrylic fibers. *J Text Mach Soc Japan* 1984; 30: 72–81.
[100] Mogahzy Y. Friction and surface characteristics of synthetic fibers. In: *Friction in Textile Materials*. Elsevier, 2008, pp. 292–328.
[101] Suchatlampong C, Davies E, von Fraunhofer JA. Frictional characteristics of resilient lining materials. *Dent Mater* 1986; 2: 135–138.
[102] Aboalasaad ARR, Skenderi Z, Kolčavová SB, et al. Analysis of factors affecting thermal comfort properties of woven compression bandages. *Autex Res J* 2020; 20: 178–185.

Author's publications

1. Mansoor, T., Hes, L., Bajzik, V., & Noman, M. T. (2020). Novel method on thermal resistance prediction and thermo-physiological comfort of socks in a wet state. ***Textile Research Journal***, 0040517520902540. **Impact factor: 1.613**
2. Mansoor, T., Hes, L., & Bajzik, V. (2020). A New Approach for Thermal Resistance Prediction of Different Composition Plain Socks in Wet State (Part 2). ***Autex Research Journal***, 1(ahead-of-print). **Impact factor: 0.85**

3. Mansoor, T., Siddique, H. F., Ali, A., Komarkova, P., Havelka, A., & Hussain, Z. (2018). Wrinkle free plaited knitted fabrics without pre-heat setting. ***The Journal of the Textile Institute,*** 109(3), 307-311. **Impact factor: 1.36**
4. Mansoor, T., Hes, L., Skenderi, Z., Siddique, H. F., Hussain, S., & Javed, A. (2018). Effect of preheat setting process on heat, mass and air transfer in plain socks. ***The Journal of the Textile Institute***, 1-12. **Impact factor: 1.36**
5. Ali, A., Nguyen, N. H., Baheti, V., Ashraf, M., Militky, J., Mansoor, T., & Ahmad, S. (2018). Electrical conductivity and physiological comfort of silver coated cotton fabrics. ***The Journal of the Textile Institute***, 109(5), 620-628. **Impact factor: 1.36.**
6. Azeem, M., Hes, L., Wiener, J., Noman, M. T., Ali, A., & Mansoor, T. (2018). Comfort properties of nano-filament polyester fabrics: thermo-physiological evaluation. ***Industria Textila***, 69(4), 315-321. **Impact factor: 0.90**
7. Hussainn, S., Glombikova, V., Akhtar, N., Mazari, A., Mansoor, T., & Khan, K. A. H. (2019). Liquid moisture transportation properties of functional underwears: Part 1. ***Autex Research Journal***, 19(2), 97-103. **Impact factor: 0.85**
8. Siddique, H. F., Mazari, A. A., Havelka, A., Mansoor, T., Ali, A., & Azeem, M. (2018). Development of V-Shaped Compression Socks on Conventional Socks Knitting Machine. ***Autex Research Journal***, 18(4), 377-384. **Impact factor: 0.85**
9. Siddique, H. F., Mazari, A. A., Havelka, A., Hussain, S., & Mansoor, T. (2018). Effect of elastic elongation on compression pressure and air-permeation of compression socks. ***Vlákna a Textil (Fibres and Textiles),*** 25(1). **Impact factor: 0.20**
10. Ahmad, I., M. Iftikhar., N. Mehmood and T. Mansoor. 2006. Comparative Study Of Some Reactive Dyes Performance On Cotton Fabric Under The Processing Variables Dyeing Time And Temperature. ***The Indus Cotton*** 3(2):372-283.

Author's publications in international conferences

1. Mansoor, T., Hes, L., & Bajzik, V., Effect of moisture content on Thermophysiological Properties of Terry Knitted Socks followed by Thermal resistance comparison among different Skin Models. Fibre Society Conference October, 2018 UC Davis United States.
2. Mansoor, T., Hes, L., Zenun, S., & Javed, M.A., Effect of moisture content on Thermophysiological Properties of Plain Knitted Socks followed by Thermal resistance comparison among different Skin Models. STRUTEX 22nd International Conference December, 2018 Liberec Czech Republic.

Curriculum Vitae

PERSONAL INFORMATION

Tariq Mansoor M.Sc

17. Listopadu 584/2, 46015 Liberec, Czech Republic

+420 77 354 5756

taheembava1@gmail.com

Date of birth: 04 April 1982

Nationality: Pakistan

EDUCATION

(December 2015-until now)

Doctoral student

Textile Evaluation Department, Faculty of Textile Engineering

Technical University of Liberec, Czech Republic

Topic: Modelling of thermal resistance and some other comfort parameters of socks in wet state

(December 2002 to November 2006)

M.Sc. Fibre Technology

Department of Fibre & Textile Technology, Faculty of Agri-Engineering & Technology, University of Agriculture Faisalabad, Pakistan

Topic: Comparative study of the reactive dyes performance with respect to dyeing temperature and time

WORK EXPERIENCE

(August 2007 to October 2015)

Assistant Manager Product Development/ Quality Assurance Lab, Interloop Limited Faisalabad, Pakistan

www.interloop.com.pk

INTERNSHIP

(August 2016 to September 2016) Interloop Limited Faisalabad, Pakistan

(July 2017 to September 2017) Interloop Limited Faisalabad, Pakistan

(October 2017 to December 2017) Faculty of Textile Technology, University of Zagreb, Croatia

Supported by CEEPUS mobility program

(February 2020 to April 2020) ITM, Technical University of Dresden, Germany

Supported by ERASMUS mobility program

Recommendation of the supervisor

Supervisor´s evaluation report on the PhD Thesis of Mr. Tariq Mansoor

"Thermal resistance prediction of wet socks and some other parameters of their comfort"

This systematic and original study deals with thermal comfort properties of socks in wet state. Socks are fabrics, where the absorbed moisture can strongly influence their thermal comfort properties, as a human foot could generate up to 50 grams of sweat per hour in a hot environment or at high physical activity. Due to this high sweat rates, thermal resistance may substantially decrease and can cause hypothermia. By means of the ALAMBETA fast working non-destructive tester, the candidate measured thermal resistance and thermal absorbtivity of 7 plain socks consisting of cotton, viscose, polyester, nylon, polypropylene, wool, and acrylic fibres, with same plaiting yarn polyester covered elastane, without any special finishing (commercial state). The selection of socks for his research was based on his previous experience in socks manufacturing company. The measurements were executed at up to 7 levels of the moisture content. Moreover, in his experiments, the candidate also respected the extension of the socks during their practical use, using his own additional device which made his experiments very realistic. The ALAMBETA testing corresponded well to the use of a socks inside a shoe (boundary conditions of first order).

In the next step, he focused on the development of a mathematical model for a prediction of thermal resistance of plain socks in the wet state, as he did not find any reliable model in the available literature except the last three. He has checked following models.

1. Mangat parallel/ series models
2. R.S Hollies model (parallel model)
3. S. Naka model (three parameters model series/ parallel)
4. Dias and Delkumburewatte (three parameters series model)
5. Fricke's model (100% Series)
6. Ju Wei model (considered polymer + air in parallel and air in series)
7. Baxter model (considered 21 % parallel+ 79% series)
8. Schuhmeister model (considered 30 % parallel+ 70% series)
9. Militky (considered 50 % parallel+ 50% series)
10. Maxwell Eucken-1 and Maxwell Euken-2(dispersed and continuous phases)

Above all models were compared with the experimental data. Unfortunately, none of these models was offering a good correlation with the experimental data from the wetted socks except Maxwell Euken-2, Schuhmeister and Militky's models. The solution was based on modifications of these models has done by adopting a combined approach of water and polymer components for determination of thermal conductivity and introduction of linear changes of the filling coefficient (volume ratio) with the increasing moisture we succeeded in predicting the thermal resistance of all samples at different moisture levels with the coefficient of determination R^2 ranging from 0.78 to 0.97. Based on the knowledge of the fibre composition (thermal conductivity of the used polymer), fabric areal density and thickness, these original models can predict the thermal resistance of the studied socks at any moisture level up to 70%. These models could be probably also applicable for other textile structures, but it should be verified first.

Besides thermal resistance of socks, the candidate also determined experimentally thermal absorbtivity of all the studied socks in wet state. Here, he also used the ALAMBETA tester. In his experiments, the candidate also respected the extension of the socks during their practical use, using his own additional device which made his experiments very realistic. The results were treated statistically and presented in diagrams. Very interesting results were also achieved by the candidate when measuring thermal resistance of socks subject to heat transfer by convection on their free surface, where the sock were worn free, not inside a shoe (boundary condition of 3rd order). He used a special thermal foot model installed in the laboratory of the Textile faculty in Zagreb (Croatia). The candidate discovered, that the gaps between the heated elements of this commercial device are a source of measuring errors. Consequently, he fixed a semi-permeable membrane on the foot model to avoid the turbulence effects. After this improvement, the candidate measured all his samples on this model with good reproducibility. Then he compared his results with the results achieved on the PERMETEST Skin model (which works in similar principle). Both devices now showed very good correlations. The results were discussed and commented.

He also measured the coefficient of friction between sock-insole interface at different moisture levels during his stay at ITM, Technical University of Dresden Germany. The results of the frictional characterization between the sock-insole interface as expected has positive correlation with the humidity levels. Furthermore, the models have been implemented in a programming language (FreeMat / Matlab) which potentially provides a software tool for textile designers and technologists to predict the thermal resistance of fabrics in a wet state for various applications.

As regards the possible plagiarism, the plagiarism detection system indicated the total plagiarism level of less than 1 %, which is excellent.

During the study, Mr. Mansoor showed full dedication to his research work, presented high creativity and original ideas, executed large number of systematic measurements and calculations when comparing various thermal resistance models. His results would surely contribute to the fundamental knowledge in the textile science and technology areas. He is an author or a co-author of 10 papers in impacted journals. I do recommend the submission of his Thesis for the defence at the Faculty of Textile Engineering of the Technical University of Liberec, Czech Republic.

In Liberec, on July 15th, 2020

Prof. Ing. Lubos Hes, DrSc

Opponent's reviews

prof. Ing. Tomáš Vít, Ph.D.
KEZ - SF - TU Liberec
Studentská 2
461 17, Liberec 1

Review of dissertation thesis

"Modelling of Thermal Resistance and Some Other Comfort Parameters of Socks in Wet State"

by Tariq Mansoor, M.Sc.

Structure of thesis

Modelling of various physical phenomena is an increasingly important element in development. It is natural that mathematical models cannot be functional without precisely performed experiments. These experiments are used to set the parameters of mathematical models and to validate them.

From the point of view of thermodynamics, the process of simultaneous heat and moisture transfer and physical modelling of this process represent a topical problem. From this point of view, any contribution to this problem is beneficial.

Presented thesis are separated into five chapters. *First chapter* brings introduction to the work.

The main objectives of the thesis are mentioned in the *second chapter*. This chapter also includes overview of analytical models for determination of thermal conductivity of fabrics and definition of important parameters of fabrics as porosity, thermal absorptivity, relative water vapour permeability and coefficient of friction.

Third chapter presents used experimental methods. *Chapter number four* presents results of author's experiments. It shows results of measurement of porosity by MCT, results of measurement of thermal resistance under different conditions and results of measurement of coefficient of friction under different conditions. All experimental results are compared to theoretical models.

The last chapter brings conclusions.

Evaluation of the importance of work for the scientific field

As the first point of the review, it is necessary to mention the fact that the *title of the thesis does not correspond to its content*. The work deals with the topic of modelling marginally only. Contrary to the title, the dissertation is mainly *focused on experimental research of material properties* of various fabrics.

The development of author's own model for determining the properties of wet fabrics is based on replacing the thermal conductivity and the filling coefficient of dry fibres with the thermal conductivity and the filling coefficient of wet fibres in three standard models. Properties of wet fibres are calculated as a weighted average of properties of fibres and water.

The dissertation is very extensive. It deals with a large number of topics. Due to the scope of the work, a detailed analysis of individual topics was not performed at a level that would be suitable for work of a given type. The work therefore seems superficial at individual points. The author usually focuses only on the description of the achieved results without attempting a deeper analysis.

The significance of the work can therefore be found mainly in its literature review part and in the presented results of experiments. The author used 200 scientific publications to define current state of the art. The results and conclusions of these publications are logically summarized mainly in the introductory chapters. Unfortunately, even here, due to the range of sources used, a more detailed analysis and the author's commentary are missing.

The significance of the work is certainly in the presented results of experiments. Author performed a detailed analysis of the porosity of various textiles and measured the thermal resistance, thermal absorptivity relative water vapour permeability and coefficient of friction for various parameters as moisture content and extension. He used three experimental devices for measurements and compared the main results.

Dependencies calculated using modified models are used to calculate theoretical values of thermal resistance and are compared to the results of experiments.

'he methods used and the achievement of the set objectives

Literature review part. The author works with a large number of sources. The description of the current state of knowledge is correct. Unfortunately, author does not add its own comments on the findings of other authors. The opponent recommends mentioning of the latest trends in the field in the dissertation.

Theoretical part. The paper cites some basic thermodynamic laws and relations (Fourier's Low, Fick's Law, Darcy's law, Kozeny's eq. etc.). But, these basics laws are not even mentioned in the work. The connection of the basic laws of thermodynamics to the findings presented in the work is not clear. In the case of other quantities, such as thermal absorptivity, it would be appropriate to state the physical significance and the application procedure for the given issue. The development of modified models is not properly described. It is not clear why the author has chosen selected approach to derive updated formulas.

Practical part. The chosen experimental methods are correct. The author uses modern experimental equipment to determine the porosity of materials and standard tests to measure thermal resistance. The procedure for evaluating the results of experiments is correct as well. The used experimental devices and experimental principles are described marginally only. The reader is forced to look for details in the provided references to better understand the principle.

A large number of different types of fabrics were analysed. It is not clear from the text whether the results presented in the graphs correspond to single measurement or are the mean value from several experiments.

The following objectives are set in the introduction to the dissertation.

- *To find / develop simple mathematical models for thermal resistance prediction in the wet state*. This objective has been met partially. Author modified standard models from other authors and compares them with the results of his own experiments. However, neither the process of model development nor the steps leading to the final form were described.

- *To investigate the effect of different moisture content [%] on the socks porosity, thermal resistance [m^2KW^{-1}], thermal absorptivity [$Ws^{½}m^{-2}K^{-1}$] and relative water vapour permeability RWVP [%].* This objective was met experimentally. A number of experiments were performed and evaluated. Beneficial results have been achieved.
- (to investigate) E*ffect of extension on porosity, thermal resistance, thermal absorptivity & RWVP.* This objective has been met.
- (to investigate) *Thermal resistance (predicted / experimental) in the extended state (controlled moisture content %) for simulating a real extension and minimizing the effect of the dimensional changes.* This objective has been met.
- *To compare the thermal resistance (dry state) measured by thermal foot model (TFM), Permetest and Alambeta.* This objective has been met.
- *Coding of the developed thermal resistance models in FreeMat / Matlab (appendix 5).* The appendix contains code that is used to display and compare results from models of other authors together with the results of experiments. This is not a developer model. Creating a simple tool for comparing results cannot be taken as a result of dissertation. This objective was partially fulfilled.
- *Validation of models for other kind of fabrics (appendix 3).* This objective has been met.

Other objectives,

- *Yarn porosity (theoretical and experimental);*
- *Volume porosity of socks with and without extension by model;*
- *Volume porosity and pore size distribution of socks by X-ray micro tomography scanning without extension;*
- *Effect of moisture content on sock-material (insole) coefficient of friction;*

are formulated incomprehensibly and their fulfilment cannot therefore be evaluated.

Opinion on the results of the dissertation

Beneficial results of experiments are presented in the form of tables and graphs in the chapter number four. Graphs 28, 30, 32, 34 and 38 show a significant jump in results at moisture content values of 15-30%. This jump is not explained anywhere. It is not discussed whether this jump is of a physical nature or whether it is an experimental error.

Results from derived modified models of thermal resistance shows good agreement with the results of the experiments.

Comments on systematic, clear, formal and linguistic level

The work follows the basic scheme of the dissertation. On the other hand, *the work contains a number of inaccuracies*.

For example: the list of symbols is incomplete, some quantities are indicated in the text by various symbols, the meaning of some quantities is not described at all, the meaning of × (usually vector product) in the formulas for the calculation of thermal conductivity is not clear, wrong naming is used for some physical properties (j_{AX} should be named as diffusion flux or diffusion flux density, the capital letter J_{AX} usually indicates the molar diffusion flux density, p_i should be partial pressure, it is unusual to define different coefficient of mass diffusion for concentration and partial pressure gradients, the definition and units of thermal resistance are incorrect etc.). Chapter 2.1.1 is named "Thermal resistance", but it deals with thermal conductivity.

The opponent does not allow himself to evaluate the level of English grammar. However, he is convinced that the text deserves linguistic proofreading.

The work contains a number of typographical mistakes.

Comments on student publications

The author presents in the list a sufficient number of publications that have been published in peer-reviewed journals. In 4 of them he is listed as the first author.

Opponent's opinion

The thesis contains a number of shortcomings that the author of the dissertation should avoid.

- The title of the thesis does not correspond to the content. The name refers more to the theoretical work, but the core of the work itself is in the performed experiments. The development and physical background for modified models is not described.
- The work lacks a theoretical basis for the solved problem. It is inappropriate to not mention the Fourier's law in the work dealing with thermal conductivity.
- Significant changes, jumps, in the measured dependencies are not properly commented.
- The work contains a number of inaccuracies, especially in the assumptions. The meaning of the quantities used is not given.

On the other hand, it is necessary to appreciate the breadth of topics that the author deals with and the research carried out by other authors.

Despite the above-mentioned shortcomings, the author has shown that he is able to perform independent scientific work and achieve unique results.

With emphasis on the above points

I recommend the thesis for the defence

Questions:

1. What are the latest trends in the modelling of thermodynamical, but also mechanical, processes in fabrics? Why is FEM not used?
2. Explain the concept of thermal absorptivity. Why it is possible to consider this quantity as a measure of comfort? What are the limitations? Is there a difference between thermal absorptivity and effusivity?

In Liberec, November 21st 2020

prof. Ing. Tomáš Vít, Ph.D.

TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Maschinenwesen Institut für Textilmaschinen und Textile Hochleistungswerkstofftechnik Institutsdirektor: Univ.-Prof. Dr.-Ing. habil. Dipl.-Wirt. Ing. Chokri Cherif

Technische Universität Dresden, Institut für Textilmaschinen und Textile Hochleistungswerkstofftechnik, 01062 Dresden

ITM

Univ.-Prof. Dr.-Ing. habil.
Yordan Kyosev
Inhaber der Professur
Montagetechnik für textile Produkte

Telefon: 0351 463-39313
Telefax: 0351 463-39301
E-Mail: yordan.kyosev@tu-dresden.de

TU Liberec
Faculty of Textile Engineering

Review of the Doctoral Thesis of **Tariq Mansoor, M.Sc.,** with the topic **"Modelling of thermal resistance and some other comfort parameters of socks in wet state"**

The thesis is written in 152 pages, from which 82 pages are main text, followed by reference and appendices. The author cited exactly 200 literature sources, comparing model of different researchers. The complete work is represented in five chapters – 1. introduction, 2. purpose and aim of the thesis, which consists of the state of the art in this area, 3. Materials and Methods, 4. Results and discussions and 5. Conclusions. My comments following the procedure are as following:

a) Evaluation of the importance of the Ph.D. thesis for the given field

The submitted thesis consist of large amount of experimental data for thermal resistance of knitted structures for socks in different wet state. Their analysis and results represents good contribution to the textile science and can be used in the development of socks in the future.

Postadresse (Briefe)
TU Dresden, Institut für Textilmaschinen und Textile Hochleistungswerkstofftechnik, 01062 Dresden
Postadresse (Pakete u.ä.)
TU Dresden, Institut für Textilmaschinen und Textile Hochleistungswerkstofftechnik,
Helmholtzstraße 10, 01069 Dresden
Besucheradresse
Hohe Straße 6, Zi. 143

Steuernummer (Inland) 203/149/02549
Umsatzsteuer-ID (Ausland; VAT) DE 188 369 991

Bankverbindung
Commerzbank AG, Filiale Dresden
IBAN DE52 8504 0000 0800 4004 00
BIC COBADEFF850

Internet
http://tu-dresden.de/mw/itm

Kein Zugang für elektronisch signierte sowie verschlüsselte elektronische Dokumente.

Mitglied von:
DRESDEN concept
Exzellenz aus Wissenschaft und Kultur

b) Comments on the problem-solving procedure, the methods used and the achievement of the stated objective

The samples are tested experimentally, which is very timely intensive procedure. At the beginning are given comparisons of different models for the thermal resistance, conductivity etc. but in the work are used mainly statistical methods for analyzing of the results. Keeping in mind, that the modeling both of the knitted structures itself and the heat and moisture transfer trough these require solid mathematical and programming background, which is not typical for the textile engineering students, I think that PhD candidate has selected suitable methods for analysis.

c) An opinion on the results of the Ph.D. thesis and the importance of the author's specific contribution

The main contribution of the PhD candidate to main opinion is in the larger experimental data related to the moisture content, the thermal resistance and the thermal absorptivity and the comparison o the different models those of Prof. Militky, of Mod. Schuhmeister and ME-2 Modified. Interesting are as well the results about the coefficient of friction and the moisture content.

d) Other statements concerning mainly the evaluation of the method, clarity of structure, layout and the language level of the Ph.D. thesis

The text of the thesis is placed in the different chapters, which makes not easy to follow the content, but this structure might be requirements of the faculty?. I would recommend in the future the theory, methods and results, related to one property to be following as sections in one chapter, related to this property, then it would be more easy to represent the background, analyze the processes and the results. Principally, the physics or the theory of the complete processes – what happens if the moisture goes inside of the different materials is given very briefly and the author concentrated directly to the few published models. More detailed analysis at deep level – what happens in the fibers, between the fibers, between the yarns would allow good explanation of the results, which now is limited to description of the curves.

The formatting of the thesis, equations and appendix is at several places could be more consistent and more beautiful.

At this place it has to be mentioned, that the thesis was finalized in the time of COVID where the access to laboratories was very limited and the communication to experts was as well difficult due to their higher loading in preparing the teaching for pure distance learning. In this meaning the PhD student has performed good work.

e) Comments on the student's publications

The PhD applicant has very good record of publications, there are 10 papers in peer reviewed journals with impact factor, in four of which he is first author and two presentations of international conferences. These papers demonstrates an active research time.

f) To opponent's unambiguous statement whether he recommends the Ph.D. thesis for defence.

I can recommend the thesis for defence.

Best regards

Prof. Dr.-Ing. habil. Yordan Kostadinov Kyosev

09.03.2021 Dresden