İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

MODELLING OF HEAT TRANSFER BEHAVIORS OF SOCKS MADE FROM NEW FIBERS USING FINITE ELEMENT METHOD

Master Thesis by

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Department : Textile Engineering

Programme: Textile Engineering

JANUARY 2007

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JANUARY 2007

<u>İSTANBUL TEKNİK ÜNİVERSİTESİ★ FEN BİLİMLERİ ENSTİTÜSÜ</u>

YENİ LİFLERDEN ÜRETİLMİŞ ÇORAPLARIN ISI İLETİMİNİN SONLU ELEMANLAR YÖNTEMİYLE MODELLENMESİ

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CONTENTS

ABBREVIATIONS

CATIA :Computer Aided Three Dimensional Interactive Application
SPSS :Statistical Program for Social Science
ANOVA :Analyses of Variance
ASTM :American society for Testing and Materials
ISO :International Standard Organization
BS :British Standard

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SYMBOL LIST

K	: Thermal conductivity
R	: Thermal resistance
d	: Thickness
r	: thermal resistivity
U	: Thermal transmittance
Q	: The total rate of heat transfer
Q_c	: Conductive component
Q_e	: Evaporative component
H	: Total heat transfer
H_c	: Conductive heat loss
H_e	: Evaporative heat loss
H_{r+c}	: Dry heat transfer (radiation and conduction)
k_c	: Coefficient for convective heat transfer
A	: Surface area of the body
T_{sk}	: The mean weighted skin temperature of the surface of the body
T_{ab}	: The dry bulb temperature
k_e	: Evaporative coefficient
P_{sk}	: Saturated vapor pressure of water at skin temperature
P_{ab}	: The ambient vapor pressure
V	: The wind velocity
T_g	: The globe temperature
AT_{db}	: Combined coefficient for clothing thermal insulation, incorporating both convective and radiative heat transfer
ΔT	: The temperature difference between two surfaces of the textile layer
I	: Thermal insulation
ΔP	: The difference in the partial water vapor pressure between two surfaces
E	: Water vapor permeability
γ	: Interfacial tension
θ	: Equilibrium contact angle
S	: Solid
L	: Liquid
V	: Vapor
W_I	: Work of immersion
W_P	: Work of penetration
W_C	: Work of cohension
W_S	: Work of spreading
η	: Viscosity of the liquid
t	: Time
M	: Mass rate
h	: height of liquid rise in the capillary channel
E_r	: The sum of the latent and sensible respiration heat loss

C_v	: Effective volumetric heat capacity of the fibrous batting ($kJm^{-3}K^{-1}$)
C_a	: Water vapor concentration in the inter-fiber void space (kgm^{-3})
C_f	: Water vapor concentration in the fiber (kgm^{-3})
C_{fs}	: The water concentration in the fiber surface
C_{ab}	: Air stream of new moisture content
λ	: Latent heat loss of (de)sorption of fibers or condensation of water vapor
ε	: Porosity of the fibrosu batting
τ	: Effective totuosity of the fibrous batting
h_{cf}	: The mass transfer coefficient at the fiber surface
S_v	: The specific volume of the fabric
H_f	: The fractional relative humidty of the adjacent air
q	: Heat flow rate
k	: Conduction coefficient
T	: Temperature
R	: Thermal resistance
A	: Surface area
δ	: Thikness
q''	: Heat flux
P_e	: Half of the applied power
k_s	: Conduction coefficient of sock
A_s	: Area of sock
$\dot{Q}$	: Heat transfer rate passing through one layer of the socks

YENİ LİFLERDEN ÜRETİLMİŞ ÇORAPLARIN ISI İLETİMİNİN SONLU ELEMANLAR YÖNTEMİYLE MODELLENMESİ

ÖZET

Konfor, insanın bir çevre içerisinde kendini iyi hissetme halidir. Giysiler bu hissi, vücut hareketlerini sınırlamaması ve vücudu kendi ısısını düzenleme mekanizmasına mani olmaması veya yardımcı olması durumunda verebilmektedir. Vücut hareketiyle ilgili olan kısım daha çok giysi yapısı ve kumaş özellikleriyle alakalı bir durumken vücut ısısının düzenlenmesi konfor özellikleri olarak tabir edilebilen kumaşın nem, su, hava ve ısı geçirgenlik değerlerinden oluşmaktadır. Hazır giyim sanayi incelendiğinde iç giyim ve çorap sektörlerinin piyasaya sürülen konfor özellikleri iyileştirilmiş yeni lif cinslerinin ilk ve en yoğun kullanıldığı alanlar olduğu ortaya çıkmaktadır. Bunun başlıca nedeni tene doğrudan temas eden bu giysilerin insan üzerindeki diğer giysilerin konforu içinde önemli bir paya sahip olmasıdır. Günlük çalışma koşulları içerisinde vücudun diğer bölgelerine göre daha az hava sirkulasyonu olan ayakkabı içinde yer alan çorabın, diğer giysilere göre daha fazla konfor sağlaması beklenir.

Bu genel değerlendirmeler ışığında doğal esaslı yeni liflerden üretilmiş mamul çorapların konfor özelliklerine yönelik çalışma kurgulanmıştır. Modal, mikro modal, bambu, soya, kitosan gibi yeni liflerden üç farklı sıklıkta üretilen ve aynı şartlarda boya-terbiye işlemlerinden geçirilen 21 numunenin su buharı geçirgenliği, hava geçirgenliği, kılcal ıslanma özellikleri yanında ısı iletimi de bu çoraplar için özel olarak geliştirilen bir düzenek yardımıyla ölçülmüştür. Ayrıca tüm bu konfor belirleyici özellikler yanında, ürünlerin boncuklaşma, patlama mukavemeti, aşınma gibi kullanım performansını belirleyen fiziksel büyüklükler de belirlenmiştir. Elde edilen sonuçlar SPSS programında ANOVA, t-testi ve korelasyon testleriyle istatistiksel olarak değerlendirilmiştir.

Son olarak; CATIA programında modellenen süprem kumaşların ısı iletim davranışı ANSYS Workbench programında çözümlenmiştir. Deneyden elde edilen sonuçlarla sonlu elemanlar yöntemiyle elde edilen sonuçlar karşılaştırılmıştır.

MODELLING OF HEAT TRANSFER BEHAVIORS OF SOCKS MADE FROM NEW FIBERS USING FINITE ELEMENT METHOD

SUMMARY

People are 'comfortable' in their garments when they are feeling good in the environment. Garments can give this effect when people both are freedom of motion and can regulate or help their thermoregulation system. Body motion is concerned with fabric construction and properties, on the other hand, body temperature regulation is related with vapor, air and heat transfer.

Owing to fact that socks and inner garments are connected with skin directly, as a result they have an important role on feeling comfortable, generally new fibers whose comfort properties are improved are used firstly and intensity at these parts of industry. During daily life, less air circulation occurs at socks in the shoes than the other part of the body so socks need to perform better comfort than the other garments.

In the light of foregoing points; a study is edited which includes socks, made from new regenerated fibers, comfort properties. In this study, the yarns from seven new fibers namely modal, micro modal, bamboo, soybean and chitosan were utilized to produce sock samples at three different tightness values. Water vapor transfer, air permeability, wicking, wetting and heat transfer properties which are related with comfort were evaluated. In addition to that pilling, abrasion and bursting strength properties which affect the end-use performance of the socks were measured. Experimental results were statistically evaluated at SPSS using ANOVA, t-test, bivariate correlation analysis.

Finally, basic knitting part was drawn at CATIA and then heat transfer behavior of this part modeled at ANSYS Workbench. The results obtained from experimental results were compared with finite element results.

1.INTRODUCTION

1.1 Introduction and Aim of The Study

The human thermoregulation system is able to adjust the rate of energy exchange from his body to the thermal environment, but this ability is only limited within small variation in environmental condition. If the environmental condition is extreme, such as too hot or too cold thermal conditions, the regulation ability of body is insufficient to keep the energy balance with the environment. In such situations, the body suffers from discomfort. Thus, as a natural physiological response, human wants to put something on his body to assist his body in resisting those environments. At most situations, that something is clothing.

During the daily life, less air circulation occurs at socks in the shoes than the other part of the body so socks need to perform better comfort properties than the other garments do.

The aim of this study is to make a research about what type of criteria is affecting directly or indirectly comfort properties of socks. For this purpose; socks produced from seven different fibers and at three different tightness value have been investigated. Also, modeling of socks with aid of a CAD program was done. Furthermore, heat transfer behaviors of socks were studied by finite element method and the results were compared with experimental ones.

2. WHAT IS COMFORT?

Comfort is defined as freedom from pain, freedom from discomfort. It is a neutral state. Textile scientists say that people are “comfortable” in their garments when they are unaware of them both psychologically and physiogically. Awareness of clothing usually leads to an expression of discomfort. It is unusual to hear expressions of “positive” comfort [1].

In general, people consider themselves to be thermally comfortable when they do not need to take off or put on additional clothing to feel cooler or warmer. When a textile scientist questions subjects about their state of thermal comfort while sitting or exercising in a room at a set temperature and humidity, they usually indicate the degree of coolness or warmness away from a central point [1].

That central or neutral point is “comfortable”; the state of “very comfortable” can not be assessed. The same situation occurs when degree of wetness is of interest. When wetness is not sensed, people judge the fabric they are wearing to be comfortable; otherwise, they indicate some degree of wetness from the neutral state. The wearer is either comfortable or experiencing some degree of discomfort [1].

Among all aspects associated with human feelings and desires, comfort represents a central concern. Indeed, just about every activity human performs in life involves a process of seeking comfort or relief from environmental and/or mental constraints. Since human is always exposed to some environmental media, it is natural that he/she will attempt to interact with this environment. The options that human will typically have are: to forcefully stay in, to get out, or to adopt. These options are driven by a host of factors including;

1. The type of environment characterized by many factors including air temperature, radiant temperature, air movement, humidity, dust, dirt, and physical obstacles,
2. Human minimum inherent status, which represents the type of environment that human is used to,

3. The level of physical activity, which typically ranges from still (or immobile) to hyper (or overexcited),

4. Human health and physical condition (excellent, good, stable, unstable, poor),

5. Human psychological condition, which may be characterized by many descriptors including happy, depressed, scared, aggressive, relaxed, anxious, etc.,

6. Human ability to provide a descriptor of the comfort status.

These factors may be divided into three main categories: environmental (factors 1 and 2), physical (factors 2, 3, and 4), and psychological (factor 5 and 6). To make matters additionally complex, these factors typically interact in a very complex manner. Furthermore, human hardly experiences a still environment or body conditions. In other words, there is a continuous change over time that leads to transitional effects [6].

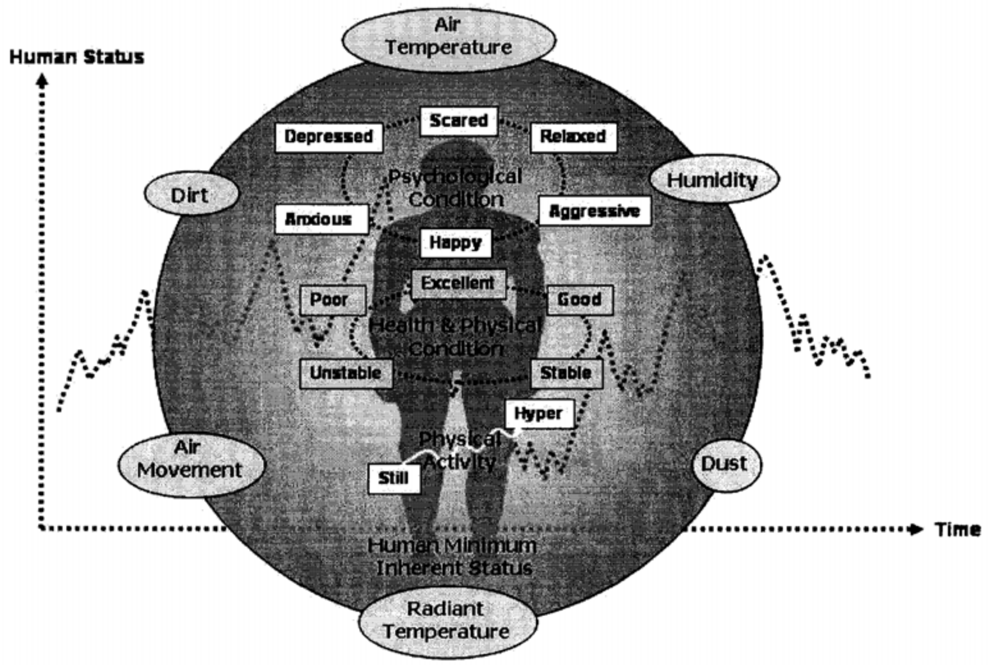


Figure 2.1: Primary Factors Influencing Human Comfort [6]

It is difficult to describe comfort positively, but discomfort can be easily described in such terms as prickle, itch, hot and cold. Further, the psychological and physiological states have a number of aspects:

- Thermophysiological comfort-‘attainment of a comfortable thermal and wetness state; it involves transport of heat and moisture through a fabric’.
- Sensorial comfort-‘The elicitation of various neural sensations when a textile comes into contact with skin’.

- Body movement comfort-'Ability of a textile to allow freedom of movement, reduced burden and body shaping, as required'.
- Aesthetic appeal-Subjective perception of clothing to the eye, hand, ear and nose which contributes to the overall well-being of wearer [2].

2.1 The Human-Clothing System

Clothing plays very important roles at the interface between a human body and its surrounding environment in determining the subjective perception of comfort is derived, we can consider human-clothing as an open system that is always in a state of dynamic interaction with its surrounding environment in physical, sensory, psychological and informational means (Figure 2.2). In this system, there are a number of processes occurring interactively which determine the status of comfort of a wearer:

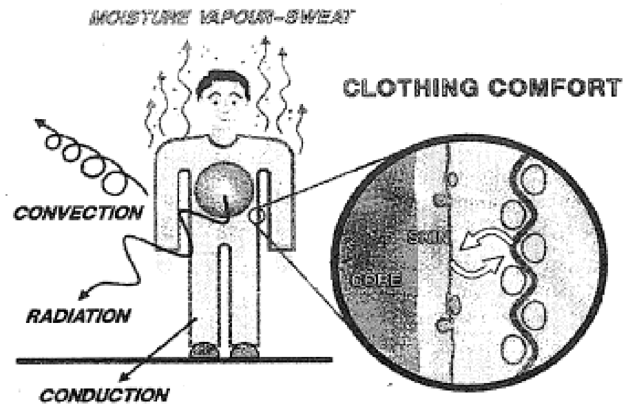


Figure 2.2: The human-clothing-enviroment system [2]

- Physical process in the clothing and the surrounding environment, such as the heat and moisture transport in the clothing, mechanical interactions between the clothing and the body and reflection and absorption of light by the clothing, which provide physical stimuli to the body.
- Physiological process in the body, such as the thermal balance of the body, and its thermoregulatory responses and dynamic interactions with the clothing and environment, which determine the physiological status of the body and its survival under critical conditions.

- Neurophysiological process, this mechanism of the sensory reception system of the body in the skin, eyes and other organs, by which sensory signals are formulated from the interactions of the body with the clothing and surrounding environments.
- Psychological processes of the brain which form subjective perception of the sensory sensations from the neuro physiological sensory signals and then formulate subjective overall perception and prefences by evaluating and weighing various sensory perceptions against past experiences and internal desires [2].

These four types of processes are occurring concurrently. The physical processes in the environment and clothing follow the laws of physics, which determine the physical conditions for the survival and comfort of the body. The thermoregulatory responses of the body and the sensory responses of the skin nerve endings follow the laws of physiology. The thermoregulatory and sensory systems respond to the physical stimuli from clothing and environment to ensure appropriate physiological conditions being met for the survival of the body, and to inform the brain of various physical conditions that influence the status of comfort. The psychological processes of which we have least understanding are more complex. The brain needs to formulate subjective perceptions from the sensory signals from the nerve endings, and to evaluate and weigh these sensory perceptions against past experiences, internal desires, and external influences. Through these process, the brain formulates subjective perception of overall comfort status, judgements, and prefences [2].

On the other hand, the psychological power of the brain can influence the physiological status of the body through various means such as sweating, blood-flow justification, and shivering. These physiological changes will change physical processes in the clothing and external environment. These four types of processes interact with each other dynamically to determine the comfort status of the wearer at any specific moment. Therefore, comfort status is subjective perception and judgement of a wearer on the basis of integration of all of these physical, physiological, neuro physiological and psychological processes and factors [2].

2.2 Psychology and Comfort

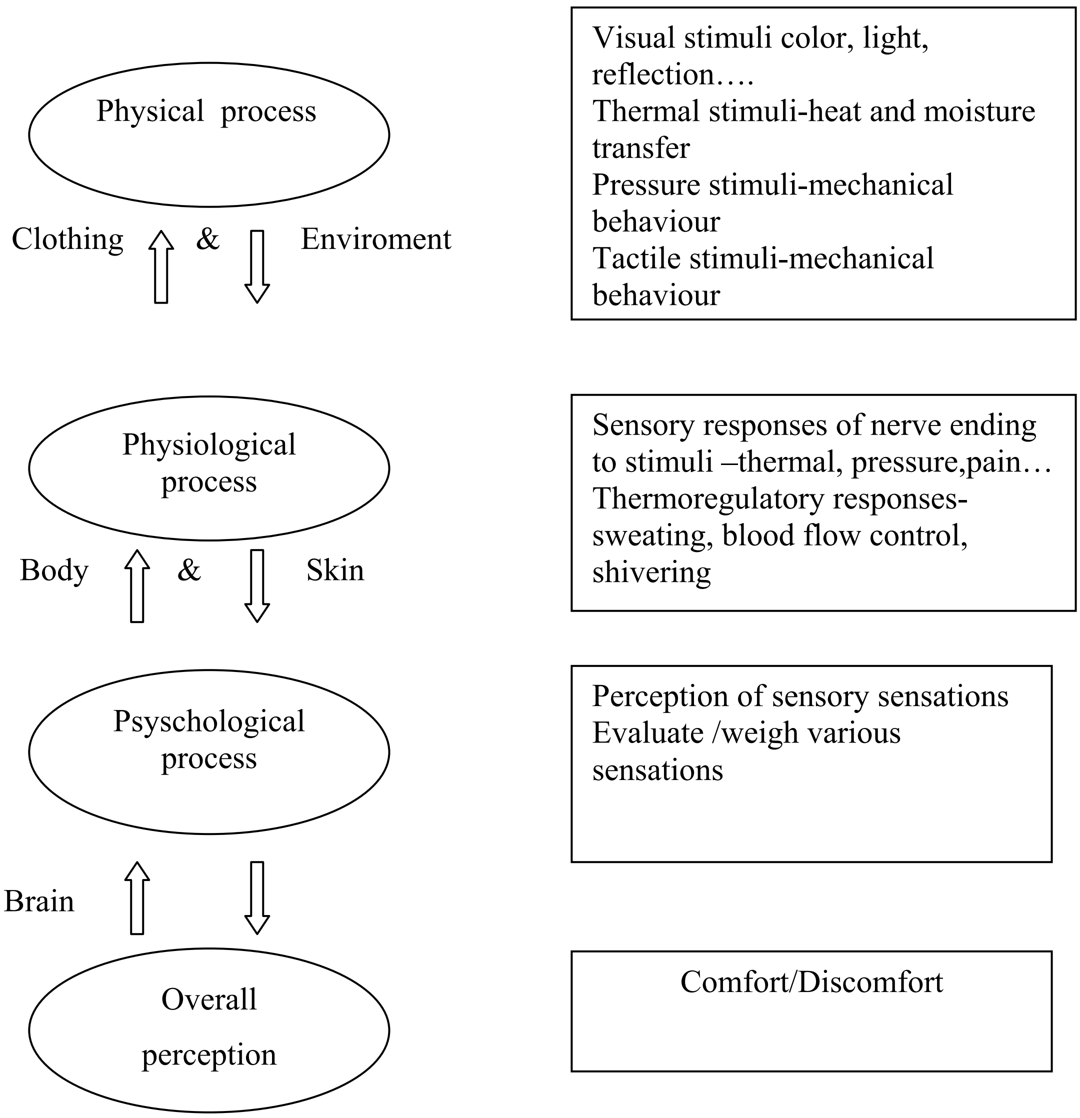


Figure 2.3: The flow chart for the subjective perception of comfort [2]

The psychology of comfort is the study of how the brain receives individual sensory sensations, and evaluates and weights the sensations to formulate subjective perception of overall comfort and preferences which become our wear experience and influence our further purchase decisions [2].

Since there are no physical instruments to measure what a wearer is thinking or feeling objectively, the only way to obtain the subjective perceptions is by use of psychological scaling. With psychological scaling, the process of making judgments is based on the scales of individual words or language that we collect from experience share with peers throughout life [2].

3. THERMAL PHYSIOLOGY AND COMFORT

The human thermal regulation system is able to adjust the rate of energy exchange from his body to the thermal environment, but this ability is limited only while the environmental condition varies within a small limited range. If the environmental condition is extreme, such as too hot or too cold thermal conditions, the regulation ability of body is insufficient to keep the energy balance with the environment. In such situations, the body suffers from discomfort and health problem. Thus, as a natural physiological response, human wants to put something on his body to assist his body in resisting those environments. At most situations, that "something" is clothing. When the appropriate clothing was put on the body, human body gets additional ability to regulate the thermal balance with the environment. The clothing acts as buffers or barriers to the free exchange of heat and moisture between the wearer and the environment [7].

On the other hand, thermal comfort is by definition a subjective sensation. It is a psychological phenomenon and not a physiological state. It will be therefore influenced by individual differences in mood, personality, culture background and other individual, organizational and social factors. Because different clothing ensembles have different abilities to assist the human body adjusting the rate of energy exchanges, clothing can meet the individual demands for thermal comfort. Watkins described clothing as a portable environment [7].

It is our most intimate environment, which can be carried everywhere, creating its own room within a room and its own climate within the larger climate of our surroundings.

The ability of clothing in assisting the human body to adjust the rate of energy exchanges is related to the values of clothing thermal insulation and moisture vapor resistance which are affected by many factors, such as materials, designs and construction. An ideal clothing for thermal comfort is such that allows the wearer to feel comfortable in as a wide range of environments and physical activity as possible. The term "comfort" here means the clothing thermal comfort which distinguishes the other comfort of garment such as freedom comfort of body movement, tactile comfort and so on [7].

Under the conditions where the thermal comfort cannot be achieved by the human body's own regulation ability, clothing must be worn to support its temperature regulation by resisting or facilitating the heat exchange between the human body and the environment. It is therefore important to know what kind of clothing ensembles can make our body thermally comfortable. Today, more and more people are involved in various activities in extremes of temperature and other hazardous environments, such as the pole lands, offshore, high mountains, deep caves, even outer space, where the function of clothing can be a matter of life or death. For indoor conditions, clothing may have no survival value, but still contributes to the body comfort. Therefore, clothing thermal comfort is increasingly concerned by both clothing consumers and manufacturers [7].

3.1 Terminology

The measure of the insulation of a material is its *thermal resistance.* It is defined as the thermal difference between the two faces divided by the heat flux and has units of K m^2W^{-1}. The magnitute of the heat flux at a point is inversely proportion to the thermal resistance of the material that is the higher the resistance, the lower is the heat loss [3].

Thermal resistance is also expressed in togs. The *tog* is defined as one-tenth of the ratio of the temperature difference across a fabric or other material or assembly of materials to the resulting rate of heat flow in watts per square meter, a thermal resistance of 1 tog corresponds to a heat transfer of 10 W m^{-2} per degree ^{0}C temperature difference:

$$10 togs = \left(\frac{\deg reeC}{watts / metre^2} \right) \qquad \textbf{(3.1)}$$

1 tog=0.41 ^{0}C s m^2 cal^{-1}

=0.567 ^{0}F h ft^2 Btu^{-1}

The warmth of clothing fabrics, quilts and other textile products is measured in togs. The higher the tog value, the greater is the thermal insulation provided [3].

Table 3.1: Typical thermal resistance values for clothing and furnising fabrics [3]

Fabric or Article	Thermal-resitance Value (tog)
Shirts	0.1
Suiting	1
Sweaters	1
Carpets	2
Curtains	0.2
Sheets	0.2
Blankets	1
Continental quilty	10

The *clo* unit of insulation is defined as a mean thermal resistance of $0.155^0Cm^2\ W^{-1}$. It is the amount of insulation necessary to maintain comfort and a mean skin temperature of 33^0C in a room at 21 ^0C with air movement not over 10 ft min^{-1} and relative humidity not over 50% with a body metabolism of 50 kcal $m^{-2}h^{-1}$.

Three types of measurement of clo are possible and should be distinguished from each other in discussion;

1. Thermal resistance, from thickness:

clo=1.6 x (thickness in cm)

=4 x (thickness in inch)

2. Thermal resistance;

1 clo=$0.155^0C\ m^2\ W^{-1}$

=$0.18\ m^2\ h\,kg^{-1}\ cal^{-1}$

or

1 clo=$0.648\ ^0C\ s\ m^2\ cal^{-1}$

=$0.880\ ^0F\ h\ \ ft^2\ Btu^{-1}$

=1.55 tog

The relationship between sample thickness and thermal insulation is expressed in terms of *thermal insulation values* (TIV) where

$$TIV = 1 - \left(\frac{\text{Heat loss from covered hot body}}{\text{Heat loss from uncovered hot body}} \right) \times 100\% \qquad \textbf{(3.2)}$$

Thermal conductivity gives the rate of flow of heat by conduction through unit area of material of unit thickness when a difference in temperature of one degree Celcius exists between its opposite faces. The overall thermal conductivity (K) of a material can be calculated from its togs/in by following relationships;

$$K = \frac{25.4}{togs/inch} \quad (\text{W cm m}^{-2}\,{}^{o}\text{C}^{-1}) \tag{3.3}$$

$$K = \frac{6.08 \times 10^{-4}}{togs/inch} \quad (\text{cal cm}^{-1}\ \text{s}^{-1}\ {}^{0}\text{C}^{-1}) \tag{3.4}$$

For thermal conductivity, the higher the togs/inch value, the better the material is intrinsically as a thermal insulator.

Thermal resistance, R, and thermal conductivity, K, are related as follows;

$$R = \frac{d}{K} \tag{3.5}$$

where d is the thickness.

The rate of heat flow between skin and fabric is determined by the *thermal diffusivity* of the skin and thermal inertia of the fabric. Thermal diffusivity is a measure of the rate at which the temperature front is transmitted by the skin to the thermoreceptors located just below the skin surface and thermal inertia, the product of thermal conductivity, density and specific heat, determines the rate of transfer of heat into the fabric. Hence the lower the thermal inertia of an object brought into contact with the skin, the less intense is the sensation of coolness [3].

Thermal resistivity, r, under steady-state conditions, is the temperature gradient, in the direction perpendicular to the isothermal surface, per unit heat flux; it is the reciprocal of the thermal conductivity. It can be defined only when thermal conductivity can be defined [3].

Thermal stabilty is the resistance to permanent changes in properties caused solely by heat [3].

Thermal transference is the steady-state heat flow from (or to) a body through applied thermal insulation and to (or from) the external surroundings by conduction, convection and radiation. It is expressed as the time rate per unit area of the body surface per unit temperature difference between the body surface and the external surroundings [3].

Thermal transmittance, U is the ratio of the steady state heat flux from the surroundings on one side of a body, through the body, to the surroundings on its opposite side (the rate of heat flow per unit area of a surface that must be identified) to the temperature difference between the two surroundings. The transmittance can be calculated from the thermal conductance and the surface coefficients as follows;

$$\frac{1}{U} = \left(\frac{1}{h_1}\right) + \left(\frac{1}{c}\right) + \left(\frac{1}{h_0}\right) \qquad \textbf{(3.6)}$$

The *minimum ambient temperature* is defined as the temperature at which the thermoregulation system of the human body is within the cold range, i.e. the moisture concentration near the skin is close to that of the environment so that the moisture flow can be neglected [3].

The *maximum ambient temperature* is the temperature at which the human, thermoregulation system reaches the upper temperature limit range, where the wearer of a clothing system must prevent his core temperature, under certain comfort conditions, from rising by making use of evaporative cooling [3].

The difference between the maximum and minimum ambient temperatures is called *psychrometric range* of the system. The resistance to heat and moisture transfer and psychrometric range can be measured by using thermal manikin and a skin model that were developed by the Hohenstein Institute. The parameters are dependent on the clothing design and the way it is worn, the textile material and the wind velocity [3].

Figure3.1: Hohenstein Institute skin model [4]

3.2 Heat Transfer in Textiles

The human body tries to maintain a constant core temperature of about 98.6°F (37°C). The actual value varies slightly from person to person, but the temperature of anyone is maintained within narrow limits. A rise or fall in this core temperature of ~9°F (5°C) is usually fatal. Equilibrium must be found between how much heat is produced and lost within the body. The human body is equipped with its cooling and heating equipment. For example, shivering generates heat in cold air, and perspiration evaporates in order to cool the body. However, if the body cannot cool or heat itself enough, problems may occur such as hypothermia. This is the reason that textile fabric is so important in every environment. When living in a cold atmosphere fabric can provide insulation as well as restrict heat into the body in a hotter environment [6].

In most climates, body temperature is above that of the external environment so that there has to be an internal source of heat in order to maintain the temperature difference. The required heat comes from the body's metabolism; that is the necessary burning of calories to provide power to the muscles and other internal functions. However, the body must be kept in thermal balance. The metabolic heat generated together with the heat received from external sources must be matched by the loss from the body of an equivalent amount of heat. If the heat gain and the heat loss are not in balance then the body temperature will either rise or fall, leading to a serious threat to life [6].

The efficiency of the human organism is such that of the energy taken in as food only 15-30% is converted into useful work with the remaining 70-85% of the energy being wasted as heat. Any level of physical activity above that needed to maintain body temperature will result in an excess of heat energy which must be dissipated, otherwise the body temperature will rise. A lower level of physical activity will lead to a fall in body temperature if the available heat is not conserved by increased insulation [6].

The approximate energy level which are associated with human activity are shown in Table 3.2 and range from a minimum value of about 70W when sleeping to an absolute maximum of about 1500W which is only possible in short bursts. A rate of about 500W (corresponding to hard physical work) can be kept up for a number of hours. If a person is comfortable (that is, in heat balance) at rest then a burst of hard exercise will mean that there is a large amount of excess heat and also perspiration to be dissipated. On the other hand if the person is in heat balance during strenuous exercise then he or she will feel cold when resting owing to the large reduction of heat generation [6].

Table 3.2: Energy levels associated with different activities [6]

Activity	Energy (watts)
Sleeping	70
Resting	90
Walking 1.6km/h (Imph)	140-175
Walking 4.8 km/h (3mph)	280-350
Cycling 16km/h (lOmph)	420-490
Hard physical work	445-545
Running 8km/h (5mph)	700-770
Sprinting	1400-1500

In terms of comfort, the purpose of clothing is to serve as thermal insulation, which allows controlled heat loss from the body. Clothing interacts with the air and heat flow in the ambient environment. Heat loss is either impeded or enhanced by the presence of clothing, depending on the thermal properties of the clothing. Heat is always being transferred in one way or another, wherever there is any difference in temperature. In a cold environment, heat will flow from the body to the environment. In a hot one, environmental heat will place a heat load on the body [6].

Heat may be exchanged between man and his environment by four physical modes:

- Conduction,
- Convection,
- Radiation,
- Liquid-vapor transformations

There are four mechanisms that allow the body to lose heat to the environment in order to maintain its thermal balance. The way the heat loss is divided between the mechanisms depends on the external environment [6].

Conduction

In this process heat loss is accomplished through direct contact with another substance. The rate of exchange is determined by the temperature difference between the two substances and by their thermal conductivities. For example the body loses heat in this manner when submerged in cold water [6].

Convection

This is a process in which heat is transferred by a moving fluid (liquid or gas). For example, air in contact with the body is heated by conduction and is then carried away from the body by convection [6].

Convection can occur only in the air and in the fiber; it does not occur where the air is in contact with a solid surface, so a construction of many small fibers with small air spaces between them gives the best combination for low conductivity and no convection [3].

Radiation

This is the process of heat transfer caused by electromagnetic waves. The waves can pass through air without imparting much heat to it; however, when they strike an object their energy is largely transformed into heat. Radiation can largely be ignored as a mechanism of losing heat as it is very dependent on the temperature of an object so that it is more important then heat gain from very hot bodies such as the sun, radiant heaters or fires. Heat radiation and absorption by an object are both influenced by its color. Black is both the best absorber and radiator of heat. White and polished metals are poor absorbers and radiators as most of the energy is reflected. Clothing acts to reduce radiation loss by reducing the temperature differences between the body and its immediate surroundings, as the clothing effectively becomes the immediate surroundings [6].

Evaporation

Changing liquid water into vapor requires large amounts of heat energy. One calorie will raise the temperature of one gram of water one degree Celsius; however, it takes 2424J (580 calories) to evaporate one gram of water at body temperature. If the water is evaporated from the skin surface then the energy required is removed from the skin, thus cooling it. When environmental temperatures approach skin temperature (35°C seated to 30°C heavy physical work), heat loss through convection and radiation gradually come to an end so that at environmental temperatures above skin temperature the only means for the body to lose heat is through evaporation of sweat. Sweating itself is not effective as it is the conversion of the liquid to vapor that removes the heat. This mechanism works well in a hot dry environment but evaporation of sweat becomes a problem in hot humid climates [6].

3.3 Heat Transfer From a Body

3.3.1 Heat Transfer From an Unclothed Body

In environment at a lower temperature than skin temperature, an unclothed body loses body-generated heat to the environment. About 90% is emitted from the skin surface the other 10% is lost through respiration. The skin, acting as a radiator, warms the immediately surrounding air by conduction. The heated air rises due to buoyancy, orming an envelope of air that moves upward and surrounds the unclothed body (Figure 3.2) [1].

In an indoor environment, the nude human body loses ~ 60% of its heat by radiation. The body is an excellent radiator. The walls or other nearby objects that receive this radiation also emit radiation, some of which is received and absorbed by he human body. In an environment cooler than the human body, a net loss of radiated heat occurs which the individual can detect. For example, in a newly heated room where the air temperature is at a satisfactory level for thermal comfort, thermal discomfort can be noticed because the walls and furniture are still cold [1].

When an unclothed person is exposed to a source of radiant heat greater than that of the body, net thermal load is experienced. Radiant heat from a fire, molten metal, a room radiator, and the sun all increase skin temperature and create thermal load. Each source emits different wave lengthts of thermal radiant energy, all of which are readily absorbed by the skin. The skin is a good absorber of energy over a wide spectral range [1].

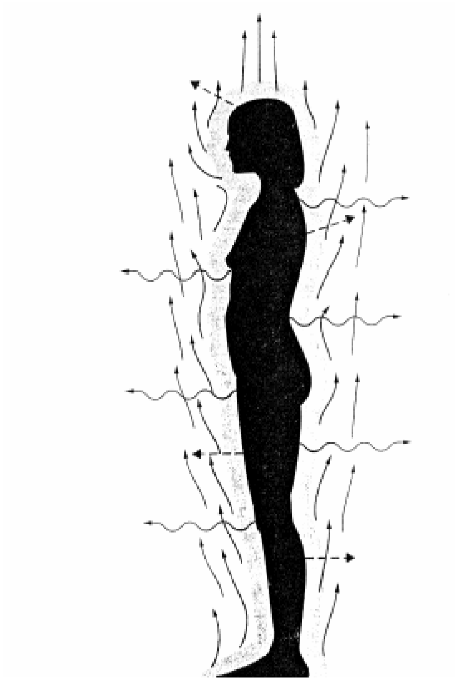


Figure 3.2: Heat dissipation from an unclothed body in an environment at 25 C [1].

3.3.2 Heat Transfer From a Clothed Body

In a homogenous solid the only mechanism present is conduction and the temperature profile is linear. The presence of radiation as mechanism increases the total heat transfer, but an interaction between conduction and radiation causes the temperature profile to depart from linearity [3].

Heat transmission through the clothing can take place in three different forms:

1. Dry transmission, which, for simplicity, will be referred to as conduction although it includes a radiation element,
2. Diffusion of insensible perspiration (water vapor),
3. Diffusion of liquid perspiration [3].

The presence of liquid sweat on the skin is taken as an indication of discomfort, and only the first two modes of transmission will therefore operate under conditions of comfort. Under these conditions, the total rate of heat transfer (Q) consists of a conductive component (Q_c) and evaporative component (Q_e) where;

$$Q=Q_c+Q_e \tag{3.7}$$

No steady state is possible unless the heat generated by the body is transmitted through the clothing at the rate which is generated.

The total thermal resistance to transfer of heat from the body to the surrounding air as the sum of three parameters, these being the thermal resistance to transfer of heat from the surface of the material, the thermal resistance of the clothing material, and the thermal resistance of the air interlayer [3].

Textile structures are not homogenous, since they are composed of a mixture of two or more materials with quite different thermal conductivities. Heat flows through the fiber/air mixture mainly by conduction. The spaces between fibers and yarns also allow some heat flux by infra-red radiation [3].

According to Rees [3], the transfer of sensible heat (that is by conduction, convection and radiation) between two boundaries requires the existance of a temperature difference between these boundaries, the ratio of the resulting thermal flux to the temperature difference being the thermal resistance of the system.

Hollies and Goldman [2] used a number of equations to describe the heat and moisture transfer in clothing:

Convective heat loss, $H_C= k_C* A * (T_{SK}-T_{ab})$ **(3.8)**

Evaporative heat loss, $H_e= k_e* A * (P_{SK}-P_{ab})$ **(3. 9)**

Mean radiant temperature, $MRT= 1+2.22\sqrt{V}* (T_g-T_{ab})+ T_{ab}$ **(3.10)**

Adjusted dry bulb temperature, $AT_{db} =(T_{ab}+MRT)/2$ **(3.11)**

where

k_C is a coefficient for convective heat transfer, which involves not only the still air layer around the body but also the thermal characteristics of the clothing worn;

A is the surface area of the body;

T_{sk} is the mean weighted skin temperature of the surface of the body;

T_{ab} is the dry bulb temperature;

k_e is the evaporative coefficient;

P_{sk} is the saturated vapor pressure of water at skin temperature;

P_{ab} is the ambient vapor pressure;
V is the wind velocity;
T_g is the globe temperature;
AT_{db} is a combined coefficient for clothing thermal insulation, incorporating both convective and radiative heat transfers.

Mecheels [3] describes the total heat transfer H through textile layers as:

$$H=H_{r+c}+H_e=(\Delta T/I)+(\Delta P/E) \qquad \textbf{(3.12)}$$

H_{r+c}= dry heat transfer (radiation and conduction)
H_e= heat transfer by evaporation
ΔT= the temperature difference between two surfaces of the textile layer
I= thermal insulation
ΔP=the difference in the partial water vapor pressure between both surfaces
E= the water vapor permeability

From calculated examples, he shows that the heat flow by radiation through an air layer does not depend on its thickness. However, the heat flow by conduction decreases with increasing thickness, still air being assumed.

The coupled heat and moisture transfer in textile fabrics has been widely recognized as being very important for understanding the dynamic thermal comfort of clothing during wear.

Henry [2] developed a system of differential equations to describe the processes involved. Two of the equations involve conservation of mass and energy. The third equation relates fiber moisture content to the adjacent air. As shown in figure 3.3, in a small element of fabric of unit area and thickness, packed with fibers exposed to a moisture gradient, water vapor diffuses through the interfiber spaces to be absorbed or desorbed by the fibers. To simplify a mathematical description of the process, a number of assumptions were made:

1. The volume changes of the fibers due to changing moisture content can be neglected,
2. Moisture transport through fibers can be ignored as the diffusion coefficient of water through fibers in negligible compared with that through air;

3. The orientations of the fiber in the fabric plays a minimum role in the water vapor transport process as the diameters of the fibers are small and water vapor can travel much more rapidly in the air than in the fibers;

4. Instantaneous thermal equilibrium between the fibers and the gas in the interfiber space is achieved during the process, as most textile fibers are of very small diameter and have a very large surface/volume ratio.

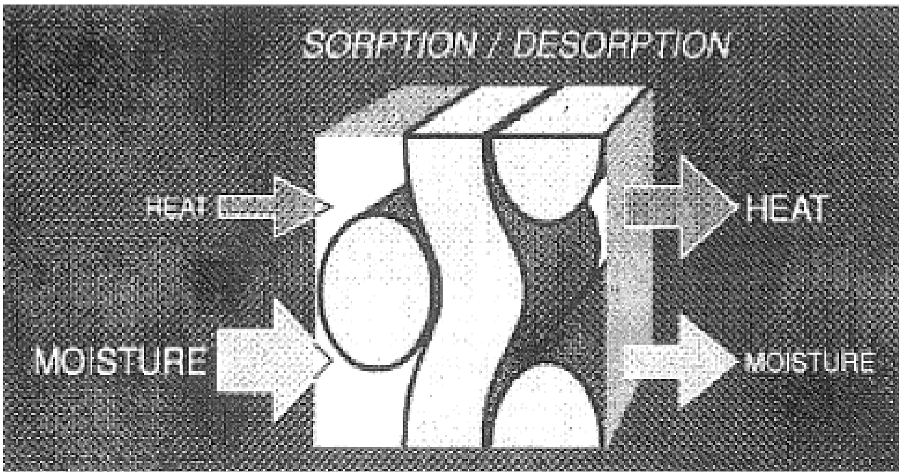


Figure 3.3: Coupled heat and moisture transfer in a fabric [2]

On the basis of these assumptions, a mass balance equation which considers the moisture accumulation by both the air and the fibers and the moisture transport through the air space, can be written as:

$$\varepsilon \frac{\partial C_a}{\partial t} + (1-\varepsilon)\frac{\partial C_f}{\partial t} = \frac{D_a \varepsilon}{\tau}\frac{\partial^2 C_a}{\partial x^2} \qquad \textbf{(3.13)}$$

In this equation, the first term on the left-hand side describes the accumulation of water vapor in the interfiber space, and the second term describes the accumulation of the absorbed water in the fibers. The moisture transport through the interfiber air space is described by the term on the right-hand side.

A second equation for the conservation of heat energy can be derived by considering changes in the heat content of the volume element that arise from a number of processes: conduction into or out of the element, change in phase of the water vapor (sorption or desorption), and temperature changes of the fibers and of the air in the interfiber space. The equation for energy conservation can be written as:

$$C_V \frac{\partial T}{\partial t} + \lambda(1-\varepsilon)\frac{\partial C_f}{\partial t} = K\frac{\partial^2 T}{\partial x^2} \quad \textbf{(3.14)}$$

In this equation, C_v and λ are dependent on the concentration of water absorbed by the fibers [2].

In a textile layer, radiation is not influenced by the mere thickness but it is very much affected by the mean number of absorptions and re-emissions of the heat rays when passing through the textile layer. The heat conduction through a textile is controlled both by the thermal conductivity of the air and of the fibers and by the thickness of the layer.

Spencer-Smith [3] discusses that the transfer of heat and water through layers of damp fabric is considered together as the resistance to total heat transfer. The reciprocal of this resistance is shown to increase approximately linearly with increasing regain of the fabric. Heat transfer is time dependent.

According to Clulow's [3] studies the transfer of heat from the body through clothing to the colder surroundings is quite complicated and involves a combination of losses by conduction through the fibers and the air in the fabric and losses by convection and radiation through the air spaces between the yarns and fibers. In addition; for maximum insulation, a fabric is needed that is neither so open that is allows too much radiation and air circulation or dense that the fibers themselves conduct too much heat; the garment is also required to cover as much of the body as possible.

At least three distinct mechanisms are involved in the heat transfer process across a clothing fabric;

a) The mechanism: dry thermal transfer, latent-heat transfer due to water-vapor transport and latent-heat transfer involving liquid-water transport

b) The driving force: temperature differences across the fabric, water-vapor pressure differences across the fabric, and capillary force between adjacent fibers

c) The governing fabric properties: thermal insulation, air permeability, vapor resistance, surface free energy of the fiber materials and yarn structure [3].

Infra-red radiation is a major source of heat flow through very low-density fiber structures. Variations in fabric construction will have little effect on the conductive heat flow through a given fabric of a given thickness [3].

3.3 Wetting and Wicking in Fibrous Materials

Wetting and wicking are important phenomena in the processing and applications of fibrous materials.

A spontaneous transport of a liquid driven into a porous system by capillary forces is termed wicking because capillary forces are caused by wetting; wicking is as result of spontaneous wetting in a capillary system. Wetting is a prerequisite for wicking. A liquid that does not wet fibers can not wick into a fabric. The wetting and wicking behavior of the fibrous structure is a critical aspect of performance of products such as sports clothes, hygiene disposable materials and medical products. Wetting and wicking processes occurring during wearing of clothes have a practical significance in clothing comfort [5].

3.3.1 Wetting

Wetting of a fibrous assembly affects many manufacturing processes, as well as the end use performance of materials. Wetting is a complex process complicated further by structure of the fibrous assembly e.g. yarns, woven/nonwoven/knitted fabrics and pre-forms for composites.

There is a distinction between two terms that are sometimes used interchangeably, 'wetting' and 'wettability'. The wetting of a solid surface is understood to be condition resulting from its contact with a specified liquid under specific conditions. Wettabilty is the potential of a surface to interact with liquids with specified characteristic [5].

For a liquid to move in a fibrous medium, it must wet the fiber surfaces before being transported through the inter fiber pores by means of capillary action. While the interactions of molecules in the bulk of a liquid are balanced by an equal attractive force in all directions, the molecules on the surface of a liquid experience an imbalance of forces. Hence, there is presence of free energy at the surface of the liquid. The excess energy is called 'surface free energy', which tends to keep the surface area of the liquid to a minimum and restricts the advancement the liquid over the solid surface. For a liquid to wet a solid completely, or for the solid to be submerged in a liquid, the solid surfaces must have sufficient surface energy to overcome the free surface energy of the liquid. The surface free energy can be quantified as a measurement of energy per area. It is usually termed 'surface tension' and is quantified as force per length, with units mN/m or dynes/cm [5].

The forces involved in the equilibrium that exists when a liquid is in contact with a solid and a vapor at the same time are given by the following equation:

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos\theta \tag{3.15}$$

where γ represents the interfacial tension that exists between the various combinations of solid, liquid and vapor; S, L, and V standing for solid, liquid and vapor and Θ is the equilibrium contact angle (Figure 3.4) [5].

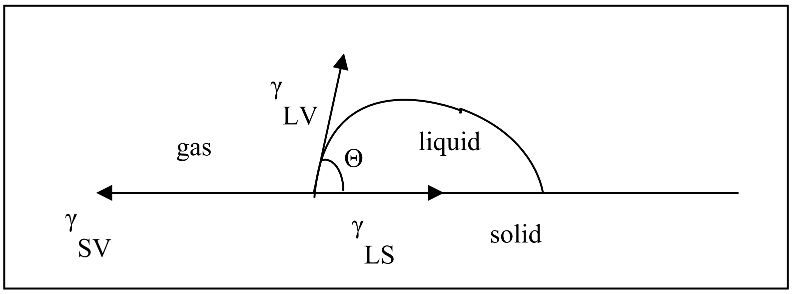


Figure 3.4: Equilibrium state of a liquid drop on a solid surface [5]

The term γ_{LV} is denoted as the surface tension of the liquid for the liquid/vapor interface.

$\gamma_{LV} \cos\theta$ has been called the 'adhesion tension' or 'specific wettability'.

Equation 3.15 is valid only for a drop resting at equilibrium on a smooth, homogeneous, impermeable and non deformable surface.

The contact angle Θ is the angle between the tangent to the liquid-vapor (air) interface and the solid-liquid interface.

3.3.1.1 Wetting Mechanism

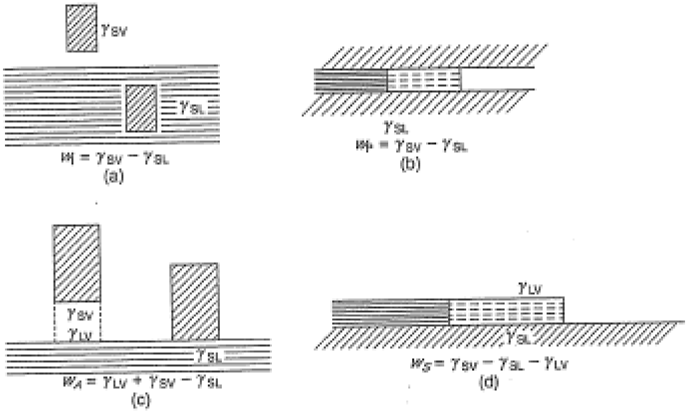


Figure 3.5: Wetting mechanisms

Wetting of textiles involve several primary processes: immersion, capillary sorption, adhesion and spreading. During immersion (Figure 3.5) or capillary sorption (Figure 3.5) a solid-vapor interface disappears and solid-liquid interface appears. The work of immersion, W_I, or the work of penetration, W_P, performed during capillary sorption, is defined as the free energy change when the contacting solid and liquid are separated.

For spontaneous penetration, e.g. a positive capillary rise, the work of penetration as to be positive. This is the case when the interfacial energy of the solid in contact with vapor exceeds the interfacial tension between the solid and the liquid. For interfaces of unit area:

$$W_I = W_P = \gamma_{SV} - \gamma_{SL} \tag{3.16}$$

Adhesion is the attraction between two surfaces in contact (Figure 3.5). When the contacting surfaces are those of a solid and a liquid, the work of adhesion, W_A or W_{SL}, is equal to the change of surface free energy of the system when the contacting liquid and the solid are separated.

The separation results in the loss of their interface with interfacial tension, γ_{SL}, and formation of two new surfaces with surface tensions γ_{SV} and γ_{LV}. The work of adhesion per unit area of interfaces is given by the Young-Dupré equation 3.15. This is the total attraction per unit area between the two phases and it can be expressed in general terms as:

$$W_A = \gamma_{LV} + \gamma_{SV} - \gamma_{LS} \qquad \textbf{(3.17)}$$

Assuming that equation 3.15 is valid, and combining it with equation 3.17, leads to an expression for the work of adhesion in terms of two measurable properties:

$$W_A = \gamma_{LV} + \gamma_{LV}\cos\theta \qquad \textbf{(3.18)}$$

This can be transformed to

$$W_A = \gamma_{LV}(1+\cos\theta) \qquad \textbf{(3.19)}$$

Application of equation 3.17 to a liquid yields the work of cohension, W_C, which is the reversible work to pull apart a liquid column creating two liquid surfaces, each having an interfacial tension γ_{LV} :

$$W_C = 2\gamma_{LV} \qquad \textbf{(3.20)}$$

Spreading is the flow of liquid at least two molecular layers thick over a solid (Figure 3.5). During spreading, the solid-liquid and liquid-vapor interfaces increase, whereas the solid-vapor interface decreases. The work of spreading, W_S, is the reversible work equal to the free free energy change that occurs when the solid an liquid are separated (reversal of spreading), and it is given by:

$$W_S = \gamma_{SV} - \gamma_{LV} - \gamma_{SL} \qquad \textbf{(3.21)}$$

For spreading to be spontaneous, the work of spreading, W_S, has to be positive. Equations 3.16, 3.17, 3.19 are valid only for ideal, smooth, homogeneous, impermeable and non-deformable surfaces. Since textile fibers do not have such ideal surfaces, their wetting phenomena are not complicated. In addition, the prediction of wetting phenomena, e.g. spreading, from wetting energy is difficult because a direct method for determining γ_{SV} , a term found in equations 3.16, 3.17, 3.21, is not available. It is more convenient to use the forces in balance at a three-phase (solid, liquid and vapor) boundary as an indication of wettability [5].

When a liquid drop is placed on fabric, it will spread under capillary forces. As suggested by Gillespie, the spreading process may be split conveniently into two phases, I and II, when some of the liquid remains on the surface and when the liquid is completely contained within the substrate, as shown in Figure 3.6.

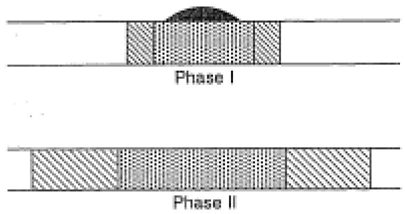


Figure 3.6: Schematic illustration of the two phases in drop spreading of liquid fabrics [5]

For two-dimensional circular spreading in textiles during phase II, Kissa [5] developed Gillespie's equation to propose the following exponential sorption:

$$A = K(\gamma_{LV} / \eta)^u V^m t^n \quad \textbf{(3.21)}$$

where A is the area covered by the spreading liquid, K is the capillary sorption coefficient, η is the viscosity of the liquid, V is the volume of the liquid, t is the spreading time and the values of the exponents u, m and n are 0.33, 0.67, 0.33 respectively.

Kissa's exponents can be applied only for fibers that are impermeable to liquids. When the liquid diffuses into the fibers (e.g. water into the cotton fiber), the exponents depend on the nature of the liquids, fibers and drop volume.

The wetting process can be resolved into two independent processes, often competitive with one another. One, the escape of accluded gases from the substrate, is essentially mechanical and the other, the rate of advance of the liquid phase into the mass to be wetted, is a physiochemical phenomenon.

3.3.2 Wicking

The transport of a liquid into a fibrous assembly, such as a yarn or fabric, may be caused by external forces or by capillary forces only. An understanding of capillarity is important in wet processing of textiles, especially dying.

In most of the wet processing of fibrous materials, uniform spreading and penetration of liquids into pores are essential for the better performance of resulting products. Wicking can resulting capillary forces drive the liquid into the capillary spaces. Wicking can be visualized as a spontaneous displacement of a solid-air interface with a solid-liquid interface in a capillary system. In a simple case, such as wicking in a capillary tube, the area of the liquid-air interface across the capillary is very small relative to the area of the wetted capillary wall, and does not change during wicking. Hence, the only considerable change is the increase of the solid-liquid interface and decrease of the solid-air interface. For the process to be spontaneous, free energy has to be gained and the work of penetration has to be positive. This is the case when the interfacial energy of the fiber surface in contact with vapor (air) γ_{SV} exceeds the interfacial energy between the liquid and the fiber surface $\gamma_{SL;}$

$$W_P = \gamma_{SV} - \gamma_{SL} \qquad \textbf{(3.22)}$$

The work of penetration W_P is a measure of the energy required for capillary penetration. Since γ_{SV} and γ_{SL} are exceeding difficult to measure independently, workers have attempted to estimate the surface energy indirectly by interaction with liquids.

Related capillary penetration to capillary pressure can draw a similar conclusion. When a liquid in a capillary wets the walls of the capillary, a meniscus is formed. The surface tension of the liquid causing a pressure difference ΔP across the curved liquid-air (vapor) interface, related to the curvature of this interface according to the equation;

$$\Delta P = \gamma_{LV}(1/R_1 + 1/R_2) \qquad \textbf{(3.23)}$$

For a capillary with a circular cross-section, the radii of the curved interfaces R_1 and R_2 are equal.

$$\Delta P = 2\gamma_{LV}/R \qquad \textbf{(3.24)}$$

If the capillary is circular with radius r, the meniscus will be approximately hemispherical with a constant radius of curvature,

$$R = r/\cos\theta \qquad \textbf{(3.25)}$$

The capillary pressure is therefore

$$\Delta P = 2\gamma_{LV} \cos\theta / r \quad \textbf{(3.26)}$$

When the capillary wall is completely wettable by the liquid then ϴ=1. For a positive capillary pressure, the values of ϴ have to be between 0^0 and 90^0. Capillary pressure is inversely related to the capillary radius.

If the penetration of the liquid is limited to the capillary spaces and the fibers do not imbibe the liquid, the wicking process is termed ‘capillary penetration’ or ‘capillary sorption’. The sorption of the liquid into fibers can cause swelling, reduce capillary spaces between fibers and complicate kinetics [5].

The capillary spaces in yarns and fabrics are not uniform and an indirectly determined effective capillary radius has to be used instead of the radius r. Further, fibrous materials encounter roughness on the surfaces and walls of the pores. A liquid may spread along grooves or rugosities on the surface, even if it does not spread on a smooth surface of the same solid. The driving force for such surface wicking depends on the geometry of the grooves, surface tension of the liquid and free energies of the solid-gas and solid-liquid interfaces [5].

Most textile processes are time limited and the rate of wicking is therefore important. However, the wicking rate is solely governed by inter facial tensions and the wettability of the fibers but by other factors as well. The wicking rate depends on the capillary dimensions of the substrate and the viscosity of the liquid [5].

The mass rate (M) at which a liquid moves through a porous channel is related to the pressure difference (p or ΔP) across the channel, in the absence of gravitational force and neglecting inertial forces (as acceleration is small), by Poiseuille’s law.

$$M = \Pi p \rho_L l r^4 / 8\eta h \quad \textbf{(3.27)}$$

If the pressure differences ΔP is due to capillary forces, then

$$M = \Pi \rho_L r^3 \gamma_{LV} \cos\theta / 4\eta h \quad \textbf{(3.28)}$$

The volume rate (V) is;

$$V = \Pi r^3 \gamma_{LV} \cos\theta / 4\eta h \qquad \textbf{(3.29)}$$

Linear rate of flow (u) is;

$$u = dh / dt = r \ \gamma_{LV} \cos\theta / 4\eta h \qquad \textbf{(3.30)}$$

where h is the height of liquid rise in the capillary channel [5].

3.3.2.1 Wicking in Fabrics

Absorbency of fabrics is influenced by their wicking ability. Wicking occurs when a fabric is completely or partially immersed in a liquid or in contact with a limited amount of liquid, such as a drop placed on the fabric. Capillary penetration of a liquid can therefore occur from an infinite (unlimited) or limited (finite) reservoir. Wicking processes from an infinite reservoir are immersion, transplanar wicking and longitudinal wicking. Wicking from a limited reservoir is exemplified by a drop placed onto the fabric surface.

Based on the extent of interactions with fibers, wicking processes can be divided to four categories.

1. Wicking of a liquid, no significant diffusion into the fiber surface, e.g. hydrocarbon oil wicking into a polyester fabric at ambient temperature; capillary penetration is the only process operating.
2. Wicking accompanied by diffusion of the liquid into fibers or into a finish on the fiber, e.g. water wicking in a cotton fabric and diffusing into fibers, water wicking into solid- release treated polyester fabric, and diffusing into the finish. Two simultaneous processes are operating- capillary penetration and diffusion of the liquid into the fibers.
3. Wicking accompanied by adsorption on fibers, e.g. an aqueous surfactant solution wicking into a polyester fabric. Several processes are operating simultaneously-capillary penetration of the liquid, diffusion of the surfactant in the liquid and adsorption of the surfactant on fibers.
4. Wicking involving adsorption and diffusion into fibers, e.g. an aqueous surfactant solution wicking into a cotton fabric. Several processes are operating

simultaneously-capillary penetration, diffusion of the liquid into the fibers, diffusion of the surfactant in the liquid and adsorption of the surfactant on fibers [5].

3.3.3 Factors Affecting Wetting and Wicking in Fibers and Fibrous Assemblies

3.3.3.1 Fibers

Factors such as type of fibers, chemical purity, orientation of molecules, surface contamination, surface finish, cross-sectional shape, surface roughness, pre-wetting, annealing, argon glow discharge and corona treatments, presence of surfactants, alkaline hydrolysis, washing, bleaching, and mercerization are found to influence the wetting behavior of fibers.

Wetting force increases linearly with diameter of filaments, indicating that wettability of filaments is the same, irrespective of some filament diameters. Whang and Gupta [5] tested wetting characteristics of some finish-extracted cellulosic fibers, namely cotton, regular rayon (roughly round but crenulated shape), and trilobal shaped rayon, using the Wilhelmy Technique. The magnitude of the wetting force of fibers increases with perimeter but the relation is linear only for the receding and not for the advancing liquid front. The wettability index of all the three fibers was nearly the same in receding but widely different in advancing. The wetting index while receding is governed mostly by the chemical make-up of the fiber, the index during advancing being additionally affected by physical and morphological structures that include molecular orientation, crystallinity, roughness, and surface texture. The wetting parameters of cellulose acetate fibers of different sizes and morphologies were quite different in the advancing mode but were very nearly the same in the receding mode. Infrared spectroscopy of these three cellulosic fibers confirms that they are chemically similar.

The cosines of advancing contact angles were 0.93, 0.83, and 0.57 for trilobal rayon, cotton, and regular rayon fibers respectively. This reflects the relative abilities of these fibers to attract and imbibe fluid by capillary action in fibrous assemblies. The trilobal viscose fiber had a high wetting index, followed by cotton and regular rayon fibers. A separate study indicated that webs of similar constructions made from trilobal rayon and cotton had much higher rates of water absorption than did a web containing regular rayon. The receding contact angles for these fibers are similar due to their similar chemical structures and they are much lower than the advancing contact angles [5].

Surface contamination on fibers, roughness, and molecular structure of fibers are the factors responsible for wetting hysteresis. The wetting hysteresis for cotton, trilobal rayon, and regular rayon were 1.06, 1.01, and 1.25 respectively. Very little or no hysteresis for the trilobal rayon fiber and high for regular rayon fiber may be explained on the basis of chemical purity, cross-sectional morphologies, and orientation of molecules in the fibers. The birefringence values of both the rayons were the same and lower than that of cotton. The trilobal rayon fibers had high purity, were smoother and had more homogeneous surfaces than regular rayon fibers. These differences are partly responsible for the difference in the hysteresis values of the two rayon fibers. The surface structural differences were evident in the wetting force fluctuations. A very high fluctuation was observed in the wetting force trace for regular rayon followed by cotton and trilobal rayon fibers. Further, the longitudinal ridges on the surface of the trilobal fibers would allow them to imbibe fluid ahead of the fluid-fiber interface in the advancing mode, to a state comparable to that in the receding mode, and led to relatively lower hysteresis in trilobal fibers [5].

Higher work of adhesion during advancing and, as a result, lower hysteresis for cotton compared to regular rayon, is due its higher chemical purity and molecular orientation than the regular rayon. It was shown that contact angle hysteresis was due to the heterogeneity of the fiber surfaces [5].

The wettability of polypropylene fibers in water is extremely low compared to polyester and nylon. However, receding wettability for polypropylene is high compared to others, Pre-wetting of polypropylene fibers in water had a much more significant effect in enhancing its wettability as compared to the response of nylon or polyester fibers under the same conditions.

Annealing of polyester at 200°C under slack conditions increases water wettability, whereas annealing under taut conditions shows no increase in wettability. Annealing at elevated temperatures causes an increase in shrinkage caused by regular chain folding and such effects may be reflected in the surface characteristics of polyester fibers or migration of oligomeric materials to the fiber surface. Annealing of polypropylene fibers both under taut and slack conditions increased their water wettability, but the shrinkage phenomenon had a much more dramatic effect [5].

The enhanced wettability is due to an increase in either the number of polymer hydrophilic groups or their accessibility to water, and/or an increase in the roughness of the sample surfaces.

In order to improve the sorption characteristics of a cellulose fabric during textile finishing, different pre-treatment processes such as washing, bleaching, and mercerization are applied. Pre-treatment increases the sorption ability and makes the material more accessible to chemicals used in the finishing processes. Fibers with the highest moisture sorption have the smallest contact angle. Contact angles of raw and pre-treated regenerated fibers are shown in Figure 3.7 Alkaline purification has the biggest influence on viscose fibers. In the case of lyocell and modal fibers, influence of alkaline purification is smaller in comparison with viscose fibers and no essential reduction in contact angles can be seen [5].

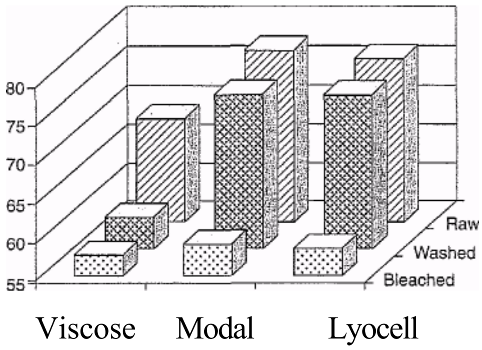


Figure 3.7: Contact angle, <p, of raw and pre-treated regenerated cellulose fibers [5]

In the case of viscose fibers, after washing, the alkaline solution of the washing agent easily penetrates into less orientated amorphous regions and breaks down the interactions between the cellulose macromolecules. The diameter of the fibers increases and the structure becomes loose leading to better accessibility of fiber interfaces to liquid. The result is a smaller contact angle, and wettability and sorptivity improvement of the viscose fibers. In comparison with viscose fibers, modal and lyocell fibers have a higher degree of crystallinity and higher molecular orientation, which means that only a small quantity of washing agent can penetrate into less-ordered amorphous regions of the fibers. This result also implies a smaller pre-treatment effect on the hydrophilic character of the fibers. The improvement of sorption characteristics due to washing in an alkaline medium can be explained by the increase of voids [5].

3.3.3.2 Yarns

Various parameters, such as yarn structure, yarn tension, twist, fiber shape, number of fibers in yarns, fiber configuration, finish, and surfactants influencing wicking of yarns affect wicking and wetting behaviors of fabrics.

Lord [5] reported that open-end yarn wicks faster and more evenly than ring yarn, but elevates about the same volume of water for a given yarn count. According to Sengupta and Murthy, for any given vertical wicking height, the wicking time of open-end spun yarn is less than that of ring-spun yarn. Microscopical examinations of yarns showed that dye had wicked to a greater height in the core of the open-end yarn than in the surrounding sheath fibers. No such differentiation was noticed with ring yarns. Open-end yarns have a relatively denser core and less dense skin when compared to ring yarns.

Chattopadhyay and Chauhan [5] studied the wicking behavior of ring and compact spun yarns (Figure 3.8). The rate of water rise was very fast at the beginning and slowed down gradually, as observed by various workers. In the first minute it was very difficult to distinguish the differences between the behaviors of different yarns. The equilibrium wicking heights observed for ring yarns were more than those of compact yarns. Ring yarns wicked faster than compact yarns. Coarser yarns wicked faster than finer ones.

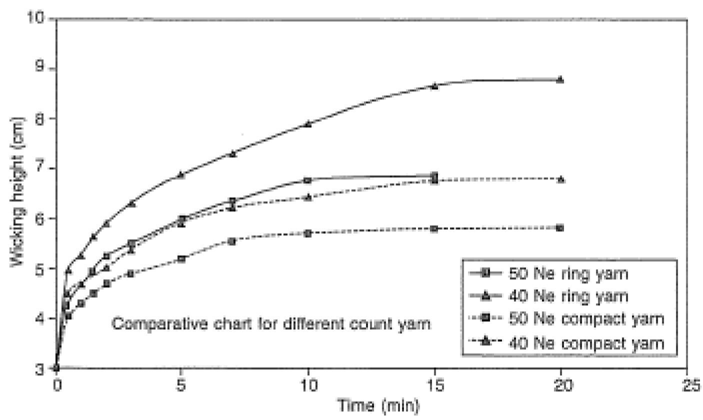


Figure 3.8: Wicking of ring and compount yarns [5]

As the packing coefficient of compact spun yarns is greater than that of corresponding ring yarns, the average capillary size would be less in compact yarns than ring yarns.

It has been stated by Staples and Shaffer [5] that smaller capillaries may create sufficient drag to slow down the rise in liquid height. According to Chattopadhyay and Chauhan there must be an optimum capillary size that will cause fastest entry of water into the yarn pores. Larger than optimum pores will also slow down entry due to low capillary pressure. Hence, both too small and too large pores are detrimental to quick wicking. The slowing down of height rise with time for any yarn can be ascribed to the gravity action of the water column within the capillary, which acts against the capillary pressure.

With open-end yarns, the highest wicking is found with a twist multiple of about 4.0, but wicking height is not found to be greatly sensitive to changes in twist multiple. Over the twist range of 4 to 12 tpi, the change of water transport rate follows the capillary transport laws fairly closely, high twist yarns exhibiting low rates. At lower twists, the decrease in transport rate is apparently due to a substantial reduction in the number and continuity of the interfiber capillaries [5].

Sengupta and Murthy [5] found that wicking was highly sensitive to the twist and structure of ring and open-end spun yarns. For the ring spun yarns, the wicking time increases steeply as the twist increases, whereas for the open-end spun yarn, the increase is gradual. The results of overnight vertical wicking (Figure 3.9) also show a similar trend, i.e. for any given twist, open-end yarn wicks more than ring-spun yarn.

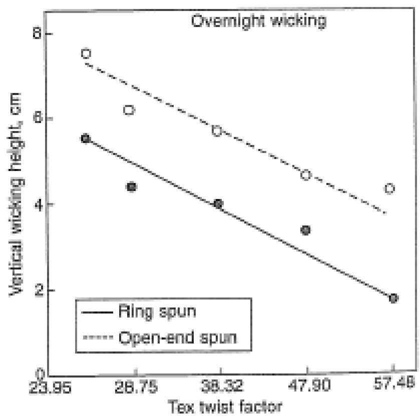


Figure 3.9: Effect of twist factor on wicking height [5]

Ansari and Kish [5] investigated the wicking behavior of polyester spun yarns produced with varying twist levels. It was observed that the wicking rate decreases with increase of twist factor from 22 to 49 $tex^{0.5}$ x turns/cm, due to reduction of capillary size. Twisted filament yarn shows a lower wicking rate than a yarn without twist. In capillary penetration of liquids, tortuosity affects wicking. Twists in the yarns influence the size of inter-fiber capillaries as a result of the helical path of the fibers in the yarns. Minor *et.al.* observed similar findings on nylon filament yarns of different twists.

Ito and Muraoka [5] reported that water transport (measured by the capacitance method) is suppressed as the number of fibers in the yarn decreases. From the results of rayon, nylon, and PET fibers, they found that, when the number of fibers is greater than ten, liquid water moves along even untwisted fibers. But when the number of fibers is less than five, wicking occurs only for twisted fibers. When the number of fibers was reduced to three, wicking did not always occur. When the number of fibers was reduced to two, there was scarcely any wicking (only once in ten times), and there was none with a single fiber. This result indicates that the mechanisms of water transport for an isolated single fiber differs from water sorption in a fiber bundle or assembled fibers where capillary spaces exist.

Hollies *et al.* [5] reported that differences in yarn surface roughness give rise to differences in wicking of yarns and fabrics made from the yarns. Wool fibers form rough yarns of high apparent contact angle because of the natural crimp and more random distribution of fibers in the yarns, whereas the yarns of synthetic fibers are compact, well aligned, and hence smooth in terms of contact angle. Increase in yarn roughness due to random arrangement of its fibers gives rise to a decrease in the rate of water transport, and this is seen to depend on two factors directly related to water transfer by a capillary process: (i) the effective advancing contact angle of water on the yarn is increased as yarn roughness is increased; (ii) the continuity of capillaries formed by the fibers of the yarn is seen to decrease as the fiber arrangement becomes more random. The measurement of water transport rates in yarns is thus seen to be a sensitive measure of the properties of fiber arrangement and yarn roughness in textile assemblies.

3.3.3.3 Fabrics

Factors such as size, shape, alignment and distribution of fibers, fiber combinations, yarn structure, fabric construction parameters, fabric position in multilayer system, desizing, scouring, bleaching, alkaline hydrolysis, enzymatic treatments, plasma, UV and ozone treatments, property of liquid, surfactants, type of finishes, use of electrolytes in disperse dyeing, and laundering of cotton are found to influence the wetting behavior of fabrics.

Hsieh *et al.*[5] reported that, in the case of fibrous structures, woven, nonwoven, or knitted fabrics, a distribution of pore sizes along any planar direction is expected. Wicking rate and liquid transported in a fabric depend on these pore sizes and their size distribution. The capillary principle dictates that smaller pores are completely filled first and are responsible for the liquid front movement. As the smaller pores are completely filled, the liquid then moves to the larger pores. The sizes and shapes of fibers as well as their alignment will influence the geometric configurations and topology of the inter fiber spaces or pores, which are channels with widely varying shape and size distribution and may or may not be interconnected. The shape of fibers in an assembly affects the size and geometry of the capillary spaces between fibers and consequently the wicking rates. The flow in capillary spaces may stop when geometric irregularities allow the meniscus to reach an edge and flatten. The distance of liquid advancement is greater in a smaller pore because of the higher capillary pressure, but the mass of liquid retained in such a pore is small. A larger amount of liquid mass can be retained in larger pores but the distance of liquid advancement is limited. Therefore, fast liquid spreading in fibrous materials is facilitated by small, uniformly distributed and interconnected pores, whereas high liquid retention can be achieved by having a large number of large pores or a high total pore volume [5].

Wicking is affected by the morphology of the fiber surface, and may be affected by the shape of the fibers as well. The common belief that fiber shape does not affect wetting is valid only for the wetting of single fibers. The shape of fibers in an assembly such as yarn or fabric affects the size and geometry of the capillary spaces between the fibers, and consequently the rate of wicking.

Comparative studies carried out by Hollies *et al.* [5] on the rate of movement of water along fabrics have shown that the penetration of the capillaries formed by the fibers in the yarns accounts for most aspects of water transport behavior. Both the amount of water carried by the fabric and the distance that it travels in unit time are influenced considerably by the randomness of the arrangement of the fibers in the yarns. The same factor seems to control the ease of wetting of the surface of the fabrics.

Ring yarn fabrics wick faster than compact yarn fabrics (Figure 3.10) Fabrics made from coarser yarns (40^s Ne) show faster wicking than those made from finer yarns (50^s Ne). Wicking behavior of fabrics follows the same order as that of yarns [5].

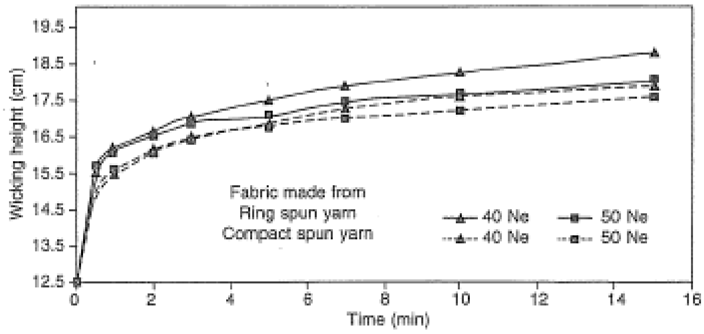


Figure 3.10: Wicking behaviour of knitted fabrics [5]

Yoon and Buckley [5] reported the vertical wicking behavior of various cotton knit fabrics. They found that wicking rate was higher in the wale direction than in the course direction. They also observed substantial variation in wicking behavior as the fiber composition varied in polyester/cotton fabric samples. 100% cotton and 50/50 blend fabrics showed a very rapid wicking behavior but the wicking rate sharply dropped as the polyester content increased. For 100% polyester fabric, they did not observe any amount of wicking within the time-scale of the experiment. The liquid transport properties of a fabric as a whole are essentially determined by the energetics between the fiber surface and the liquid. Bulk properties of the fiber material, such as regain, do not have any significant influence on the liquid transport properties.

Zhuang [9] investigated liquid transfer from fabric layer to layer and liquid interaction between different fabrics in clothing systems. A higher external pressure leads to an early onset of transfer wicking. There exists an optimum value of external pressure for the maximum water transfer. The greater the water content initially held in wet fabric, the greater the amount of water transfered. For fleece fabrics, no significant transfer wicking occurs if the raised side of the dry layer contacts either side of a wet fleece fabric layer. If the smooth side of the dry layer contacts either side of the wet fleece fabric layer, the amount of water transferred from layer to layer is greater when the fabric setting is face to face rather than face to back. No significant transfer wicking occurs for either back to back or back to face fabric settings, as shown in Figures 3.11 c and d. No transfer wicking occured when the raised side of the dry fabric contacted either side of the wet layer. This is because the capillary size at the raised side of the dry fabric was too large to activate liquid transfer.

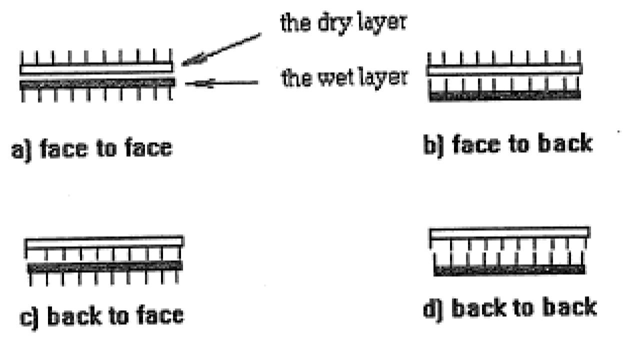


Figure 3.11: Different ways that two layers contact each other [9]

An investigation of liquid interaction within clothing systems shows that the amount of liquid transferred largelly depends on the performance of individual fabrics as well as the way in which they contact each other.For all clothing systems, liquid transferred from the wet layer to the clothing systems rapidly within the first couple of minutes followed by gradual transfer [9].

The property of the first fabric layer plays an important part in transfer wicking of each clothing system. When the Aquator fabric and polyester eyelet knit are the first layer in the clothing system, the amount of liquid transferred into the system with Aquator as the first layer is greater than that with the polyester eyelet knit. This is because Aquator is an integrated double-sided fabric with a conductive inside and an absorbent outside. The conductive side, .which is made of hydrophobic synthetic fibers, takes up liquid from the body and wicks it to the absorbent side, which is made of hydrophilic fibers. When liquid has been transferred to the Aquator, the water is mainly distributed on the surface of the first layer, which intimately contacts the second layer in the system, as shown in Figure 12.1. Due to water gathering on the surface, which increases water concentration in that area, liquid can be easily transferred to the second layer. This can decrease the amount of water remaining in the first layer, resulting in more liquid transfer from the wet layer to the clothing system [9].

For the polyester eyelet knit, however, liquid distribution is much more even, as shown in Figure 3.12 Further liquid transfer from the wet layer to the clothing system occurs only when the first layer contains enough liquid to trigger a water transfer from the first layer to the second layer, or liquid in the first layer can be quickly evaporated [9].

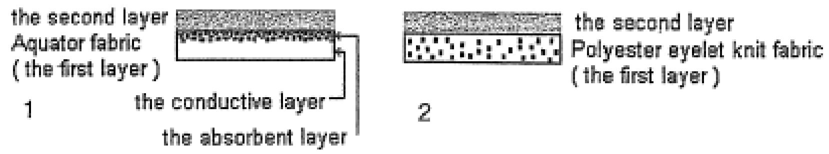


Figure 3.12: An illustration of water distribution in the first layer fabric [9]

Crow and Osczevski [9] reported that the amount of water that wicked from one layer to another depended on the pore sizes and their corresponding volumes.

The moisture transport process in clothing under humidity transience is one of the most important factors influencing the dynamic comfort of a wearer in practical wear situations. Yi [5] studied the moisture diffusion into hygroscopic fabric process by measuring the moisture take-up and temperature changes of fabrics made from wool, cotton, porous acrylic, and polypropylene under humidity transience. The mechanisms of the coupling effect between moisture diffusion and heat transfer depend on a number of properties which are functions of water content, including moisture sorption capacity, diameter, water vapor diffusion coefficient, density, and heat of sorption.

3.4 Thermal comfort

Physiologically, a human being is regarded as feeling comfortable when his skin temperature is between 33 and 35 ^{0}C and there is no deposition of liquid sweat on the skin. Clothing will alter the balance between the rate of heat production and rate of heat disposal by creating microclimate in the layer of air entrapped next to the skin. Whether or not the clothing can then be described as comfortable will depend on the activity of the wearer and the range of ambitient conditions to be encountered [3].

The thermal comfort of man depends on combinations of clothing, climate and physical activity.

Yaglou and Miller [2] defined 'effective temperature' as an index of warmth perception when a human body is exposed to various temperatures, humidity and air movements.

According to Gagge [2], when exposed steady cold and warm environments, thermal comfort and neutral temperature sensations lay between 28-30 ^{0}C when no physiological temperature regulatory effort was needed. Discomfort perceptions were related to lowering average skin temperature toward cold environments and increased sweating towards hot environments.

Hensel, Carterete and Friedman [2] pointed out the physiological basis of thermal comfort and the difference between thermal comfort and temperature sensations. Temperature sensations are mainly derived from cutaneous thermoreceptors, which are used to judge the thermal state of objects or the environment. Thermal comfort and discomfort reflect a general state of the thermoregulatory system, which is the integration of afferent signals from both cutaneous and internal thermoreceptors. Therefore, the measurements of temperature sensations and of thermal comfort need to be distinguished. McNall used two separate scales to study thermal sensations and thermal comfort in Table 3.3.

Table 3.3: Relationship between thermal sensations and thermal comfort [2]

Thermal sensations		Thermal comfort
1.	very cold	1. uncomfortably cold
2.	cold	2. colder than comfortable
3.	cool	3. much cooler than comfortable
4.	slightly cool	4. slightly cooler than comfortable
5.	neutral	5. comfortable
6.	slightly warm	6. slightly warmer than comfortable
7.	warm	7. much warmer than comfortable
8.	hot	8. hotter than comfortable
9.	very hot	9. uncomfortably hot

Fanger [6] identifies six variables, which influence the condition of thermal comfort. These variables are:

- Air temperature,
- Mean radiant temperature,
- Relative air velocity,
- Water vapor pressure in the ambient air,
- Activity level (heat production),
- Thermal resistance of clothing (clo).

Fanger [7] described the energy balance between man and environment in per unit body surface area as follows:

$$S=M-W_k-H_d-H_e-E_r \quad (W/m^2) \tag{3.31}$$

where S is the rate of body heat storage (under thermal equilibrium, $S=0$); M is the metabolic rate, i.e. internal heat production of the body; W/t is the external work; H_d is dry heat loss from the skin induced by conduction, convection and radiation. H_e is evaporative heat loss from the skin; E_r is the sum of the latent and sensible respiration heat loss.
For a clothed person, H_d and H_e may be determined by:

$$H_d = A_s \frac{(T_S - T_A)}{I_t} \tag{3.32}$$

$$H_e = A_s \frac{(P_S - P_A)}{R_t} \tag{3.33}$$

where, (T_s-T_a) and (P_s-P_a) are the temperature difference and difference of water vapor pressure between the skin and environment, respectively; I_t and R_t are total thermal insulation and total water vapor resistance of the clothing system, respectively.

The combined equations 3.31, 3.32 and 3.33 are used to determine the heat stress of a clothed man in terms of the required evaporation for thermal equilibrium, required sweat rate, and skin wetted-ness (ISO7933, Parsons 1995). They were used to determine the cold stress in terms of the required insulation for thermal comfort and evaluate the functional design and suitability of clothing systems

The successful application of equations 3.31, 3.32 and 3.33, however, very much depends on how accurately I_t and R_t can be determined, which is not a simple task. The total thermal insulation *I,* and vapor resistance R_t of a clothing system are the complex integration of the thermal insulation and vapor resistance of constituent garments and trapped air layers. l_t and R_t are also not constants. They vary depending on the way the garments are worn, body posture, body movement, and environmental conditions such as wind, rain and radiant heat.

Total thermal resistance of a clothed body to heat transfer from the body to surrounding air was considered to be the sum of the three properties:

- Thermal resistance of textile,
- Thermal resistance to heat transfer at the textile surface,
- Thermal resistance of the air interlayer. [2]

Many factors contribute to the thermal properties of textiles, some of which are listed below.

1. Thermal conductivity of the fiber substance and of the air contained within the fabric.
2. Specific heat of the fiber substance.
3. Thickness of the fabric.
4. Bulk density of the fabric (which should include consideration of the number, size and distribution of the air spaces within the fabric).
5. Surface of the fabric as affected by:

a. Type of fiber used

b. Construction of the fabric

c. Finishing treatment of fabric (raising, milling…)

6. Area of fiber used.
7. Heat loss by conduction from skin to fabric.
8. Heat loss by convection from skin through the fabric and from the fabric surface.
9. Heat loss by radiation (emissivity of the surfaces of skin and fabric).
10. Heat loss by evaporation of water from skin or fabric.
11. Heat gain due to water absorption by fabric.

12. External atmospheric conditions: temperature, relative humidity and movement of surrounding air [3].

Thickness plays a very important part in determining the functional value of clothing materials in connection with their ‘warmth’, that is, the amount of heat insulation they provide, and their ability to allow the body to dissipate its insensible perspiration and sweat.

Thermal insulation depends uniquely on the fabric thickness. Hence, the warmest fiber is the one that produces the thickness fabric. Furthermore, the warmth of fabric is governed by the entrapped air; the thicker the fabric, the greater is the amount of entrapped air and provided that the surrounding air is stagnant, the greater is the thermal resistance of the fabric. However, thickness increases the resistance to the transfer of heat and moisture because of the large additional air volume present rather than the increased fiber content [3].

Hatch et al. [12, 13, 14,15] made a research which were used the jersey knit fabrics, one knit was made from a 1.5 dpf polyester fiber, 3.5 dpf polyester fiber and % 100 combed cotton. According to results fabric structural features are the most important controllers not componenet fibers of thermal dissipation in the presence oıf moisture diffusion. The results also show that heat transfer is highly related to fabric thickness, bulk density and air volume fraction. Thermal transfer from a simulated sweating skin surface is strongly correlated with fabric porosity and air permeability. There are no significant differences between the three experimental fabrics in terms of alternation in capillary blood flow, stratum corneum water content, skin evaporative water loss or skin temperature when the fabrics were worn by exercising subjects in a hot humid environment. The polyester knit produced with the higher denier component is predicted to generate a warmer feeling because of the relative density of the fabric structure and the coarseness of the fibers. The cotton knit is predicted to have the coolest touch, probably because of its high thermal conductivity (high moisture regain increases thermal conductivity) and denser fabric structure. The polyester knit made with finer fiber has an intermediate q_{max} value.

According to Rees [3], for a fiber thickness of 1 mm, there is a thermal retention of about 30%. This is said to be probably due to the breaking up of the convection currents that are responsible to a large extent for the loss of heat from a body in air.

The ratio of the thermal resistance to thickness gives a measure of the ‘intrinsic value’ of a material as a thermal insulator according to Rees and the higher this value, the more efficient the material is as an insulator relative to its bulk.

If a still-air condition is assumed, the heat flow by radiation through an air layer does not depend on its thickness. However, the heat flow by conduction decreases with increasing thickness. The heat conduction through a textile is controlled both by the thermal conductivity of the air and that of the fibers and by the thickness of the layer [3].

Korlinsky [3] investigates the effects of the knitted construction, fabric thickness, mass per unit area, number of wales or courses per unit le the length and apparent fabric density on the thermal-insulation properties of knitted goods under free-convection conditions. He finds that fabric thickness has a decisive effect on the thermal-insulation properties but also shows that changes in the heat-transfer coefficients selected for his measurements can affect the result in some cases, so that other relationships can not be confirmed unequivocally.

Clulow [3] states that the factors that determine the warmth of a fabric are its thickness, its construction and its bulk density (the mass of fibers in a given volume). The thicker a fabric of a given construction, the greater is its heat-insulation value. In general, the greater its bulk of density for a given thickness, the less is its warmth owing to the replacement of air by fibers having a greater heat conductivity. However, if the bulk density is very low, or if the fabric for this construction is sufficiently open, radiant heat from the skin can pass through the garment and reduce its warmth.

The minor but significant influence of fiber conductivity and packing factor on the thermal resistance of fabrics has been demonstrated by Holcombe and Hoschke [3]. This is illustrated by Figure 3.13, which is a graph of the thermal resistance of a number of different underwear fabrics plotted against thickness. Holcombe and his friends state that thermal resistance is determined largely by constructional factors primarily thickness, rather than fiber type.

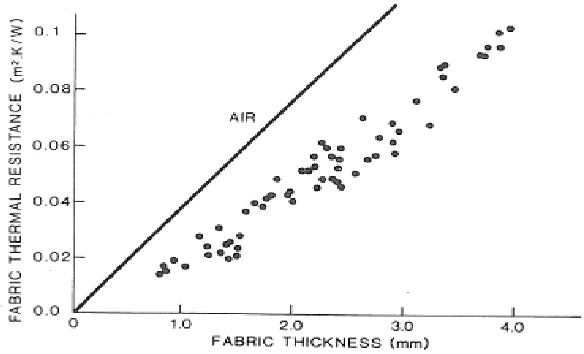


Figure 3.13: The influence of thickness on the thermal resistance of underwear fabrics [3]

Another important factor is weight. The ‘warmth –to weight factor’ of a material is defined as the ratio of its thermal resistance in togs to its mass in g cm^{-2}. A high value for this factor is obviously desirable for the provision of ‘lightweight warmth’. Thus, on the basis of equal thickness, the fabric with the most open construction is the least warm, but reverse is the case on the basis of equal weight. Hence, fabrics of cellular construction are eminently suitable for providing lightweight warmth if used under conditions where moving air is prevented from penetrating the structure [3].

Since water has a thermal conductivity 25 times as great as that of air, water entering the structure of garments causes a significant drop in insulation. The influence of water content on the thermal conductivity of some knitted materials an the performance of different materials is found to depend on their capacity to absorb moisture into the fiber structure. The influence of regain on apparent thermal conductivity is illustrated in Figure 3.14 for four different knitted interlock fabrics. As the graph shows, wool retains low conductivity up to regains of about 15%, whereas polypropylene fiber, a non-absorbent fiber, undergoes an immediate increase in conductivity even with a very small amount of added water. This is one of the reasons why wool garments are favoured for outdoor sports such as sailing and busy-walking, where exposure to spray or rain is possibility [3].

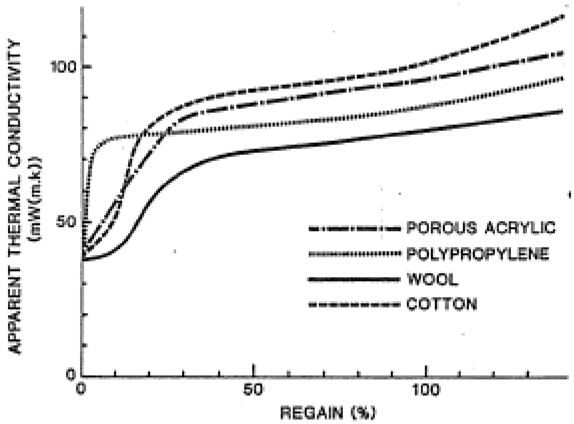


Figure 3.14: The influence of moisture content on the apparent thermal conductivity of some knitted fabrics [3]

Chen and Fan [9] tested clothing thermal insulation on a novel fabric thermal manikin covered with lightly and highly breathable skins to stimulate low and heavy perspiration. The study reveals that clothing thermal insulation during heavy perspiration is significantly less than that with low perspiration. The differences vary from 2-8 %, related to the increased moisture accumulation within clothing.

A buffering index against water vapor, is the ability of the fabric to transport water vapor sweated from the body yet not condensed on to the skin. The higher K_d value, the higher the moisture transport rate through the fabric and garment opening and therefore the better the fabric and garment opening from a thermophysiological point of view. Yoo, Hu and Kim [17] developed a vertical skin model and they tested the effect of fiber type, air layer thickness and garment openness on heat and moisture transport. The results show that the fiber type with desirable comfort affects differs according to sweating time; cotton is desirable in the initial period but polyester is more so after the initial period. On the whole, however, polyester has a higher K_d than cotton. As the thickness of the air layer increases, the vapor transport rate increases but unnecessarily large air gaps do not significantly increase wearer comfort. Garment opening has a greater influence on the microclimate than fabric does. As openness is introduced to the system, the vapor pressure lowers, decreasing faster to give a much higher K_d, and the differences among specimens gradually decrease, losing their effect at 60% openness.

Vigo, Hassenboehler and Wyatt [3] noted that:

a) Room relative humidity has little or no effect on the thermal transmittance of materials with or without moisture transport over a wide range of thickness;

b) Changes in room temperature have a negligible effect on the thermal transmittance of these materials in the dry state and a moderate effect under conditions of moisture transport;
c) Major differences observed in the thermal transmittance of these materials are dependent on their thickness and moisture-transport state;
d) No correlation exists between the air permeability or weight of the materials and their moisture transport is also observed to exert a much greater influence on thermal transmittance than the relative-humidity ranges investigated.

According to Yoon and Buckley [3], thermal insulation (or resistance) is primarily determined by fabric structure, especially thickness and porosity. This property shows relatively small but distinct dependence on the blend level. The chemical or physical nature of the fibre materials has little influence on thermal insulation. However, when compared with the cotton fabric, the polyester –fibre fabric is inferior in its thermal resistance. The thermal resistance of polyester fibre may be improved by lowering the packing factor of fibres in the yarn without having to change the chemical nature of polyester.

According to Qiu's skin model, the heat power through the sample is determined by the thermal conductivity of the sample. The greater the thermal resistance, the less heat energy is transferred through the fabrics. It is concluded that the warmth-retention property of fabrics depends on their thermal resistance.

Wind is a factor that modifies the thermal insulation value and hence the warmth of clothing fabrics. Stuart and Denby [3] state that the extent of the water vapor mass and heat transfer depend on the size of the air flow generated by the wind-induced pressure differences. Given the air-pressure differences, the extent of the air flow will depend on the air permeability of the fabric. Highly air-impermeable or windproof fabrics will allow very little air flow and hence wind will have little effect on their water vapor permeability and their thermal resistance. At the other extreme, highly air-permeable fabrics, such as knitted fabrics, will have water vapor permeability and heat insulation very dependent on wind-induced air flow, and calculations show that wind-induced permeabilities predominate over diffusion processes in such fabrics at wind speeds of several meters per second [3].

The wind affects the thermal and vapor resistances of the air adjacent to the fabric and also both resistances of the fabric itself in that it causes a movement of air inside the fabric.

There was a reduction in the thermal resistance of the pile fabric resulting from a loss in thickness due to the compressional effect of the wind pressure. When covered with an impermeable fabric in a 30 mile h^{-1} wind, there was a loss of 18% in the thermal resistance of the pile fabric. It was found that at low speeds of up to 5 mile h^{-1}, there was little effect on the thermal resistance of the pile fabric arising from vibrations in the air permeability of the cover fabric.

The insulation properties of a porous medium depend to a large extent on the fluid that fills the cell spaces. For fabrics, this is air, which has a very low thermal conductivity and is therefore a good insulator. If it were possible to fill the voids with a gas that had a lower conductivity than air, the insulation of the fabrics would be improved. On the other hand, if the voids were filled with water, which has a high thermal conductivity, the insulation of the material would be reduced. It is further shown that a thin free-air space can provide a degree of insulation by reducing convective heat loss. Filling the spaces with fibers further reduces convective loss and increases the insulating value of the space. Burton notes that, starting with a very low fiber density, the insulating properties of the air space increase with increasing density to a maximum (4 Ib ft^{-3}), after which increasing density leads to a fall in the thermal resistance [3].

Narrow air gaps between layers of clothing can add appreciably to warmth and provided that the clothing is not too tight, there will be an air gap between successive layers. It is therefore good for warmth to wear several thin layers of clothing rather than one thick one. If the clothing is very loose, however, heat will be lost by movement of the air when one walks about. In order to maintain the warmth of underwear when worn outdoors, the outer clothing must form an efficient wind barrier [3].

Air movement typically reduces the still air boundary layer above the fabric surface so that thermal and moisture resistance decreases with the air velocity of the environment surrounding clothing.

Filling materials usually have a lower bulk density than this optimum value of 0.035 g cm^{-3}; they will therefore tend to have a higher thermal resistivity if the bulk density is increased; woven and knitted fabrics, on the other hand, are too dense, that is, the lower bulk density, the higher will be the thermal resistance for a given thickness [3].

Radiant-heat transfer in fiber beds depends on fiber diameter. For a given packing fraction, the finer the fiber, the lower is the heat transfer by radiation. According to the Figure 3.15; reducing the density of a material to achieve imporved warmth without weight can be compromised if the density is reduced too far. Further, as the density of the material is reduced, good insulating properties can only be maintained if fine fibers are used.

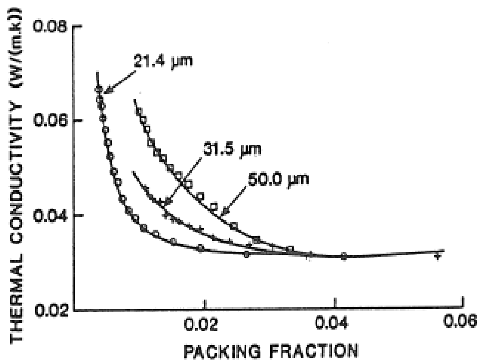


Figure 3.15: The influence of fiber diameter on the apparent thermal conductivity of low-density wool batt [3]

In addition, textile fibers are largely opaque to radiant heat, whereas air is transparent to it. It follows that the more densely the fibers are arranged in a fabric, the lower will be the convection and radiation, but the structure must not be so dense that the fibers themselves conduct too much heat. It is not surprising that textiles have a conductivity much closer to the value of still air in the absence of radiation than that of the constituent fibers [3].

The radiated heat flux through the bed has four components, flux from yarn to yarn, from hot plate to yarn, from yarn to cold plate and between plates. The total radiant-heat flux is not constant across a fabric but is a function of position. This conductive-heat flux also varies across a fabric, since the sum of the two must remain constant. Radiant heat flux from yarn to yarn is equal to zero at the surface. It increases with the distance into the fabric and reaches a maximum in the centre of the cross section. It is the dominant mode of radiant-heat transfer between yarns and surface and is greatest close to the surface. The radiant heat flux directly between the hot and cold surfaces is constant throughout the fabrics [3].

Lau et.al. [16] made a study with 100 % cotton jersey garment. Samples were made of two fabrics with different treatments on the left and right sides of the body. Wearers were then asked to compare the left and right sides of the body in terms of comfort. The difference in discomfort sensations between the wrinkle-free treated fabrics on the right bodice and untreated fabrics on the left is small. Also no differences in discomfort sensations for the two parts of the bodice made of fabrics with different wrinkle treatments.

3.4.1 Dynamic Thermal Interaction Between The Body and Clothing

David, studied about the thermal insulation of wool clothing under transient conditions and reported that the insulation could increase 50% to 70% above due to moisture sorption by the wool. In 1989, Stuart et al. examined the heat released by dried wool garments being exposed to a low-temperature and high humidity environment. They conducted wearer trials demonstrating that human subjects can perceive the heat of sorption of water vapor by wool garments in winter conditions. The authors found that heat of sorption causes wearer to rate wool garments as warmer under certain conditions than materials with little or no heat of sorption, such as acrylic. In other words, heat of sorption is the principal source of perceived warmth, and that fabric construction has a minimal effect. They reported that sufficient sorption heat is released during the transients for subjects to perceive the heat as an increase in warmth [6].

De Dear et al. [6] studied the impact of step changes of air humidity on thermal comfort by using a thermal manikin and human subjects. They found that 37-42% of the heat involved during absorption or desorption of moisture by wool garments resulting from the humidity change influenced the sensible heat balance of the wearer by using manikin. They also reported that they observed significant changes in skin temperature, especially when wool garments were worn..

Shitzer et al. [6] investigated the heat and mass transfer of the clothing-air-skin system. In their study, they considered the heat and mass transfer in the system as a steady-state problem in one-dimensional model composed of five layers, which are ambient air, fabric, airspace, skin and the body core. Their study gives a good progress in the simultaneous heat and mass transport through the skin-fabric system. Their model assumed constant physical properties, temperature-dependent skin thermal conductivity for the body and no energy penetration to the body core. For the fabric, they considered the fibers as always in equilibrium with the adjacent air.

Jones et al. [6] developed a model for the transient response of clothing systems that took account of the sorption behavior of fibers. They assumed that the fibers are always in equilibrium with the surrounding air. The authors compared the prediction of heat loss by the model with experimental data from the thermal manikin tests and found a good agreement. Then they combined their model with Gagge's two-node model to search the interactions between the body and clothing, but did not report data to confirm the validity of this combined model.

Li and Holcombe [6] developed a mathematical model to describe heat and moisture transport behavior of clothing and its interaction with the human thermoregulation system under transient wear conditions. The model they developed takes into account the dynamic sorption behavior of clothing material and the thermoregulation mechanisms of the human body. They used a modification of Gagge's two-node model to simulate human physiological regulatory responses. In clothing, heat and moisture transport is coupled with the sorption or desorption of water vapor in the fibers and the associated energy changes. When the physical activity and ambient conditions are specified, the model they developed can predict the thermoregulatory responses of the body and the temperature and moisture profiles of the clothing. They reported that predictions of skin and fabric temperature and microclimate humidity agree with the experimental results measured for garments made from wool and polyester fibers.

3.4.2 Moisture Exchange Between Fiber and Air

3.4.2.1 The Drying Behavior of Fabrics

The moisture exchange between a fiber and its adjacent air is a complex process, depending on whether the moisture is present as liquid on the fiber surface, as vapor stored internally. This is best illustrated from the drying behavior of fabrics [2].

Lyons and Vollers [2] found that drying process of textile materials has three distinct stages. In the first stage, a wet fabric adjusts its temperature and moisture flows with its surrounding environment. The second stage is a 'constant drying rate' period, in which the drying rate remains constant as the rates of heat transfer and vaporization reach equilibrium. Liquid moisture moves within the fabric to maintain a saturation condition at the surface. The third stage is a 'declined drying rate', during which moisture flow to the surface is insufficient to maintain saturation and plane of evaporation moves into the fabric. Fibers begin to desorb moisture until equilibrium is reached between the fabric and the environment.

When the fiber content is above the fiber saturation moisture content, the drying rates of both fabrics are constant and approximately the same, because the drying process is determined by a surface evaporation process. When fabric water content decreases to below the saturation moisture content, the drying rate declines as liquid water at the fiber surface has evaporated and the water absorbed within the fibers is released. This drying process continues until equilibrium with the ambient conditions is reached [2].

When the fabrics' water content is above their saturation regain, the temperatures of both fabrics are approximately the same and below the ambient temperature, because the dominant process is evaporation of free water. As their water contents approach their equilibrium regain, their temperatures begin to rise until all excess moisture has evaporated and equilibrium is achieved with the surroundings [2].

The liquid transport in a fabric influences the mass transfer but does not involve energy exchange. However, it determines the dynamic distribution of liquid in the fabric, which in turn determines the front of water evaporation. Experimental investigations have show that the liquid transfer has significant impact on the heat transport processes in clothing, and on its thermal comfort and tactile comfort performances.

3.4.2.2 Evaporation and Condensation

Crank described the evaporation-condensation process mathematically in equation 5.34. This equation applies when fabric water content is above the saturation regain of the fiber,; that is, liquid water is present in capillaries within the fabric structure or at the fiber surface. The exchange of water is an evaporation-condensation process.

$$\frac{\partial C_f}{\partial t} = h_{cf} S_v (C_{fs} - C_a) \quad \textbf{(3.34)}$$

where C_{fs} is the water concentration in the fiber surface (kg m^{-3}); C_a is the water concentration in the adjacent air (kg m^{-3}); h_{cf} is the mass transfer coefficient at the fiber surface (ms^{-1}); S_v is the specific volume of the fabric (m^{-3}) [2].

3.4.2.3 Moisture Sorption and Desoption

When the fabric water content is below the saturation regain of the fiber, the exchange of water can be considered as a sorption or desorption process. David and Nordon developed an experimental relationship between the rate of change of water content of the fibers and the absolute difference between the relative humidity of the air and fiber. The rate equation was given as:

$$\frac{1}{\varepsilon}\frac{\partial C_f}{\partial t} = (H_a - H_f)x \quad \textbf{(3.35)}$$

where

$$x = k_1(1 - \exp[k_2 \,|\, H_a - H_f \,|\,]) \quad \textbf{(3.36)}$$

k_1 and k_2 are parameters that are adjustable according to experimental results.
Also they developed a solution of the equations by the finite difference methods, which provided space-time relationships for moisture concentration and temperature within the air-fiber mass. The authors stated that the model did not consider the sorption-desorption kinetics of the fibers, and that proper boundary conditions need to be specified in evaluating the coupled heat and moisture transfer processes in the clothing during the wear.

3.4.2.4 Boundary Conditions

The initial condition is determined by the history of the thermal and moisture environment of the fabric. For instance, when a fabric is equilibrated in a given environment, the moisture content and temperature can be regarded as uniform throughout the fabric at known values:

$$T(x,0) = T_0 \quad \textbf{(3.37)}$$

$$C_a\,(x,0)= C_{a0} \quad \textbf{(3.38)}$$

$$C_f\,(x,0)=f(H_{a0},\, T_0) \quad \textbf{(3.39)}$$

David and Nordon studied the situation where the fabric boundaries are exposed to an air stream of new moisture content C_{ab} and temperature T_b. By assuming the rate of moisture diffusion and heating are sufficiently rapid that the bulk moisture content and the temperature of the air stream are equal to those at the surface of the fabric, they specified the pertinent boundary conditions as:

$$T(0,t)= T(L,t) =T_b \quad \textbf{(3.40)}$$

$$C_a\,(0,t)= C_a\,(L,t)=C_{ab} \quad \textbf{(3.41)}$$

Those boundary conditions can not be achieved in practice because a boundary layer of air exists and limits the transfer of heat and moisture between the fabric and the air stream [2].

Li and Holcombe used a set of equations to describe this layer of air, which takes account the convective nature of the boundary conditions:

$$D_a \frac{\partial C_a}{\partial t}|_{x=o} = h_c(C_a - C_{ab}) \quad \textbf{(3.42)}$$

$$D_a \frac{\partial C_a}{\partial t}|_{x=o} = -h_c(C_a - C_{ab}) \quad \textbf{(3.43)}$$

3.4.2.5 Moisture Diffusion Into The Fiber

Moisture is considered diffusing radially into a cylindrical medium (fiber) with a constant diffusion coefficient (D_f) and at the fiber surface the moisture content is in equilibrium with the moisture content of the adjacent air.

Initially, the moisture content is uniform and the boundary condition at the center of the fiber is one of symmetry:

$$C_f(x, r, 0) = C_0 \tag{3.44}$$

and

$$\frac{\partial C_f}{\partial t}\Big|_{r=o} = 0 \tag{3.45}$$

The moisture content at the fiber surface (r=R) is equilibrium with the moisture content of the adjacent air, so that:

$$C_f\,(x, R_f, 0) = f(C_a(x,t)) = \Phi(x,t) \tag{3.46}$$

where f is the moisture sorption isotherm of the fiber.

4. MATERIALS AND METHOD

The details regarding the fiber types as well as knitting variables employed for the samples are given in Table 4.1.

Unlike ordinary socks, nylon and lycra was not utilized in the production of the socks for the work in an attempt to investigate the effect of fiber type on comfort properties of samples. In addition to that, all sock samples were dyed and finished under the same predefined conditions.

Table 4.1: Material properties and coding of samples

TYPE	COUNT	CODE	DENSITY
% 100Cotton	Ne 30/1	11	SLACK
		12	MEDIUM
		13	TIGHT
% 100Modal	Ne 30/1	21	SLACK
		22	MEDIUM
		23	TIGHT
% 100Viscon	Ne 30/1	31	SLACK
		32	MEDIUM
		33	TIGHT
% 100MicroModal	Ne 30/1	41	SLACK
		42	MEDIUM
		43	TIGHT
% 100Bamboo	Ne 30/1	51	SLACK
		52	MEDIUM
		53	TIGHT
% 100Chetosan	Ne 30/1	91	SLACK
		92	MEDIUM
% 100Soybean	Ne 30/1	101	SLACK
		102	MEDIUM
		103	TIGHT

From Table 4.2, weight, thickness and stitch density of fabrics can be seen

Table 4.2: Physical properties of fabrics

CODE	WEIGHT (g/m^2)	CV(%)	THICKNESS (mm)	STITCH DENSTIY ($/cm^2$)	CV(%)
11	195,63	2,202	0,9252	95,35	6,16
12	204,67	3,237	0,8876	109,51	9,06
13	199,38	3,853	0,9460	114,35	10,79
21	182,17	4,230	0,7496	98,14	11,84
22	185,48	4,364	0,7198	101,00	12,22
23	190,99	2,891	0,7428	107,59	8,10
31	196,73	3,995	0,9002	99,31	11,19
32	208,64	5,255	0,8736	107,73	14,72
33	200,70	5,236	0,8558	111,81	14,66
41	168,06	3,339	0,6948	98,58	9,35
42	187,69	5,033	0,7010	103,01	14,09
43	182,83	4,471	0,6872	102,92	12,52
51	195,85	2,993	0,7240	114,32	8,38
52	240,62	3,046	0,7488	115,00	8,53
53	193,46	3,485	0,7364	109,84	9,76
91	179,53	1,936	0,8140	102,21	5,42
92	179,37	2,655	0,8512	107,47	7,43
101	160,34	4,726	0,7724	92,69	13,23
102	167,84	3,493	0,7416	104,54	9,78
103	163,21	3,508	0,7528	108,52	9,82

4.1 Material

4.1.1 Cotton

Cotton is a natural cellulosic fiber and has a lot of characteristics, such as;

- Good conductor of heat. In other words, it draws heat away from your skin to keep you cool, making it comfortable to wear.
- Absorbs and releases perspiration quickly, thus allowing the fabric to "breathe" so it is cool to wear.
- 10 to 20 percent stronger when wet than when dry. Tenacity is 27 to 44 cN/tex
- Has low elongation and elastic recovery.

- Its good absorbency makes comfortable in hot weather and suitable for materials where absorbency is important. It is relatively slow to dry because the absorbed moisture must be evaporated from the fiber [53,54].

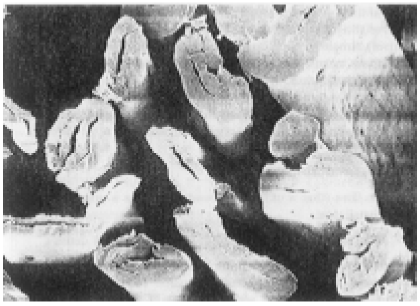


Figure 4.1: Cross sections of cotton fibers

4.1.2 Viscose

Viscose**,** from cellulose, has many of the qualities of cotton, a natural cellulose fiber. Viscose is extremely absorbent, comes in a variety of qualities and weights, and can be made to resemble natural fabrics. Viscose drapes well, has a soft, silky hand, and has a smooth, napped, or bulky surface. Viscose wrinkles easily and may stretch when wet and shrink when washed [54]. Strength is reduced in wet conditions, so that heavy duty end uses would not be expected. It is a limp handling fiber because its polymer system is so very amorphous [56]. Viscose fibers stretch and, having low elastic recovery, tend to remain stretched. The elastic recovery of viscose is low, as it is its resillance [55].

Table 4.3: Physical properties of viscose fiber

	Regular	High Wet Modulus
Dry tensile strength (cN/tex)	18	22,5-45
Wet tensile strength (cN/tex)	9	27
Breaking elongation (%)	8-14	9-18

4.1.3 Modal

Modal is a bio-based fiber made by spinning reconstituted cellulose from beech trees. It is about 50% more hygroscopic, or water-absorbent, per unit volume than cotton is.

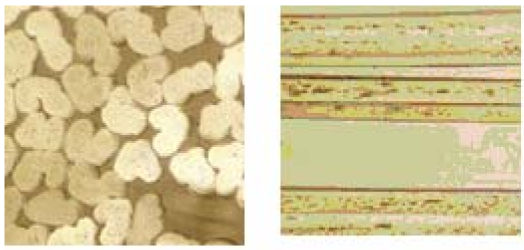
It is designed to dye just like cotton, and is color-fast when washed in warm water. Modal is essentially a variety of rayon.

Textiles made from modal do not fibrillate, or pill and are resistant to shrinkage and fading [53]. Also they have,

- Low fiber stiffness
- Smooth fiber surface
- Natural softening agent
- Highest color brilliance [57]

Table 4.4: Physical properties of modal fiber

Dry tensile strength (cN/tex)	35
Wet tensile strength (cN/tex)	20
Dry elongation at break (%)	13



A B

Figure 4.2: A- Cross section of modal fiber B- Longitudinal view of modal fiber

4.1.4 Micro-Modal

Micro Modal® is the softest fiber made by Lenzing. Fabrics of MicroModal® are feather-light and natural skin huggers. The natural starting material for MicroModal® is beech wood from sustainably managed forests. This natural raw material guarantees ideal wear properties since the fiber is gentle to the skin. Products of this micro quality are persuasive in both their handle and fineness [57].

Figure 4.3: Longitudinal view of micro modal fiber

4.1.5 Bamboo

Bamboo fiber has particular and natural functions of anti-bacteria and deodorization. Even after fifty times of washing, bamboo fiber fabric still possesses excellent function of anti-bacteria. Its test result shows over 70% death rate after bacteria being incubated on bamboo fiber fabric.

Bamboo nature anti- UV character (different from the man-made additive) is quite high.

The cross-section of the bamboo fiber and bamboo yarn is filled with various micro-gaps and micro-holes. With this unparalleled micro-structure, bamboo fiber and bamboo yarn can absorb and evaporate sweat in a split-second [58].

Table 4.5: Physical properties of bamboo fiber

Dry tensile strength (cN/tex)	23,3
Wet tensile strength (cN/tex)	13,7
Dry elongation at break (%)	23,09
Moisture regain (%)	13,03

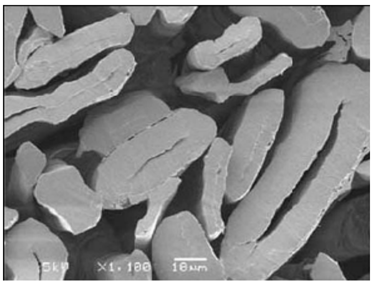


Figure 4.4: Cross sections of bamboo fibers

4.1.6 Chitosan

Chitosan is a product derived from chitin, a compound of natural origin obtained from the shell of crab and shell fish.

The chitosan‘s structure is very similar to cellulose. It keeps skin from drying because its moisture keeping property is excellent.

The antibacterial and antimicrobic performance is given with the inhibition of the bacteria’s growth, so having an anti smell function too. The high level of comfort, the anallergicity and the high humidity absorption give to the clothes realized with this fiber the capability to be used to direct skin contact, as in underwear, socks and so on.

It is totaly biodegradable [59, 60].

4.1.7 Soybean

Soybean fiber is the only renewable botanic protein fiber. It has good affinity to human body’s skin and posses 18 kinds of amino acid, which render the fiber a health protection effect.

Knitting fabrics from soybean protein fiber have soft, smooth and light handle. Its moisture absorption capacity and transmission are excellent which make it comfortable and sanitary. It has outstanding anti-crease, easy wash and fast dry property.

The moisture absorption of bean fiber is similar to cotton fiber, but its ventilation is more superior to of cotton [60].

Table 4.6: Physical properties of soybean fiber

Strength, dry	cN/tex	38-40
Strenght, wet	cN/tex	25-30
Elongation at break (%)	%	18-21
Moisture regain	%	8.6

Figure 4.5: Cross section of soybean fiber

4.2 Method

After the sock samples had been produced, they were conditioned under the standard atmospheric conditions for one week. Then the following properties were tested in accordance with relevant standards.

4.2.1 Comfort Properties

4.2.1.1 Heat Transfer

For calculating heat transfer in the socks, two different tests have been conducted for different fiber types. One of them is conduction heat transfer and the other is convection heat transfer.

When the material is in a continuous environment; the system is as follow:

The heat conduction equation is written as follows;

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k_z \frac{\partial T}{\partial z}) \qquad \textbf{(4.1)}$$

For the case of one dimensional heat conduction, the above equation is simplified as;

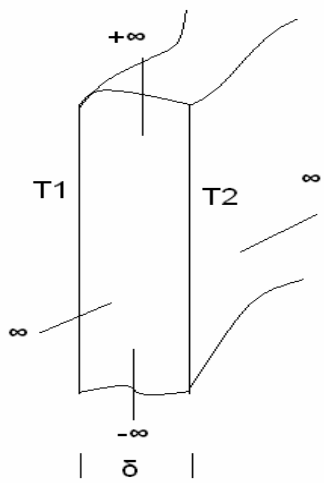


Figure 4.6: One dimensional heat conduction

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k \frac{\partial T}{\partial x}) \qquad \textbf{(4.2)}$$

$$\frac{\partial}{\partial t} = 0 \text{ (steady state)} \qquad \textbf{(4.3)}$$

$$\frac{d}{dx}(k\frac{dT}{dx}) = 0 \quad \textbf{(4.4)}$$

$$k\frac{d^2T}{dx^2} = 0 \quad \text{(k=constant)} \quad \textbf{(4.5)}$$

$$T = C_1x + C_2 \quad \textbf{(4.6)}$$

$$k\frac{dT}{dx} = C_1 \quad \textbf{(4.7)}$$

$$q^{II} = -k\frac{dT}{dx} \rightarrow \text{ (W/m}^2\text{) heat flux is constant} \quad \textbf{(4.8)}$$

$$Aq^{II} = -kA\frac{dT}{dx} \cong -kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{T_1 - T_2}{\delta} = q \quad \textbf{(4.9)}$$

q= heat flow rate (W)

k= conduction coefficient (W/mK)

T= temperature (K)

$$k = \frac{\frac{q}{A}}{\frac{(T_1 - T_2)}{\delta}} = \frac{T_1 - T_2}{R} \quad \textbf{(4.10)}$$

$$R = \frac{\delta}{kA} \quad \text{(mK/W)} \quad \textbf{(4.11)}$$

R= Thermal resistance

The sock and the heater have a three dimensional shape so that the heat conduction equation should be written in the three dimensional form. On the other hand, the heat conduction experiments are conducted in one dimensional form.

Now we should analyze the terms on the right hand side of the equation 4.1.

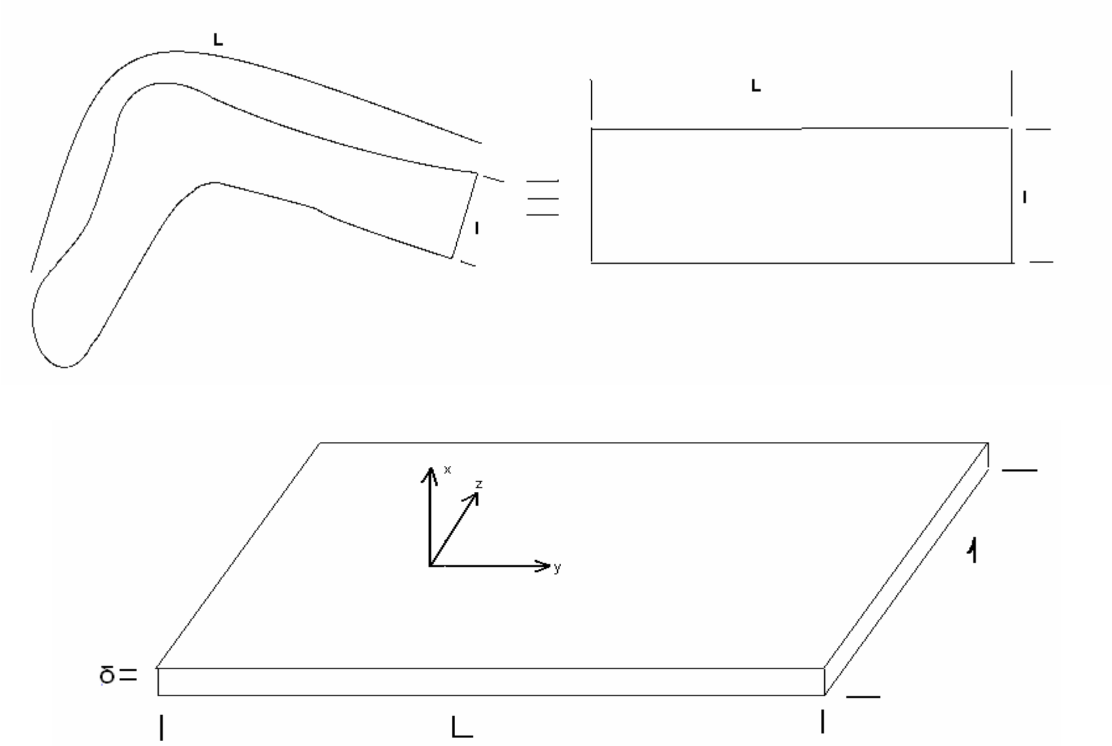


Figure 4.7: Position of sock plate

The L-shaped of the sock (and the heater) can be supposed as a plate as shown in Figure 4.7.

In order to compare the conduction terms of equation 4.1, we need to express these terms in with characteristic quantities of the experimental set up. Here, it is easily seen that the characteristic lengths of x, y and z are δ (thickness), L (lenght) and l (width) respectively.

$$\frac{\delta}{L} << 1$$

$$k\frac{\partial^2 T}{\partial x^2} \sim k\frac{\Delta T}{\delta^2} \quad \textbf{(4.12)}$$

$$k\frac{\partial^2 T}{\partial y^2} \sim k\frac{\Delta T}{L^2} \quad \textbf{(4.13)}$$

$$k\frac{\partial^2 T}{\partial z^2} \sim k\frac{\Delta T}{l^2} \quad \textbf{(4.14)}$$

If we compare the conduction terms in y, z and x directions by using the above terms having the same order with the differential terms, then we get the equations as follow;

$$\frac{k(\partial^2 / T / \partial y^2)}{k(\partial^2 / T / \partial x^2)} \approx \frac{k(\Delta T / L^2)}{k(\Delta T / \delta^2)} = \frac{\delta^2}{L^2} = (\frac{\delta}{L})^2 <<< 1 \quad \textbf{(4.15)}$$

and

$$\frac{k(\partial^2 / T / \partial z^2)}{k(\partial^2 / T / \partial x^2)} \approx \frac{k(\Delta T / l^2)}{k(\Delta T / \delta^2)} = \frac{\delta^2}{l^2} = (\frac{\delta}{l})^2 <<< 1 \quad \textbf{(4.16)}$$

Hence the terms $\frac{\partial^2}{\partial y^2}$ and $\frac{\partial^2}{\partial z^2}$ in equation 4.1 can be neglected and the steady state heat conduction equation becomes as follows;

$$\frac{d}{dx}(k\frac{dT}{dx}) = 0 \quad \textbf{(4.17)}$$

$$q = \frac{T_1 - T_2}{\delta / kA_{Sockplate}} = \frac{T_1 - T_2}{R_{Conduction}} \mathrm{A_{Sockplate}} \quad \textbf{(4.18)}$$

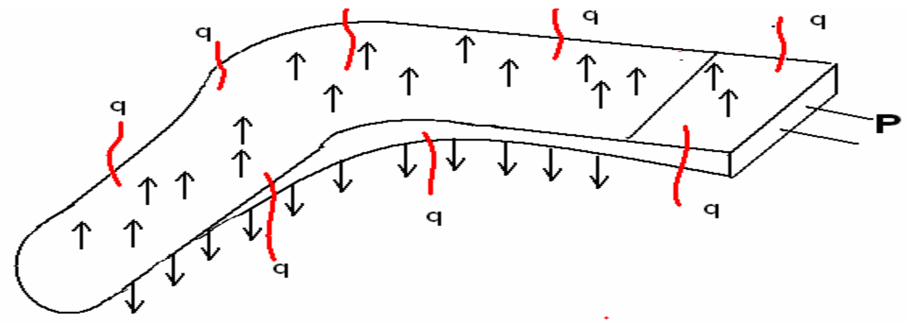
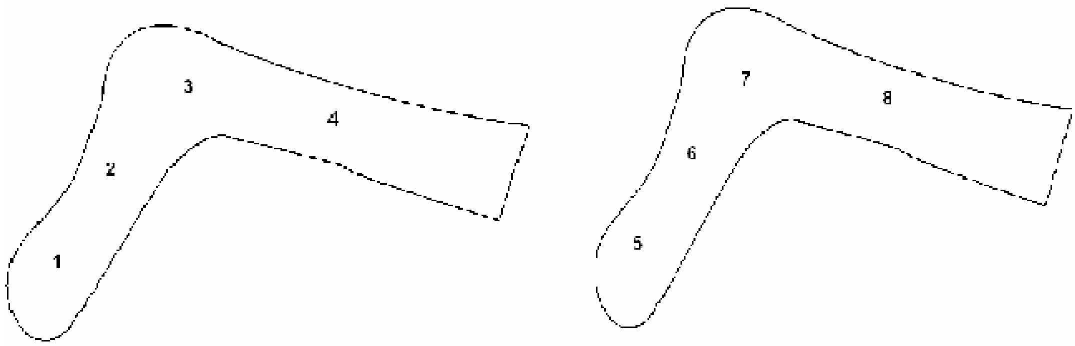


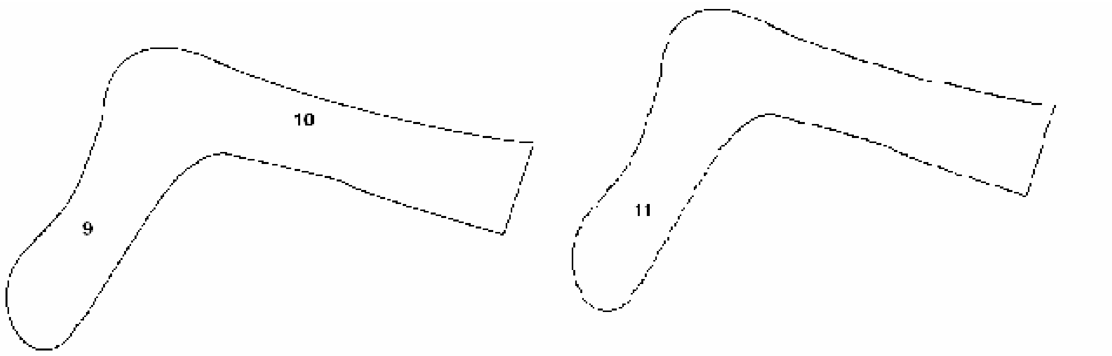
Figure 4.8: Schematic diagram of heat flux on sock

In order to measure the conduction heat transfer, a special experimental setup is used, which was designed with reference to ISO 8302. A special form which is used for ironing socks was made suitable for testing with small changes. 8 thermocouples (Figure 4.9) were used on the hot sheet and 3 thermocouples (Figure 4.10) were used for the cooling plate.



A **B**

Figure 4.9: Arrangement of the thermocouples of heating plate A-Below plate
B-Above plate



A **B**

Figure 4.10: Arrangement of the thermocouples of cooling unit A- Above plate
B- below plate

Figure 4.11: Places of thermo receptors in hot unit

The hot plate was covered by the socks and then the hot plate was placed between two cold plates. 4 clamps were used to press the plates (Figure 4.12).

Figure 4.12: The special experimental set for measuring conduction coefficients of socks

The system was heated for 3 hours. During the experiment 45 measurements, which were taken for every 2 minutes, were taken. After the system reached to the thermal equilibrium 128 measurements had been taken for 2 minutes. Keithley device which was attached to the system was employed take the measurements. For an example, in Figure 4.13, the temperature variation of soybean tight sock until it reached to thermal balance can be seen. Also in Figure 4.14; the temperature variation of soybean tight sock after reaching the thermal equilibrium.

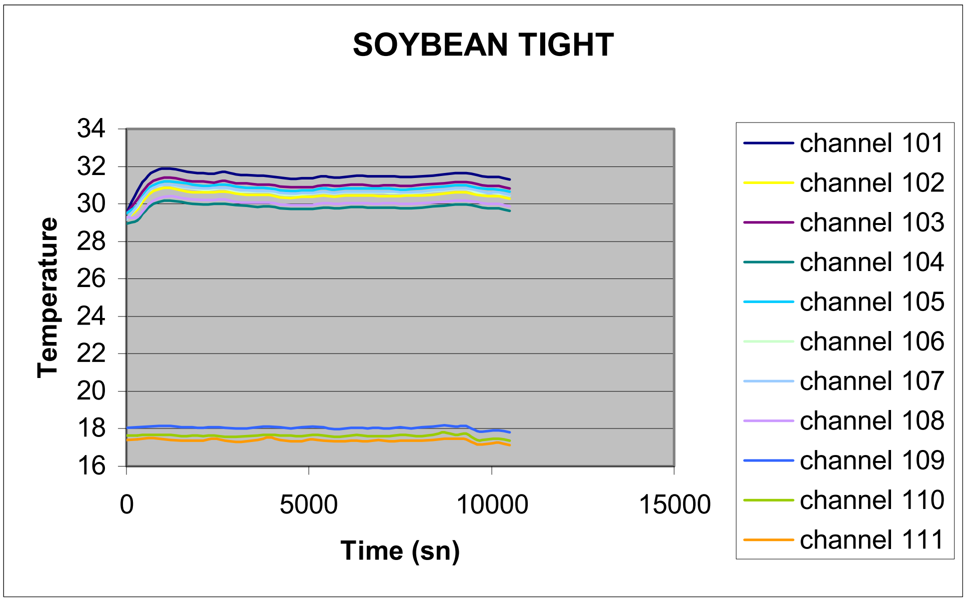


Figure 4.13: The temperature variation of soybean tight sock during 3 hours

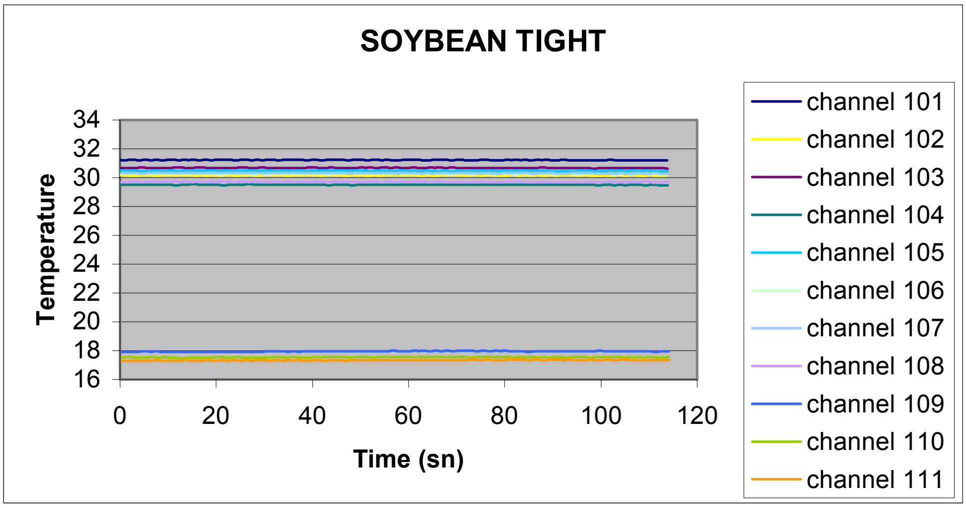


Figure 4.14: The temperature variation of soybean tight sock after reaching the thermal equilibrium

Due to the fact that the socks are not big enough to cover the heating plate, all the heat flux produced by the heater does not pass through the socks (see Figure 4.15).

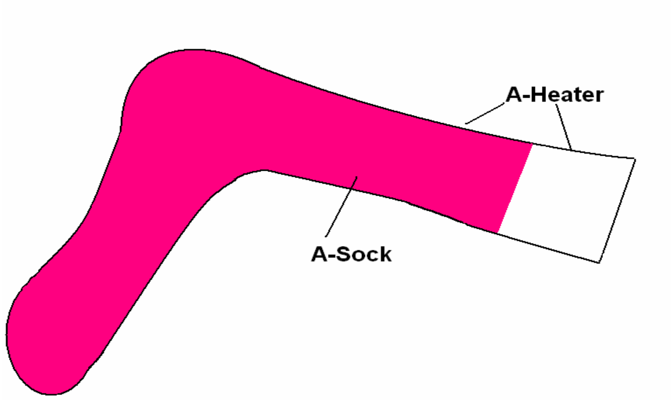


Figure 4.15: The sock area

Therefore, the equations mentioned above became as follow;

$2A_T$= total heater area (m^2) (double layer)

$2P_e = \frac{V^2}{R}$ the applied power (W) (double layer) **(4.19)**

$q^{II} = \frac{P_e}{A_T}$ (heat flux) **(4.20)**

$\dot{Q} = A_S q^{II}$ (W) heat transfer rate passing through one layer of the socks **(4.21)**

$$\dot{Q} = A_S k_S \frac{T_H - T_C}{\delta} \rightarrow A_S \frac{T_H - T_C}{(\delta / k_S)} \quad \textbf{(4.22)}$$

$$\delta / k_S = R \text{ thermal conduction resistance} \quad \textbf{(4.23)}$$

δ= Mean thickness of sock (m)

$$k_S = \dot{Q} \frac{1}{A_S \frac{\Delta T}{\delta}} = \delta \frac{\dot{Q}}{A_S \Delta T} \quad \textbf{(4.24)}$$

$$A_S q^{II} = A_S \frac{P_e}{A_T} = A_S k_S \frac{\Delta T}{\delta} \quad \textbf{(4.25)}$$

$$P_e = A_T k_S \frac{\Delta T}{\delta} \quad \textbf{(4.26)}$$

$$k_S = \frac{P}{A_T \Delta T} \delta \left[\frac{W}{mK} \right] \quad \textbf{(4.27)}$$

Temperature of the inside surface of the fabric is determined by the data taken from the inside thermocouples and the temperature of the outside of the fabric is determined by the data taken from the outside surface of the cooler which is in contact with the fabric.

For the natural convection heat transfer, the same mechanism was employed with the difference that the cooler plates were taken out so T_{Cold} on the formula is obtained by measuring the temperature of the environment (Figure 4.16).

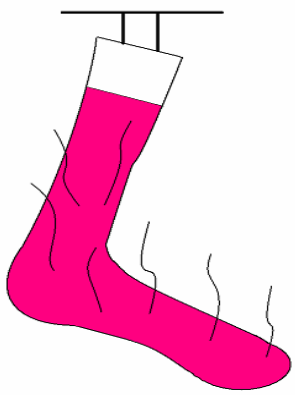


Figure 4.16: Position of sock during convection

The system was heated for 3 hours until reaching the thermal equilibrium and during this period 45 measurements were taken for every 2 minutes. Also after reaching the thermal equilibrium, 64 measurements were taken. The situation for cotton slack sock before and after reaching the thermal equilibrium can be seen in Figures 4.17 and 4.18 respectively.

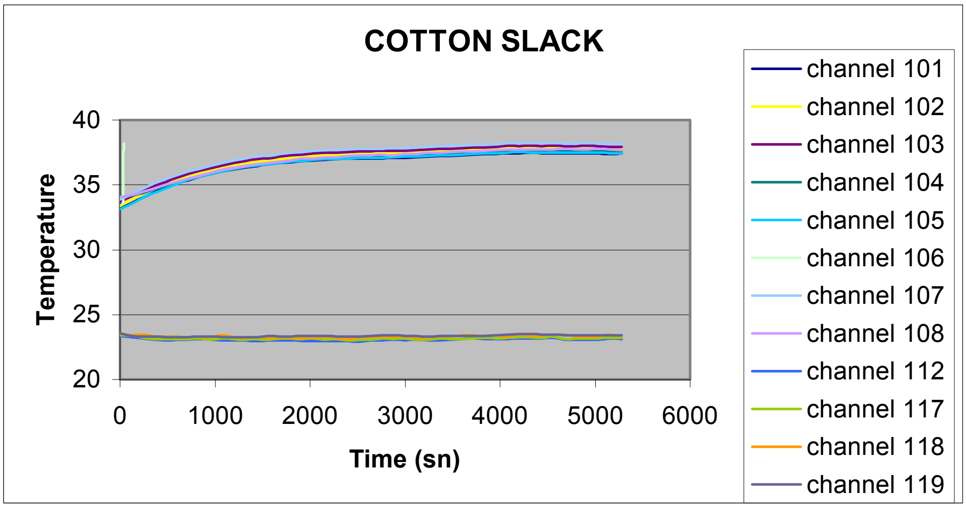


Figure 4.17: The temperature variation of cotton slack sock during 3 hours

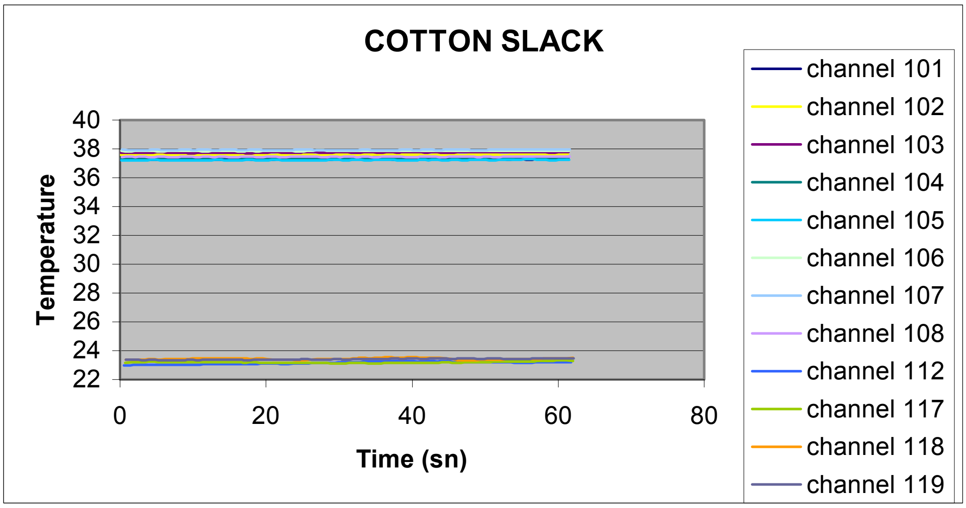


Figure 4.18: The temperature variation of cotton slack sock after reaching the thermal equilibrium

As mentioned above, owing to not having enough sock area on the plate; the equations become as follow;

$$2P_e = \frac{V^2}{R} \quad \text{the applied power (double layer)} \qquad \textbf{(4.28)}$$

$$q^{II} = \frac{2P_e}{A_T} \quad (\mathrm{W/m^2}) \qquad \textbf{(4.29)}$$

A_T= sum of the heater area (double layer)

$$\dot{Q} = A_S q^{II} = hA_S(T_H - T_{Air}) \qquad \textbf{(4.30)}$$

$$\dot{Q} = A_S \frac{(T_H - T_{Air})}{1/h} \qquad \textbf{(4.31)}$$

$\dot{Q}$= heat transfer rate

As= Area of sock (m^2)

T= Temperature (K)

4.2.1.2 Transfer Wetting Test

Measurement of transfer wetting test is based on Zhuan and his friends [9] test method. The samples were mounted horizontally to conduct transfer wetting experiments. A 74,5 mm diameter dish was placed on top of the layers and external pressure which was 15,6 kg/m^2.was exerted

Fabric samples were cut into 74,5 mm diameter circules, which were the same size as the dish placed on the fabrics. The amount of water initially held in the wet fabric was controlled by completely soaking the sample in distilled water and then removing the excess water with a paper towel. The wet fabric was weighted periodically.

As soon as the dry layer fabrics, which was the same fabric as the wet layer, was placed on the top of wet layer, liquid transfer was continuously allowed for a certain period of time, then the amount of liquid transfer was measured by weighting the dry fabric layer at 5, 10, 15, 20, 25 and 30 minutes.

4.2.1.3 Measurement of Drying Speed

This test is based on research of Fourth and Caplan [36,37]; each specimen was soaked in distilled water for ½ hour. When no air bubbles were produced upon squeezing under water, the socks were considered wet-out. Wet-out socks were suspended vertically for 15 second and then laid flat on a double thickness of dry paper towel for 2 minutes on each side. Weighing was made immediately following the 15 seconds vertical suspension. Weightings were made at ½ hour and 1 hour intervals as drying progress. When the measurement value is 105% of the weight before getting wet, the measurement was stopped. Drying rates, expressed as % weight loss per unit hour during the initial constant period.

4.2.1.4 Measurement of Wicking

According to DIN 53924 Standard was applied for wicking measurement and it was repeated 3 times.

4.2.1.5 Air Permeability

ASTM 0373 Standard was used. Air flow was applied to the test heads of 20 cm^2 at 249 pa pressure. The pressure difference between the side of the fabric was determined as $ft^3/min/ft^2$ and this data was multiplied with 0,303 and transformed in $m^3/min/m^2$.

4.2.1.7 Measurement Water Vapor Permeability Test

Water vapor permeability test was based on the ASTM E96-00.

Figure 4.19: Water vapor permeability test model

4.2.2 Physical and Dimensional Properties

4.2.2.1 Fabric Weight

TS 251 was used to measure fabric weight. Measurements were taken from both foot and neck.

4.2.2.2 Dimensional Stability

This test was done in accordance with ISO 3759 Standard. The samples were dried according to BS4923 standard. Measurements were taken from both neck and foot.

4.2.2.3 Thickness

5 measurements were taken from nose, heel, base and neck and the test was conducted according to BS 2544 and then average values were obtained.

4.2.2.4 Bursting Strength

TS 393 EN ISO 13938-1 standard was used.

4.2.2.5 Abrasion Resistance

ASTM D4966 test method was used and abrasion under 9 kPa pressure after 20000 revolutions was measured.

4.2.2.5 Measurement Moisture Regain Test

It was based on ASTM D2654 standard.

Moisture Regain:

$$R = \frac{M - D}{M} X100 \qquad \textbf{(4.32)}$$

M= Wet weight

D= Dry weight

The data obtained were evaluated using ANOVA, bivariate correlation analysis, post hoc test. For this purpose, SPSS 13 software package was employed.

Apart from that, plain jersey structure was modelled using CATIA V5R16 in an attempt to evaluate heat transfer behavior of plain jersey fabrics from cotton yarns using finite element method.

5. RESULTS

5.1 Results of Physical Performance Properties

5.1.1 Abrasion Resistance of Fabrics

As seen from the Figure 5.1 and Table 5.1; the most abraded fabric group is micro modal; whereas soybean fabrics are the least abraded samples.

Table 5.1: Abrasion resistance of fabrics

Fabric Type	Abrasion resistance of fabrics (%)
11	7,04
12	6,83
13	7,18
21	9,80
22	8,08
23	8,42
31	5,14
32	7,41
33	7,58
41	18,00
42	19,23
43	19,34
51	5,21
52	5,26
53	6,88
91	5,21
92	3,57
101	3,31
102	3,85
103	1,55

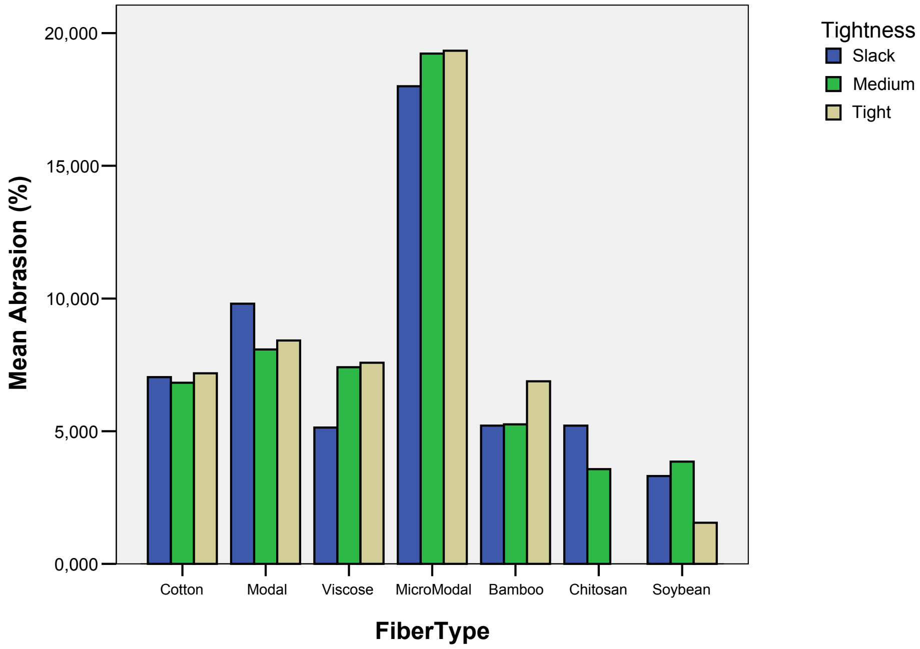


Figure 5.1: Abrasion resistance of fabrics

ANOVA Results:

1. Effect of fiber type

According to the results; there is a statistically significant difference at the $p < 0.05$ level between abrasion resistance of fiber groups [$F(6,53)=320{,}958$ $p=0{,}000$]. For evaluating the difference between fibers post hoc test has also been done. This test shows that only viscose and cotton fibers can behave in the same manner (sig. 0,459); the other fiber groups are, however, follow a different pattern.

2. Effect of tightness factor

In the light of the results obtained; there is a statistically significant difference at the $p < .05$ level between fabrics for the tightness factors under discussion.

Bivariate correlation analysis results

According to bivariate correlation analysis; there is a relationship between thickness and abrasion resistance of fabrics at -0,43 level which is a medium relationship at 99 % significant level. Also, thickness helps to explain 18,49 % of variances in abrasion resistance of fabrics. As may be seen from the Figure 5.2; for modal and cotton fabrics abrasion resistance increases as thickness increases too and the correlation coefficient between abrasion resistance and thickness of cotton fabrics is 0,997and it is 0,801 for modal fabrics. However, for viscose and chitosan fabrics abrasion resistance decreases as thickness increases and the correlation coefficient between abrasion resistance and thickness of viscose fabrics is -0,940 and chitosan fabrics is -1.000 at 99 % significant level.

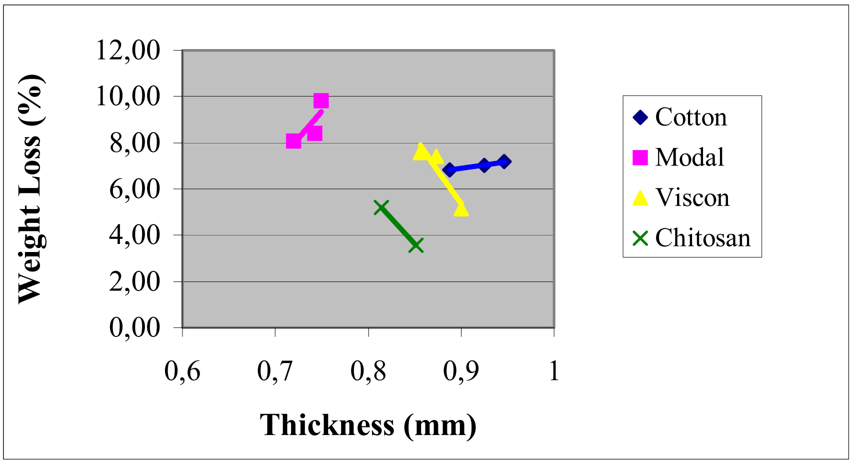


Figure 5.2: Thickness against abrasion resistance

The statistical analysis also shows that yarn twist influences the abrasion resistance of fabrics. The correlation between yarn twist and abrasion resistance of fabrics is -0,664 which means abrasion resistance decreases as yarn twist increases. Also it helps to explain 44 % of variances in abrasion resistance of fabrics at 99 % significant level.

5.1.2 Results of Moisture Regain of Fabrics

Table 5.2: Moisture regain values of fabrics

Fabric type	Moisture Regain of Fabrics (%)
11	23,8
12	9,09
13	12,5
21	22,22
22	33,3
23	22,22
31	10,52
32	13,04
33	12,5
41	15
42	11
43	11,11
51	16,67
52	13,04
53	14,28
91	5
92	5,55
101	5,26
102	10
103	5

As seen from the Figure 5.3 and Table 5.2; moisture regain of modal fabrics tends to be higher, when compared to the other sample groups, whereas chitosan ones give the lowest moisture regain results.

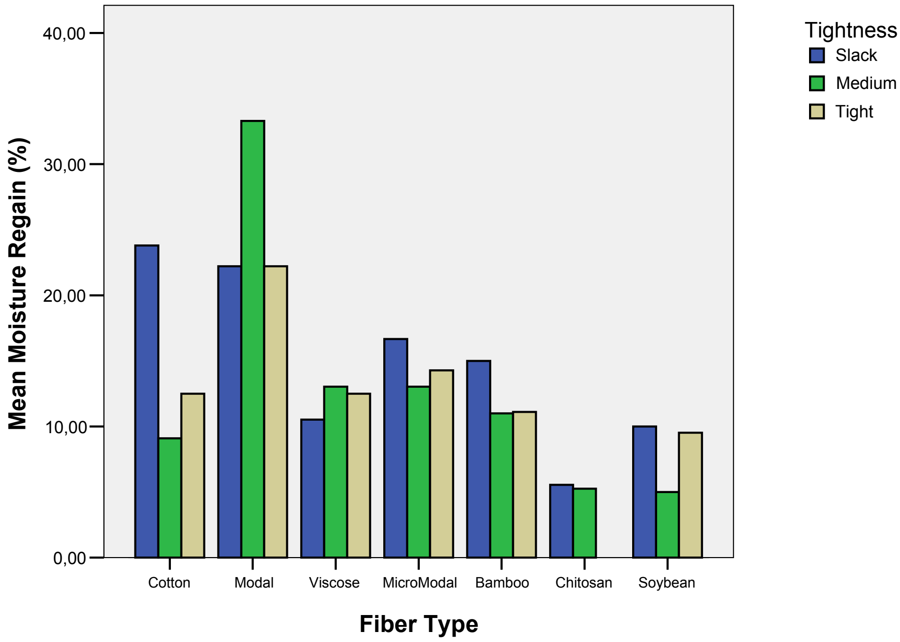


Figure 5.3: Moisture regain of fabrics

ANOVA results:

1. Effect of fiber type

According to the statistical analysis there is a significant difference between fiber groups at 95 % significant level [F(6,53)=25,893 p=0,000]. Especially modal fabrics are significantly different from the other fabrics. The moisture regain values of cotton-micro modal (sig. 0,789) and viscose-bamboo (sig. 0,841) fabrics tend to be very close to each other with reference to post hoc test.

2. Effect of tightness factor

From the statistical analysis, it is clear that there is a significant difference between fabrics for different tightness values. Only for chitosan fabrics, tightness is not an influential parameter for moisture regain, as there is not a statistically significant difference between its different tightness values (sig. 0.385).

Bivariate correlation analysis results:

Statistical analysis demonstrate that there is a -0,357 correlation between stitch density and moisture regain of fabrics at 95 % significant level which shows that moisture regain of fabrics decreases as stitch density decreases. It helps to explain

12,74 % in variances of moisture regain of fabrics. As may be seen from the Figure 5.4; moisture regain of cotton and micro modal fabrics have a tendency to decrease as stitch density increases. The correlation between stitch density and moisture regain of cotton fabrics is -0,891 and micro modal is -0,948 at 99 % significant level. Also high correlation values are also obtained for chitosan and viscose fabrics.

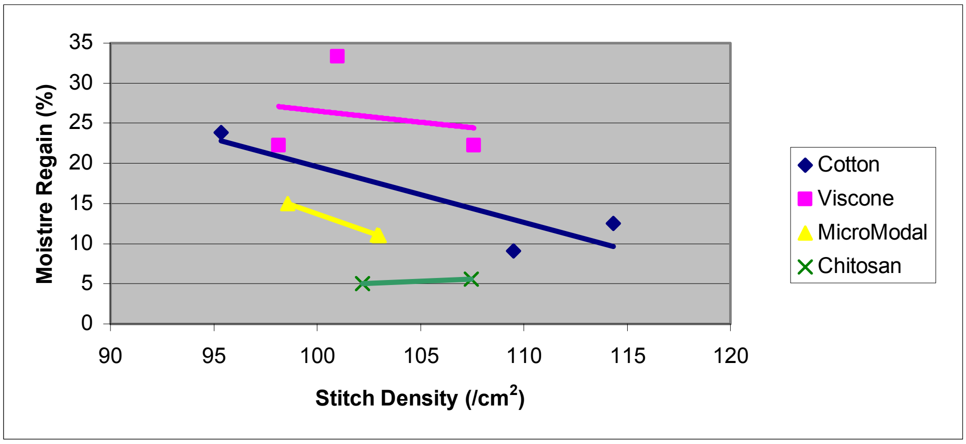


Figure 5.4: Moisture against stitch density

5.1.3 Bursting Strength of Fabrics

From Figure 5.5 and Table 5.3 it may be observed that; bursting strengths of soybean fabrics are significantly higher when compared to the others. Soybean fabrics are followed by the cotton fabrics. Bamboo fabrics, however, have lower bursting strength values. For viscose, modal, bamboo and chitosan fabrics; bursting strength tends to increase as tightness increases.

Table 5.3: Bursting strength of fabrics

Fabric Type	Bursting Strength(kg/cm^2)
11	5,58
12	6,36
13	5,93
21	4,44
22	4,76
23	5,12
31	4,50
32	4,70
33	5,00
41	4,94
42	5,46
43	5,27
51	3,60
52	3,75
53	3,79
91	4,75
91	5,10
101	5,47
102	6,79
103	6,43

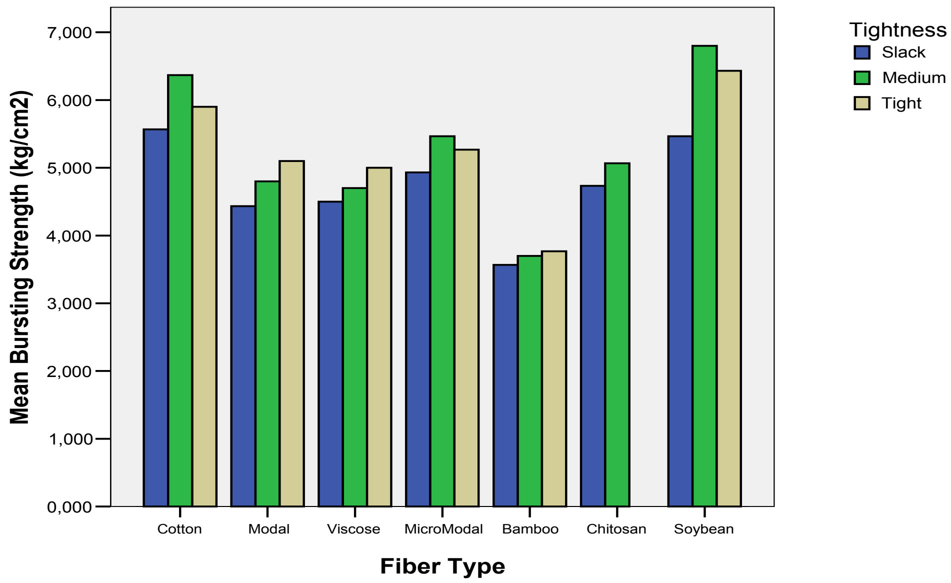


Figure 5.5: Bursting strength of fabrics

ANOVA results:

1. Effect of fiber type

ANOVA results show that fiber type is an influencial parameter for bursting strength [F(6,53)=27,179 p=0,000 95 t level]. The effect size (eta squared) is 0,7547 which is very high. For evaluating the difference between fibers, post hoc test has also been done. Accordingly, bamboo fabrics differ slightly from the others. Modal and viscose fabrics, on the other hand, appear to present a similar pattern for the behavior of bursting strength (sig. 0,847).

2. Effect of tightness factor

From the ANOVA results, it may be concluded that fabric tightness has a statistically significant effect on bursting strength [F(19,40)= 13,218 p=0,00 95 % significant level]. Only for chitosan, bamboo and modal fabrics, tightness is not an influencial parameter for bursting strength, as there is not a statistically significant difference between its different tightness values.

Bivariate correlation analysis results:

Statistical analysis show that there is a positive correlation between weight and bursting strength of cotton, modal, soybean and micro modal fabrics which implies that bursting strength of these fabrics increase as their weight increase (Figure 5.6).

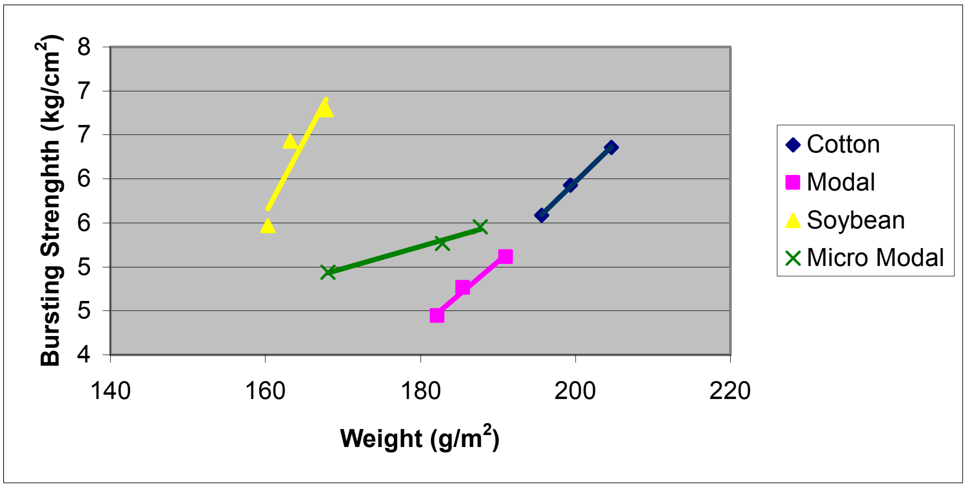


Figure 5.6: Weight against bursting strength

In the light of the literature survey, the correlation between bursting strength of fabrics and thickness, stitch density, breaking strength as well as extension values of the corresponding yarns were also investigated, but no correlation could be found.

5.1.4 Dimensional Stability Results of Fabrics

For evaluating the dimensional stabilities of socks, both widthwise and lengthwise shrinkages were tested in accordance with the relevant standard. The tests were applied on both neck and foot parts of the socks.

5.1.4.1 Results of Widthwise Dimensional Stability

Neck results:

From the Figure 5.7 and Table 5.4; it may be seen that bamboo shows the highest shrinkage in widthwise direction. They are followed by viscose, cotton, chitosan and soybean socks. The lowest widthwise shrinkage values are obtained for micro modal socks, no shrinkage occurred in 41 sock. Finally, although most of the fabrics have a tendency to shrink, 31 sock tends to extend in the neck part.

Table 5.4: Widthwise dimensional stability of neck (%)

Fabric Type	Widthwise dimesional stability of neck(%)
12	-3,125
13	-1,875
21	3,125
22	-0,625
23	-5
31	0,3125
32	-4,375
33	-6,5625
41	0
42	-0,9375
43	-2,8125
52	-6,5625
53	-6,875
91	-3,125
92	-2,8125
101	-3,4375
102	-1,875
103	-1,875

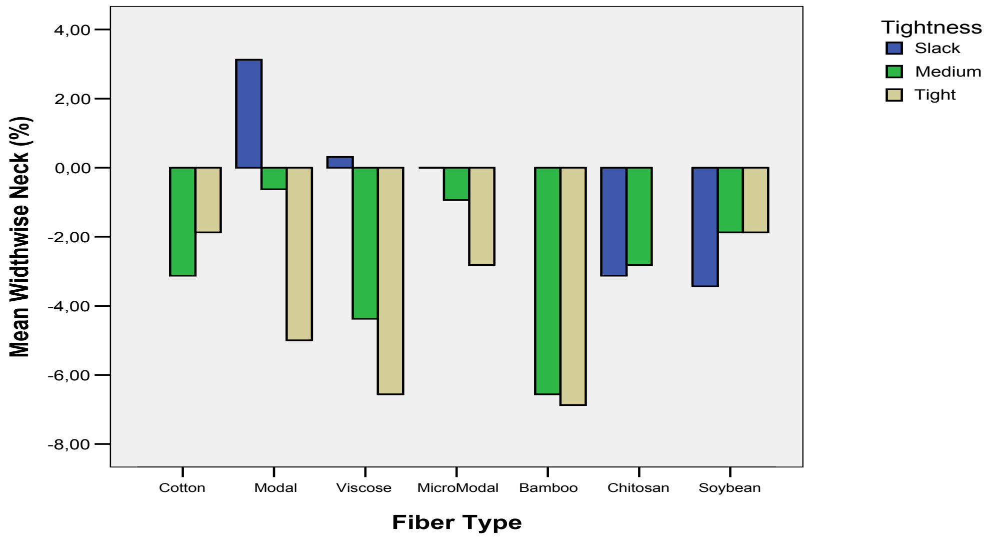


Figure 5.7: Widthwise dimensional stability of neck part of the socks

ANOVA results imply that both fiber type and fabric tightness do not have a statistically significant effect on the widthwise dimensional stability of the socks in the neck part. This may be resulted from the fact that the dimensions on which the measurements were taken are not big enough to reflect the differences in fabric properties.

Correlation analysis results show that there is a negative correlation between weight (-0,457) and also stitch density (-0,477, for modal -0,911) which show dimensional stability of neck part of the socks decrease as both weight and stitch density increase.

Findings in the literature imply that yarn twist has an effect on dimensional stability of knitted fabrics. Therefore, correlation between yarn twist and widthwise dimensional stability of the socks was questioned and for micro modal and chitosan socks relatively high correlation coefficients were obtained.

Foot results:

From the Figure 5.8 and Table 5.5, it may be seen that bamboo socks tend to give relatively higher widthwise shrinkage values. These are followed by soybean, cotton and viscose socks. The results also revealed that for each fiber type widthwise shrinkage does not follow a regular pattern depending on the changes in tightness (i.e. slack, medium and tight).

Table 5.5: Widthwise dimensional stability of foot (%)

Fabric Type	Widthwise dimensional stability of foot(%)
12	-6,5625
13	-6,875
21	-0,625
22	-3,4375
23	-10
31	-0,625
32	-8,125
33	-10
41	-5,9375
42	-9,375
43	-5,625
52	-15,625
53	-8,125
91	-5
92	-1,25
101	-4,375
102	-8,125
103	-13,125

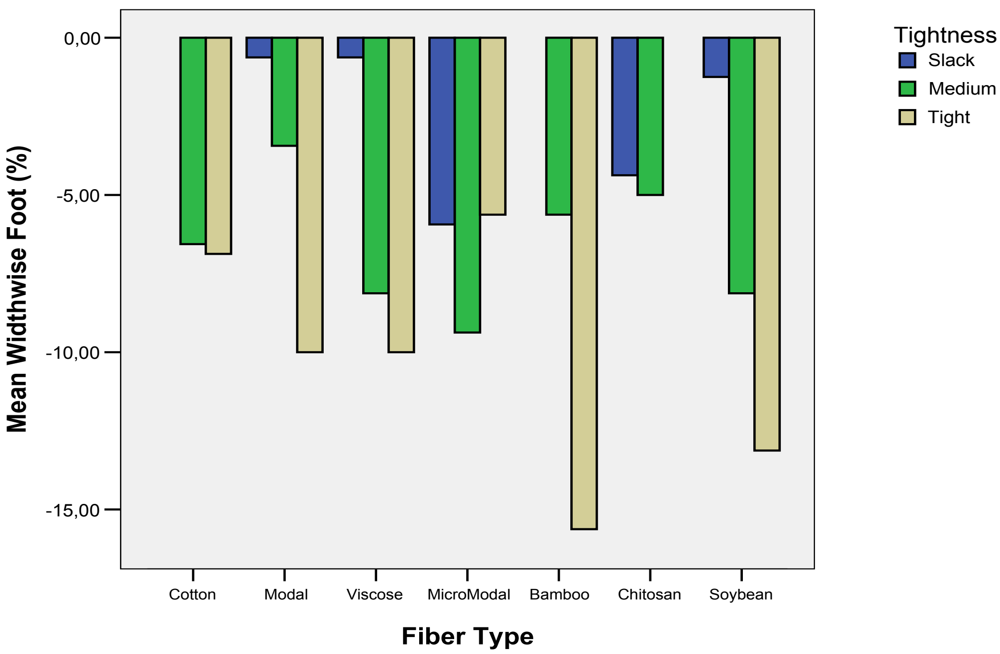


Figure 5.8: Widthwise dimensional stability of foot part

ANOVA results:

As in the case of the neck parts of the socks, a statistically significant difference could not be obtained for fiber types as well as the corresponding tightness values under discussion.

Bivariate correlation analysis results:

The analysis demonstrate that there is a -0, 336 correlation between stitch density and widthwise dimensional stability of foot part of the socks at 95 % significant level. Also it helps to explain 11,28 % in variances of widthwise dimensional stability of foot part of the socks.

Generally speaking, there is not a correlation between yarn twist and widthwise shrinkage in foot part, except for soybean socks. The correlation coefficient obtained for these samples is 0,876 at 95 % significant level.

T-test was conducted between the measurements taken from foot and neck parts of the socks. And depending on the results there is a significant decrease at dimensional stability values of from neck (mean=-2,691) to foot (mean=-6,684), $t(35)=3{,}049$ $p<0{,}05$. The eta squared statistic (0.2098) indicated a large size effect.

It may be concluded that there is a statistically significant difference between the measurements and accordingly it is advised to take measurements from each part of the sock so that widthwise dimensional stability of a sock can be characterized much better.

5.1.4.2 Results of Lengthwise Dimensional Stability

Neck results:

From the Figure 5.9 and Table 5.6; it may be seen that viscose socks show the highest shrinkage in lengthwise direction. They are followed by cotton and soybean socks. The lowest lengthwise shrinkage values are obtained for micro modal socks like widthwise results.

Table 5.6: Lengthwise dimensional stability of neck part of socks

Fabric Type	Lengthwise dimesional stability of neck(%)
12	-10,625
13	-11,25
21	-6,25
22	-16,875
23	-8,75
31	-15,625
32	-10,625
33	-10
41	-6,25
42	-3,125
43	-10,625
52	-11,25
53	-10
91	-6,25
92	-6,875
101	-12,813
102	-10,625
103	-8,75

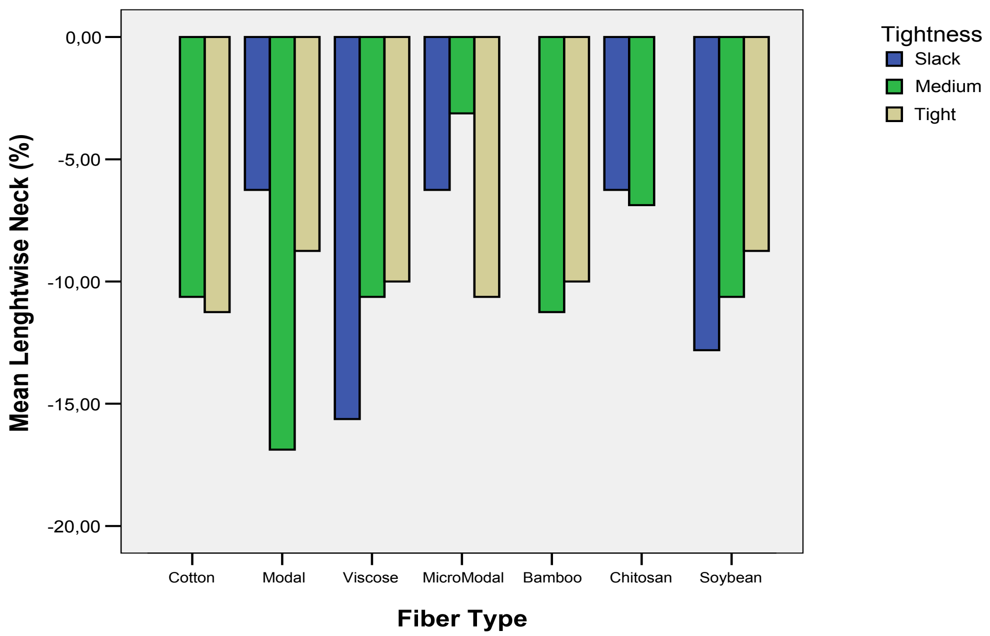


Figure 5.9: Lengthwise dimensional stability of neck part of the socks

ANOVA results imply that both fiber type and fabric tightness do not have a statistically significant effect on the lengthwise dimensional stability of the neck part. Only for different tightness values of modal socks, there is a significant difference at 95 % significant level.

In the light of the literature survey, the correlation between lengthwise dimensional stability of neck and stitch density, yarn twist and weight were investigated, but no correlation could be found.

Foot results:

From the Figure 5.10 and Table 5.7; it may be seen that soybean socks tend to give relatively higher lengthwise shrinkage values. They are followed by viscose and bamboo socks. However, chitosan socks have the lowest shrinkages values. For bamboo, cotton and viscose socks; shrinkage values increase as tightness decreases.

Table 5.7: Lengthwise dimensional stability of foot part of the socks (%)

Fabric Type	Lengthwise dimesional stability of foot(%)
12	-11,25
13	-7,5
21	-4,375
22	-15
23	-6,25
31	-13,75
32	-12,5
33	-8,75
41	-11,25
42	-6,25
43	-10
52	-12,5
53	-10,625
91	-7,1875
92	-8,4375
101	-13,125
102	-11,875
103	-11,875

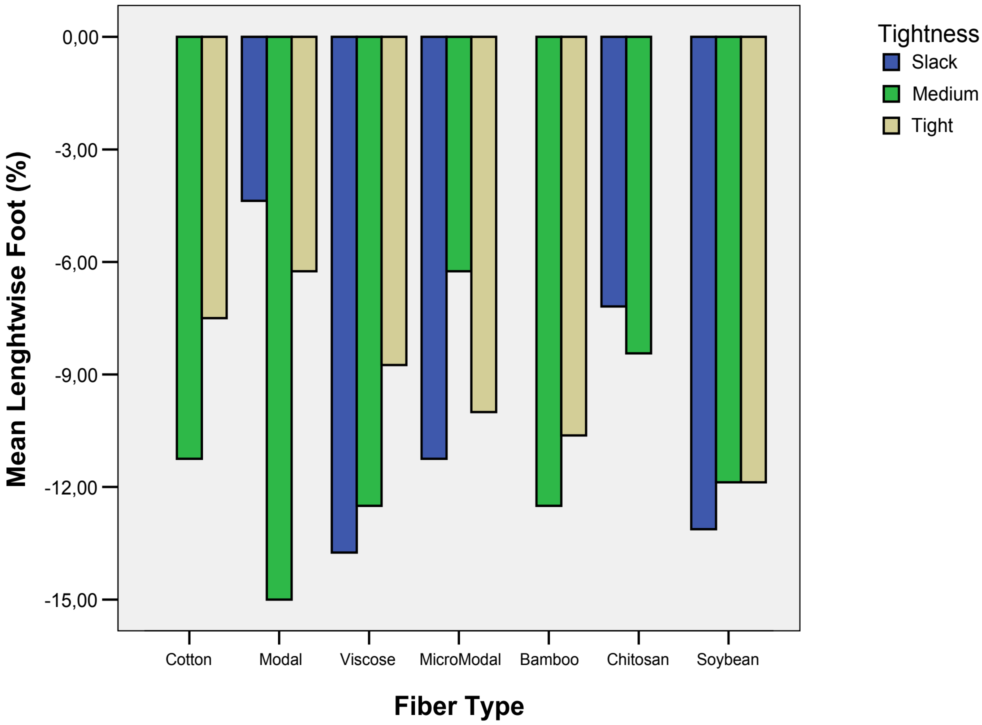


Figure 5.10: Lengthwise dimensional stability of foot part of the socks

ANOVA results show that both fiber type and fabric tightness do not have a statistically significant effect on the lengthwise dimensional stability of the foot part. However, between chitosan and soybean socks, there is a significant difference (sig.0,197).

In the light of the literature survey, the correlation between widthwise dimensional stability of foot and stitch density, yarn twist and weight were investigated, but no correlation could be found.

T-test was conducted between the measurements taken from foot and neck parts of the socks. Depending on the results between lengthwise dimensional stability of neck (mean=-9,809) and foot (mean=-10,1389) there is not a significant difference [t(35)=0,486 p>0,05].

5.1. Results of Comfort Properties

5.2.1 Results of Air Permeability

Figure 5.11 and Table 5.8 reveal that cotton fabrics give the lowest air permeability values whereas modal fabrics have the highest values. They are followed by micro modal, soybean and bamboo fabrics. For viscose and soybean fabrics, air permeability decreases as tightness increases.

Table 5.8: Air permeability of fabrics

Fiber Type	Air Permeability ($m^3/dk/m^2$)
11	72,69
12	88,45
13	69,34
21	158,50
22	184,53
23	163,07
31	111,43
32	94,25
33	88,15
41	169,28
42	158,40
43	156,57
51	148,43
52	131,86
53	136,64
91	90,99
92	99,02
101	144,16
102	147,52
103	158,70

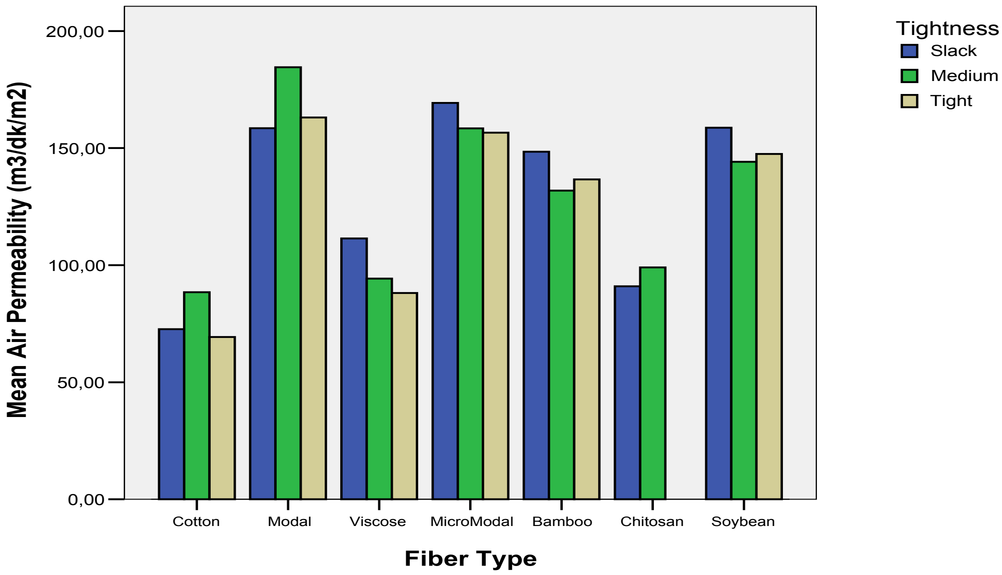


Figure 5.11: Air permeability of fabrics

ANOVA results:

1. Effect of fiber type

ANOVA results show that fiber type has a statistically significant effect on air permeability [F(6,53)=105,562 p=0,000]. For evaluating the difference between fibers, post hoc test has also been done. In the light of the results of the tests, it may be concluded that cotton, bamboo and soybean fabrics differ significantly from the others. Viscose and chitosan, on the other hand, perform in the same way as far as air permeability is concerned (sig. 0,595).

2. Effect of tightness factor

ANOVA analysis also implies that changes in tightness affect air permeability for almost each fiber type studied.

Bivariate correlation analysis results:

Statistical analysis demonstrate that there is -0,899 correlation between thickness and air permeability at 99 % significant level which means as thickness increases, air permeability decreases. Furthermore, it helps to explain 79,03 % of variances in air permeability of fabrics. From the comparative study of the results, it is shown that correlation between thickness and air permeability for cotton fabrics -0,766 (95 %

significant level), whereas it is -0,950 and -0,767 for modal and bamboo fabrics. In the case of viscose fabrics, however, the relation between air permeability and thickness is different from the fabrics mentioned above such that air permeability increases, as thickness increases, through the correlation is found to be quite high (0,868, 99 % significant level). (see Figure 5.12)

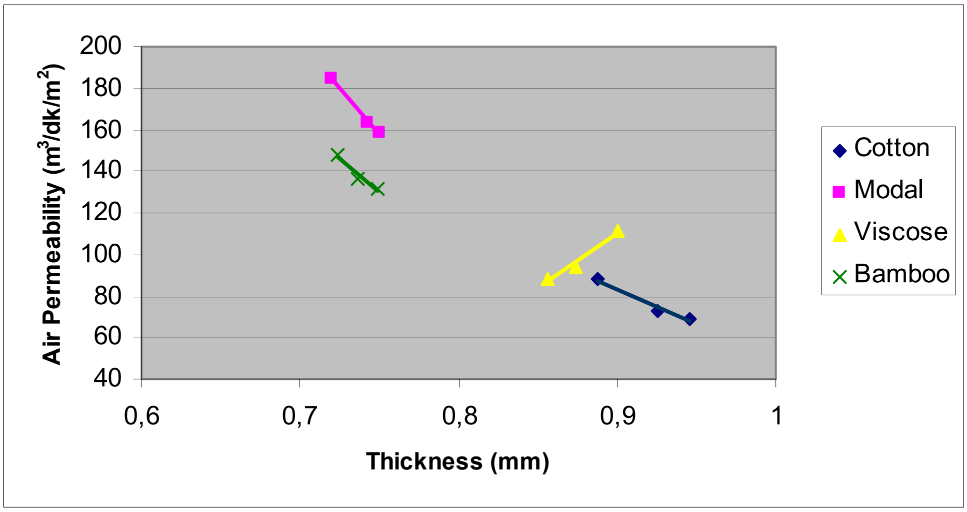


Figure 5.12: Thickness against air permeability

5.2.2 Results of Drying

As may be seen from Table 5.9, chitosan fabrics tend to dry faster, when compared to the other fabrics. Cotton, modal, micro modal and soybean fabrics follow them in turn. In order to compare the drying rates of the fabrics, the drying time of chitosan fabric (92), which is 5 hours, was taken as a reference, for all fabrics (Table 5.9). With reference to Figure 5.13, it is the viscose fabrics which give relatively slow drying rates. (see Figure 5.13).

Table 5.9: Drying times and drying rates of fabrics after 5 hours

Fabric Type	Drying Time(h)	Drying Rate (%)
11	7,00	130,94
12	8,00	156,57
13	6,00	118,53
21	6,00	109,83
22	7,00	113,91
23	8,00	135,67
31	8,00	133,84
32	8,00	146,68
33	8,00	146,24
41	6,00	113,67
42	6,00	109,70
43	8,00	122,72
51	8,00	144,06
52	8,00	130,92
53	8,00	130,58
91	6,00	112,79
92	5,00	102,17
101	7,00	116,32
102	7,00	118,29
103	7,00	125,81

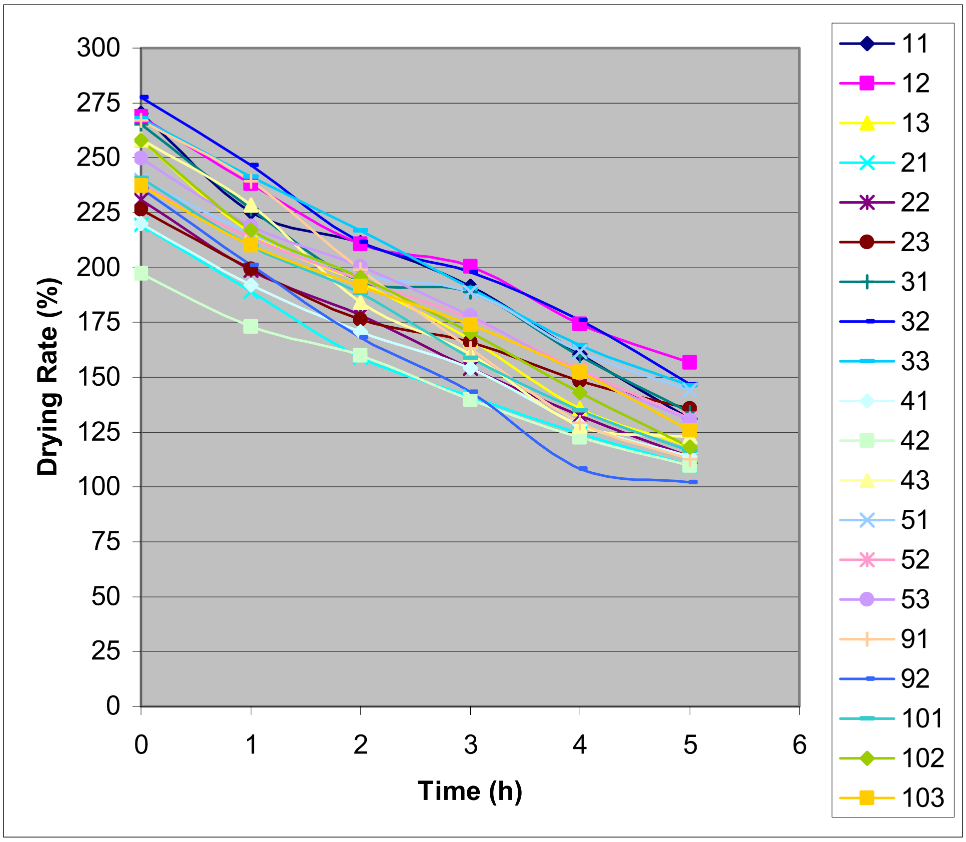


Figure 5.13: Drying rates of fabrics during the 5 hours

ANOVA results:

1. Effect of fiber type

In accordance with ANOVA results, it is clear that there is a statistical significant difference ($p < .05$ level) between drying rates of fabrics and fiber type, when 5 hour drying time is taken as a reference points for all groups [$F(6,53)=14,365$ $p=0,000$]. For evaluating the difference between fibers post hoc test has also been done. It shows that the drying behaviors of cotton and bamboo fabrics are similar (sig. 0,970). Modal and soybean fabrics also have a similar tendency (sig.0,940).

2. Effect of tightness factor

The analysis demonstrate that there is a statistically significant difference between fabrics tightness and drying rate for 5 hour drying time for all samples at 95 % significant level.

Bivariate correlation analysis results:

The statistical analysis results imply that for cotton (-0,999), chitosan (-1.00), micro modal (-0,987), viscose (-0,903) and bamboo (-0,856) there is a negative high correlation between thickness and drying rate of the samples (95 % significant level) which indicate that drying rate increases as thickness decreases (see Figure 5.14).

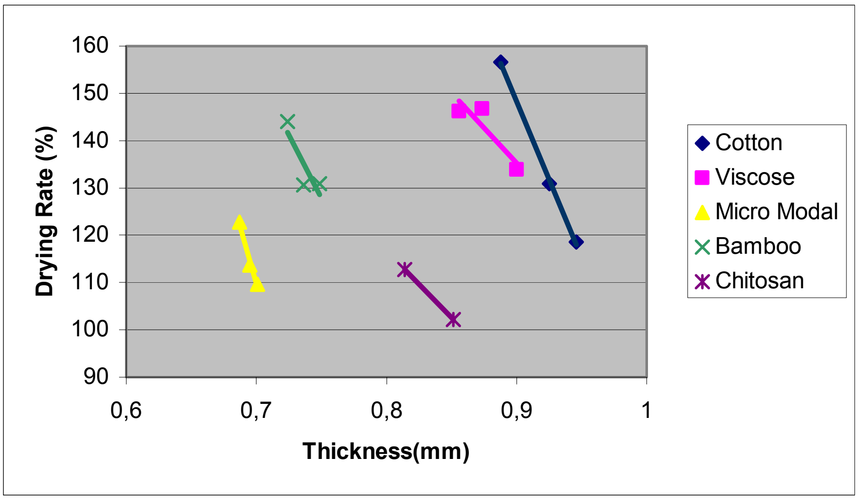


Figure 5.14: Thickness against drying rate

The correlation between stitch density and drying rates of the samples are also tested and it is shown that there is a high correlation between these two parameters for modal (0,988), viscose (0,936), soybean (0,824) and chitosan (-1.00). However, for chitosan fabrics it is observed that the correlation is negative, which means drying rate decreases as stitch density increases (see Figure 5.15).

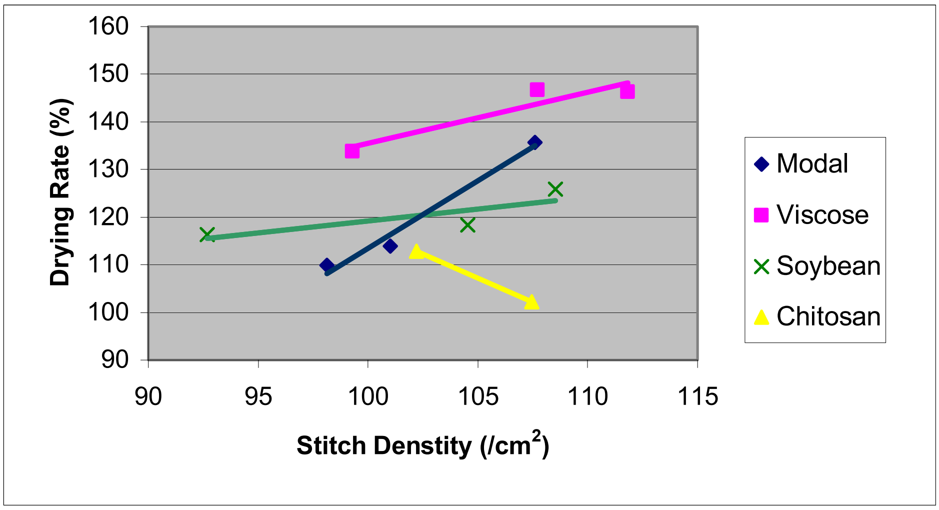


Figure 5.15: Stitch density against drying rate

There is a 0,499 correlation between weight and drying rates of fabrics after 5 hours (99% significant level) which imply that drying rate increases as weight increases. As shown in Figure 5.16, this tendency is much more obvious can be seen for chitosan, modal and viscose fabrics.

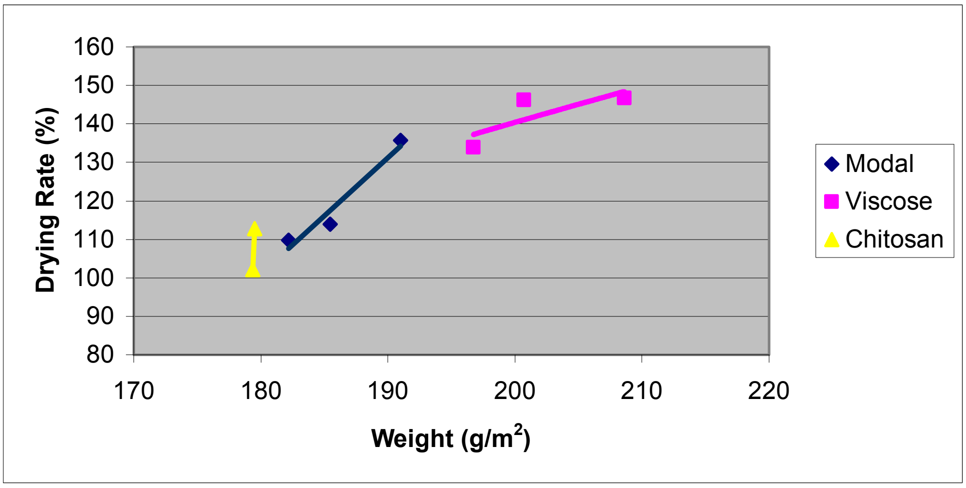


Figure 5.16: Weight against drying rates

Finally, the correlation between air permeability and drying rate is tested and it is found that for viscose fabrics (-0,339) drying rate decreases as air permeability increases whereas for cotton (0,776) and bamboo (0,760) fabrics the opposite correlation is observed (see Figure 5.17).

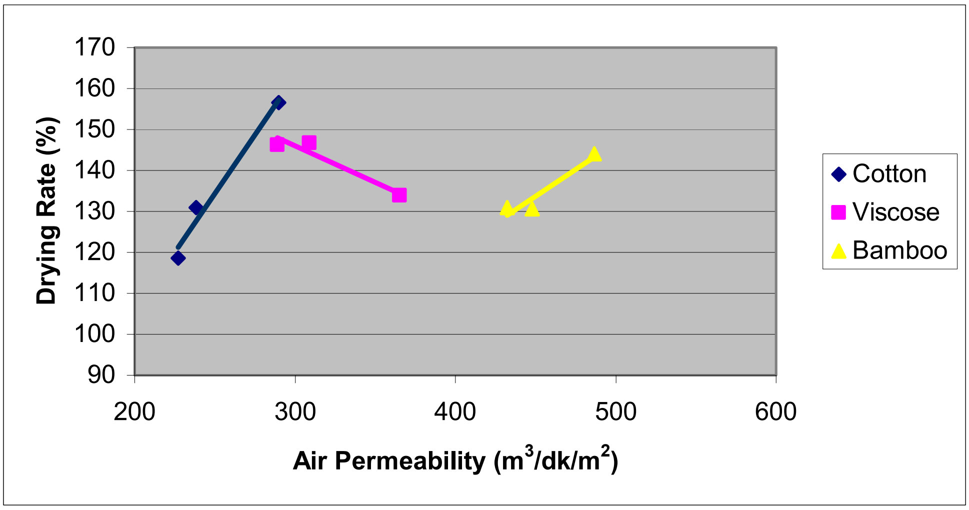


Figure 5.17: Air permeability against drying rate

5.2.3 Results of Transfer Wetting

The values got from test results are substituted in equation 5.1 so for each measurement points wetting proportions could be obtained.

$$C = \frac{C_1 - C_0}{C_r - C_0} \qquad \textbf{(5.1)}$$

C_1 = weight of wetted sample

C_0= weight of dry fabric

Cr= weight of wetting sample

As may be seen from the Figure 5.18 and Table 5.10; the transfer wetting of cotton fiber differs from the other fibers and has the lowest value and it is followed by viscose fabrics. On the other hand, the transfer wetting of micro modal fiber has the highest value. Especially micro modal medium fabric has the maximum transfer wetting rate after 30 minutes, while cotton slack fabric has the minimum.

Table 5.10: Transfer wetting rates during 30 minutes

Sample \ Min	**0**	**5**	**10**	**15**	**20**	**25**	**30**
11	0	0,08508	0,10687	0,12101	0,12937	0,14864	0,14924
12	0	0,09273	0,12766	0,14953	0,16349	0,17513	0,18605
13	0	0,11737	0,14801	0,16793	0,18622	0,19901	0,21245
21	0	0,18995	0,27141	0,30454	0,3363	0,35817	0,37961
22	0	0,25245	0,32898	0,38494	0,41937	0,45327	0,47731
23	0	0,16236	0,20729	0,2396	0,2624	0,28716	0,29779
31	0	0,14083	0,18362	0,218	0,23828	0,25609	0,2686
32	0	0,14841	0,18957	0,21642	0,23751	0,25389	0,26529
33	0	0,17303	0,21683	0,24646	0,26906	0,28984	0,30446
41	0	0,34403	0,40226	0,44118	0,4652	0,48338	0,50465
42	0	0,41301	0,47253	0,51289	0,542	0,56243	0,58062
43	0	0,30048	0,35361	0,37511	0,39781	0,40792	0,41591
51	0	0,16299	0,21178	0,2436	0,27143	0,2937	0,31691
52	0	0,23419	0,28656	0,31783	0,34052	0,36225	0,38066
53	0	0,19537	0,25182	0,28546	0,28911	0,34261	0,34973
91	0	0,29949	0,35542	0,39637	0,4218	0,44284	0,46534
92	0	0,19401	0,23662	0,25894	0,2822	0,30137	0,31248
101	0	0,1924	0,23663	0,27097	0,29549	0,31379	0,32636
102	0	0,23855	0,27968	0,30761	0,33268	0,34769	0,36855
103	0	0,23068	0,28512	0,31508	0,33358	0,34711	0,35469

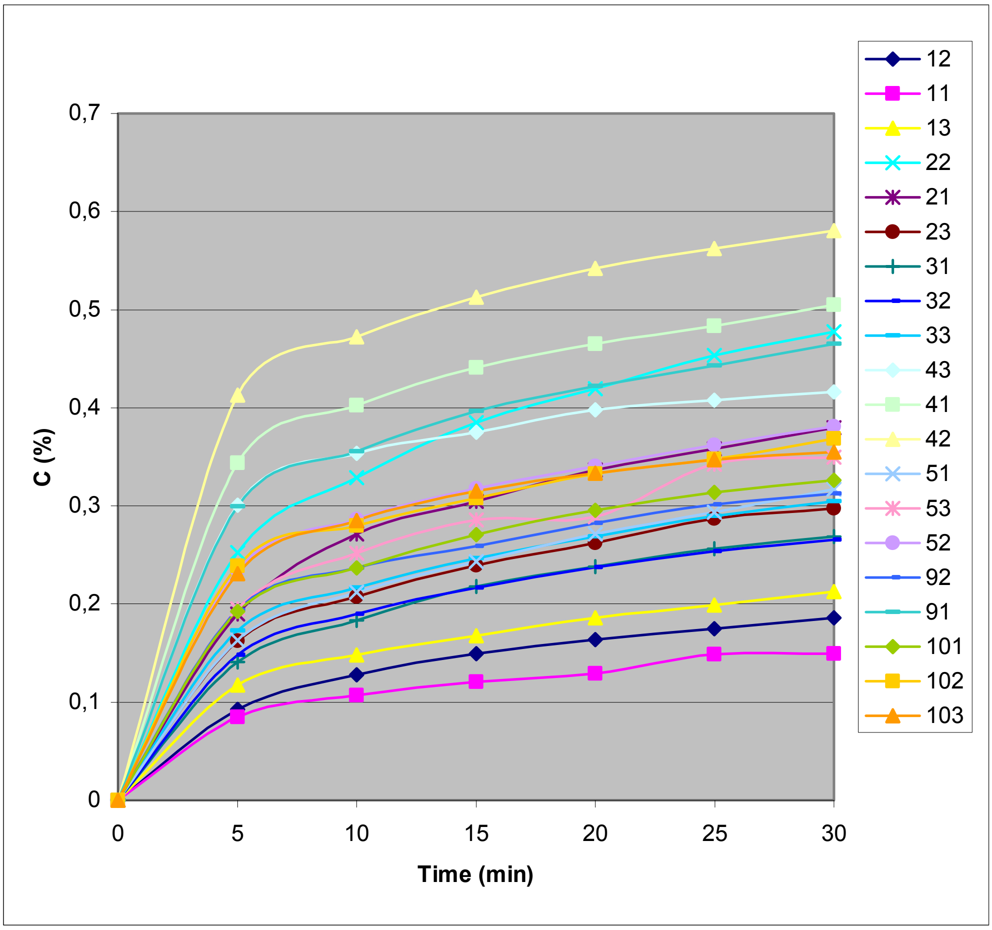


Figure 5.18: Transfer wetting rates of fabrics during 30 minutes

ANOVA results:

1. Effect of fiber type

According to the results; there is a statistically significant difference at the p< .05 level between transfer wetting rates of fiber groups [F(6,53)=13,696 p=0,000]. The effect size of eta squared is 0,608 which is quite high. For evaluating the difference between fibers post hoc test has also been done. This test shows that both modal-chitosan fibers (sig. 0,925) and bamboo-soybean fibers (sig. 0,984) follow the same pattern.

2. Effect of tightness factor

There is a statistically significant difference between transfer wetting of fabrics for different tightness values at 95 % significant level [F(19,40)=7,197 p= 0,000].

Bivariate correlation analysis results:

At the end of the 30 minute testing period, there is a correlation between thickness and transfer wetting rates (-0,691 $p<0{,}01$). This may demonstrate that transfer wetting of fabrics decreases as thickness increases. Especially this relationship stands out with modal fabrics (-0,705 $p<0{,}05$)

Also there is a – 0,459 correlation between mean transfer wetting rates of fibers and yarn twist at 99 % significant level which indicates that transfer wetting rates decreases as yarn twist increases. As may be seen from Figure 5.19; cotton yarn has the lowest transfer wetting values while its yarn twist is relatively higher. On the other hand, micro modal yarn twist is lowest and accordingly the samples from micro modal yarn give significantly higher wettability values.

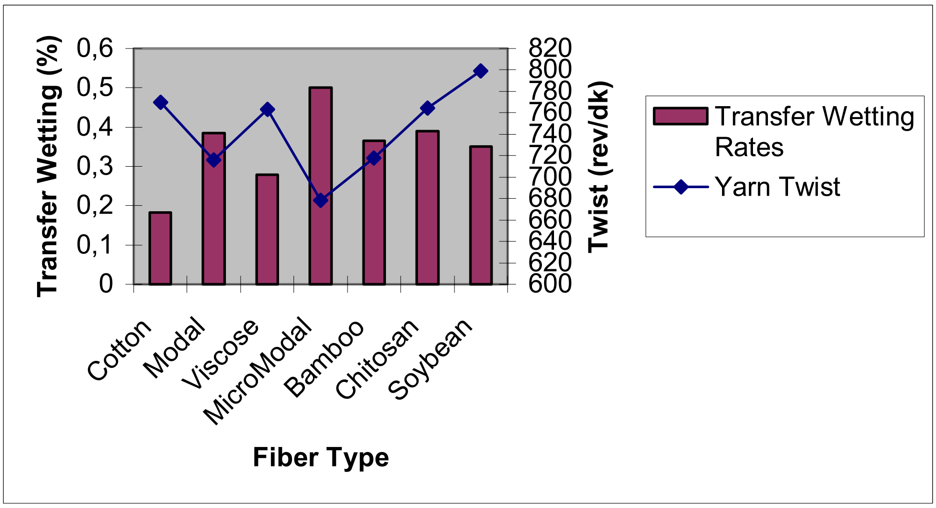


Figure 5.19: The relationship between yarn twist and mean transfer wetting rates of fibers

In the light of the literature survey, the correlation between transfer wetting and stitch density and weight were investigated, but no correlation could be found.

5.2.4 Results of Wicking

From the results in Figure 5.20 and Table 5.11; it appears that wicking of the cotton fabrics are the best. They are followed by chitosan, viscose and soybean in turn. For bamboo and chitosan fabrics; wicking heights decrease as tightness increases. On the other hand; for soybean and viscose fabrics the opposite is observed.

Table 5.11: Wicking of fabrics during 5 minutes

Min / Sample	0	0,5	1,0	1,5	2,0	2,5	3,0	3,5	4,0	4,5	5,0
11	0	2,33	3,07	4,03	4,60	5,00	5,40	5,67	6,07	6,30	6,47
12	0	2,20	3,03	3,67	4,13	4,57	4,93	5,17	5,47	5,70	5,93
13	0	2,33	3,33	3,93	4,40	4,80	5,10	5,43	5,67	5,93	6,13
21	0	0,87	1,50	1,93	2,37	2,83	3,07	3,37	3,73	3,93	4,13
22	0	0,97	1,40	1,83	2,13	2,40	2,70	2,90	3,10	3,37	3,67
23	0	1,07	1,57	2,10	2,57	2,93	3,23	3,53	3,73	4,00	4,17
31	0	0,53	1,23	1,77	2,10	2,63	3,07	3,33	3,60	3,90	4,17
32	0	1,43	2,40	3,00	3,50	4,07	4,43	4,80	5,10	5,33	5,60
33	0	1,87	2,83	3,37	3,93	4,30	4,63	4,97	5,17	5,30	5,67
41	0	1,07	1,57	2,03	2,43	2,77	3,00	3,27	3,53	3,80	4,00
42	0	1,83	2,53	2,87	3,23	3,50	3,80	3,93	4,17	4,33	4,47
43	0	1,73	2,43	2,80	3,13	3,43	3,63	3,80	4,00	4,23	4,37
51	0	1,27	1,87	2,47	2,97	3,30	3,60	3,83	4,03	4,23	4,43
52	0	0,70	1,23	1,73	2,10	2,43	2,70	2,97	3,17	3,37	3,63
53	0	0,53	0,87	1,33	1,63	1,87	2,13	2,47	2,67	2,83	3,07
91	0	2,67	3,60	4,13	4,60	4,97	5,30	5,60	5,83	6,13	6,33
92	0	2,60	3,53	4,10	4,50	4,97	5,27	5,53	5,87	6,10	6,27
101	0	1,10	2,20	2,90	3,17	3,63	3,90	4,13	4,33	4,60	4,80
102	0	1,80	2,67	3,10	3,53	3,83	4,10	4,37	4,53	4,70	5,00
103	0	1,60	2,40	3,03	3,40	3,80	4,10	4,33	4,60	4,80	5,10

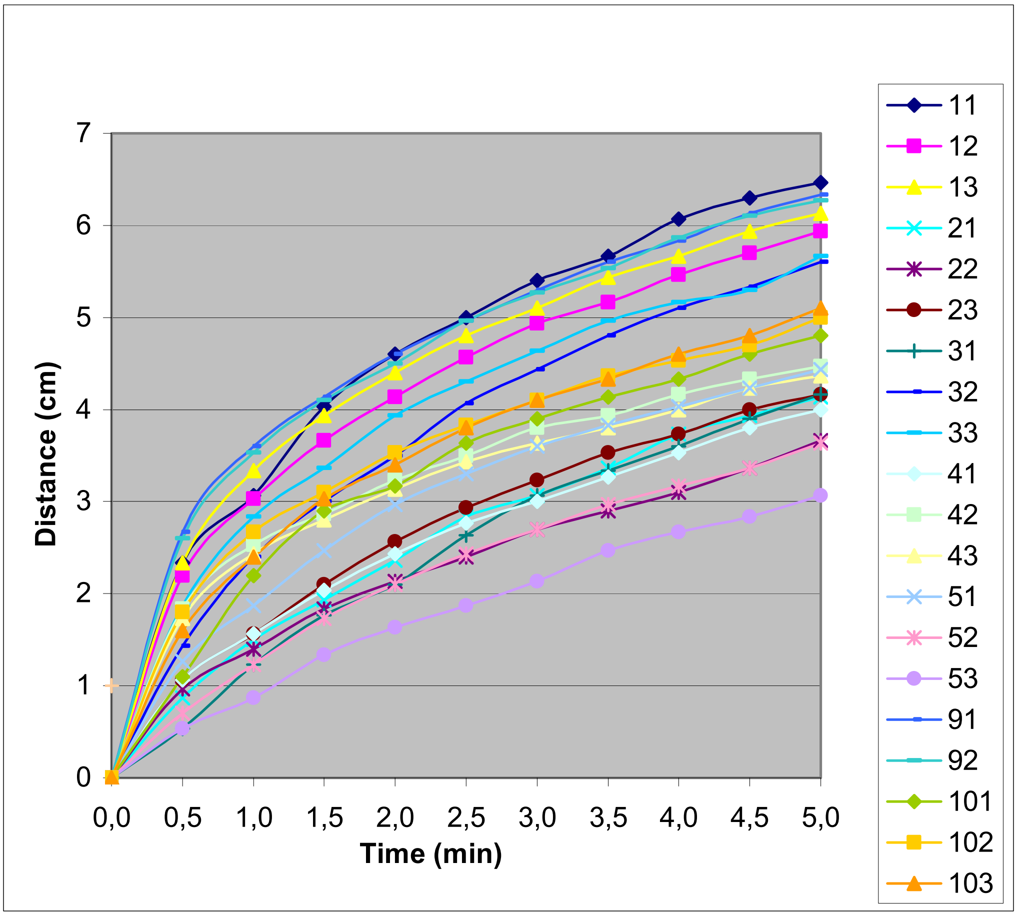


Figure 5.20: Wicking of fabrics during 5 minutes

ANOVA results:

1. Effect of fiber type

According to the results; there is a statistical significant difference at the $p < 0.05$ level between wicking heights of fiber groups [$F(6,53)=31,250$ $p=0,000$]. The effect size is 0, 77 which is quite high. For evaluating the difference between fibers, post hoc test has also been done. This test shows that modal and bamboo fibers whose wicking heights are low behave in the same manner (sig. 0,793).

2. Effect of tightness factor

There is a statistically significant difference between fabrics in terms of wicking for different tightness values of the samples at 95 % significant level [$F(19,40)=35,607$ $p=0,000$]. For wickability of micro modal, soybean and chitosan fabrics, tightness factor does not seem to be an influential parameter on wicking.

Bivariate correlation analysis results:

Statistical analysis demonstrate that there is a 0,689 correlation between thickness and wicking height of fabrics at 99 % significant level, which means wicking heights increase as thickness increases, but for viscose fabrics opposite correlation is observed (-0,910).

Also there is a 0,512 correlation between yarn twist and wicking heights of fabrics (99 % significant level). Especially this relationship stands out with soybean fabrics (0,871).

From the comparative study of the results, it is shown that there is a positive correlation between weight and wicking heights for modal (0,794) and viscose (0,714) fabrics correlation (95 % significant level), whereas it is negative for cotton fabrics (-0,737 $p<0,01$) (see Figure 5.21).

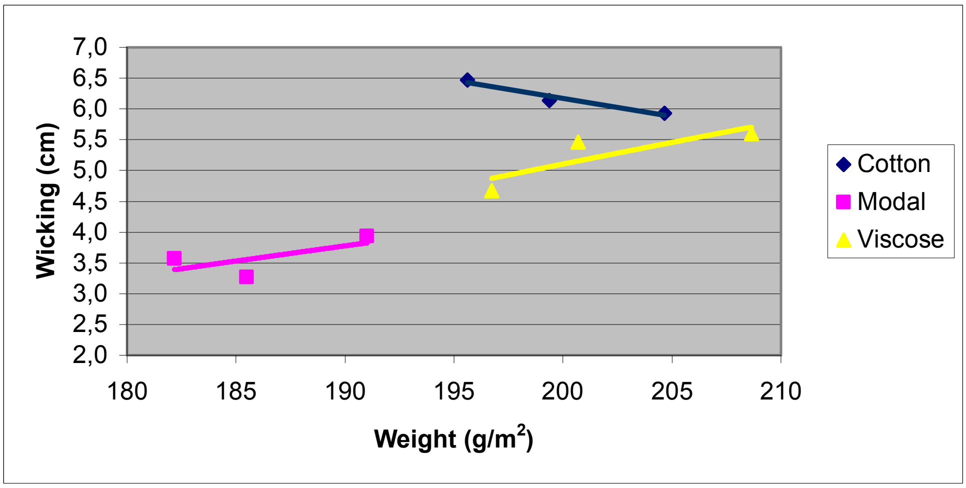


Figure 5.21: Weight against wicking heights

The correlation between wicking heights and stitch density of the samples are also tested and it is shown that there is a positive correlation between these two parameters for modal (0,0859 $p<0,05$), viscose (0,936 $p<0,01$) and bamboo (0,790 $p<0,05$) fabrics which demonstrate that wicking heights increase as stitch density increases for these fabrics (see Figure 5.22).

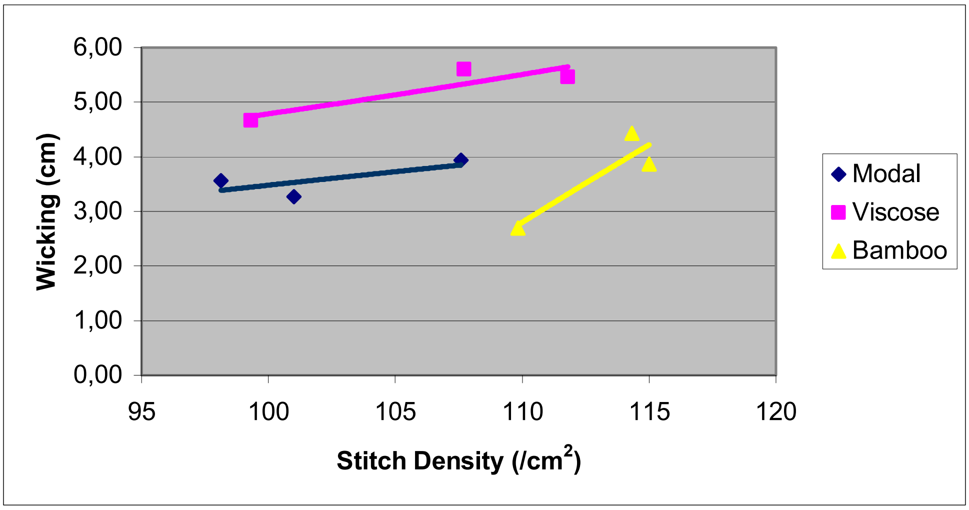


Figure 5.22: Stitch density against wicking

The correlation between transfer wetting and wicking of the samples is -0,426 at 99 % significant level. This result may also be seen from the values obtained. For instance, although cotton and chitosan fabrics have higher wicking heights, their transfer wetting rates are significantly lower compared to the other fabrics. However, for modal and micro modal fabrics opposite situation is observed.

5.2.5 Results of Water Vapor Permeability of Fabrics

Figure 5.23 and Table 5.12, reveal that chitosan fabrics give the highest water vapor permeability values whereas cotton fabrics have the lowest values. Chitosan fabrics are followed by bamboo, micro modal and soybean fabrics. For micro modal fabrics, water vapor permeability increases as tightness increases.

Table 5.12: Water vapor permeabilty of fabrics

Fabric Type	MVTR ($g/m^2 24h$)
11	481,64
12	511,75
13	483,62
21	512,26
22	524,97
23	479,27
31	502,66
32	498,25
33	498,36
41	483,84
42	511,75
43	538,64
51	525,76
52	514,86
53	528,19
91	595,08
92	542,20
101	500,62
102	518,93
103	511,24

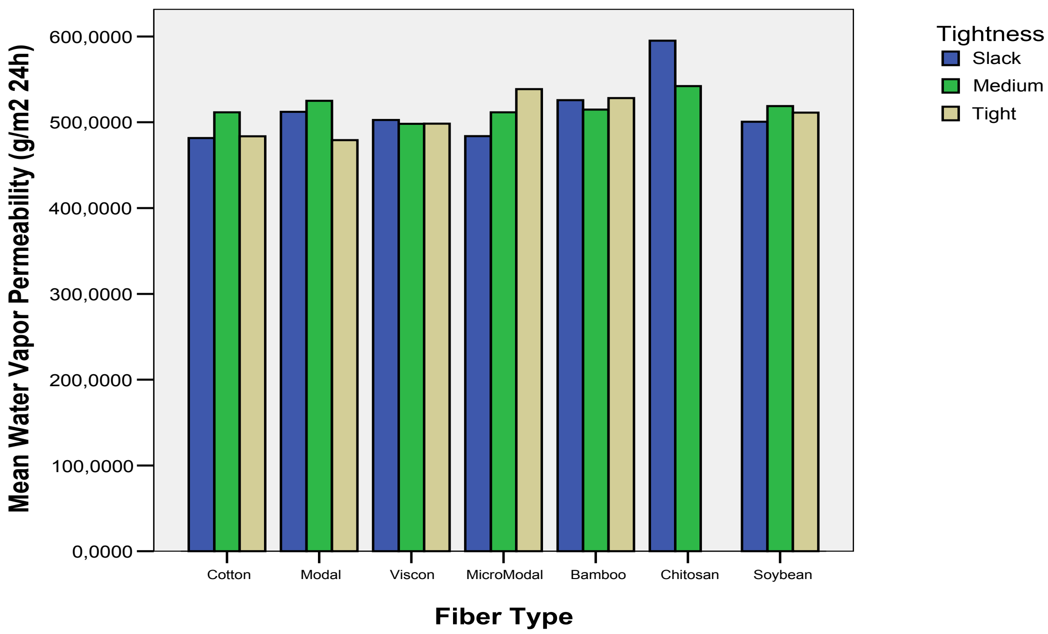


Figure 5.23: Water vapor permeabilities of fabrics

ANOVA results:

1. Effect of fiber type

ANOVA results show that fiber type has a statistically significant effect on water vapor permeability [F(6,53)=15,429 p=0,000]. For evaluating the difference between fibers, post hoc test has also been done. In the light of the results of the tests, it may be concluded that chitosan fabrics differ significantly from the others. Micro modal and soybean fabrics, on the other hand, perform in the same way as far as water vapor permeability is concerned (sig. 0,884).

2. Effect of tightness factor

ANOVA analysis also implies that changes in tightness affect water vapor permeability for each fiber type studied.

Bivariate correlation analysis results:

From the comparative study of the results, it is shown that water vapor permeability increases for cotton (0,932), micro modal (0,728), chitosan (1.00) and soybean (0,975) fabrics as weight increases. In the case of viscose, bamboo and modal fabrics, however, the relation between water vapor permeability and weight is different from the fabrics mentioned above such that water vapor permeability decreases, as thickness increases (-0,764, - 0,996 and -0,772) (see Figure 5.24).

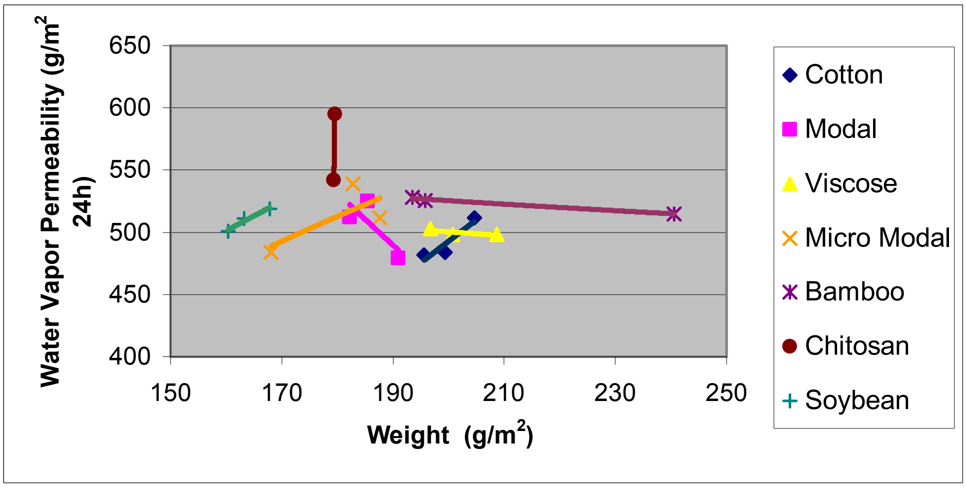


Figure 5.24: Weight against water vapor permeability

Moreover, there is a negative correlation between stitch density and water vapor permeability for cotton, bamboo, soybean and chitosan fabrics at 95 % significant level whereas it is positive for viscose fabrics (0,908) (see Figure 5.25).

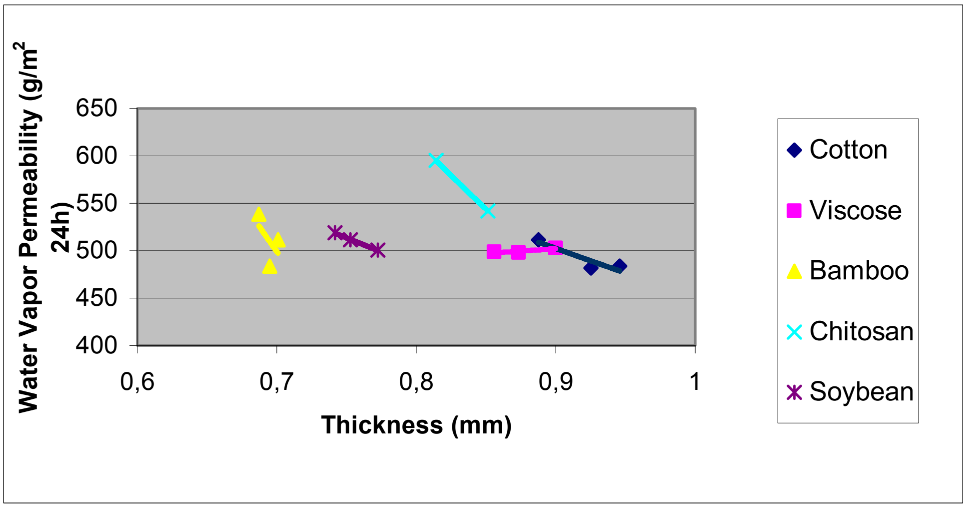


Figure 5.25: Thickness against water vapor permeability

5.2.6 Results of Heat Transfer

Two different test methods have been used to evaluate the heat transfer coefficients of fabrics. One of them is convection coefficient of fabrics and the other is conduction coefficient of fabrics.

5.2.6.1. Conduction Coefficients of Fabrics

In the Figure 5.26 and Table 5.13; it may be seen cotton fabrics have the highest conduction coefficients values whereas soybean fabrics have the lowest ones. Cotton fabrics are followed by viscose and modal fabrics in turn. For bamboo, micro modal and chitosan fabrics, the conduction coefficient increases as tightness factor increases, whereas, for modal and viscose fabrics; values decrease as tightness increases. For soybean and cotton fabrics a different pattern of behavior is observed, when compared to the other samples.

Table 5.13: Conduction coefficients of fabrics

Fabric Type	K_R (W/m.°C)x10^{-2}	R_I (m^2.°C/W)x10^{-2}
11	5,07	1,93
12	3,64	2,56
13	5,21	1,91
21	3,94	1,94
22	3,76	1,93
23	3,55	2,07
31	4,97	1,98
32	4,48	2,03
33	4,43	2,03
41	3,12	2,32
42	3,16	2,2
43	3,24	2,14
51	2,93	2,5
52	3,05	2,46
53	3,26	2,3
91	3,06	2,77
92	3,35	2,57
101	3,02	2,61
102	2,79	2,65
103	2,91	2,62

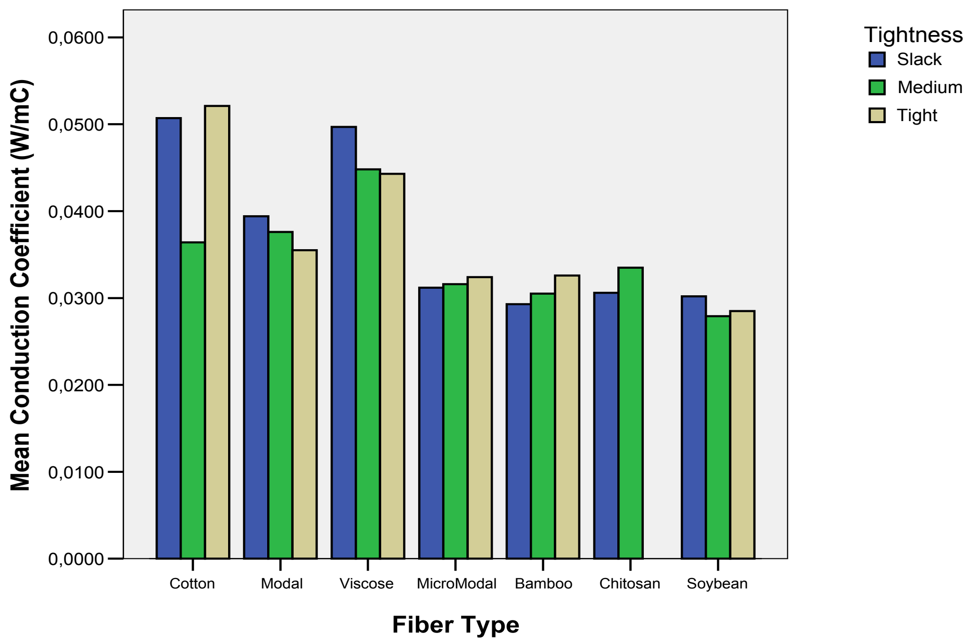


Figure 5.26: Conduction coefficients of fabrics

ANOVA results:

1. Effect of fiber type

In accordance with ANOVA results, it is clear that there is a statistical significant difference ($p< .05$ level) between conduction coefficients of fabrics [$F(6,53)=44,799$ $p=0,000$]. For evaluating the difference between fibers, post hoc test has also been done. It shows that conduction coefficients of modal fiber differ significantly from other fibers. Also, viscose-cotton (sig 0,932) and micro modal-chitosan (sig. 0,855) fabrics present a similar pattern for the behavior of the conduction coefficient.

2. Effect of tightness factor

The analysis demonstrates that there is a statistically significant difference between fabrics tightness and conduction coefficients of fabrics at 95 % significant level.

Bivariate correlation analysis

Statistical analysis demonstrate that there is a 0,791 correlation between thickness and conduction coefficient at 99 % significant level which means conduction coefficient increases as thickness increases. Furthermore, it helps to explain 62,56 % of variances in conduction coefficient of fabrics. From the comparative results, it is shown that correlation between thickness and conduction coefficient for cotton is 0,961, viscose is 0,947, chitosan is 0,999 and soybean is 0,990 at 99 % significant level (see Figure 5.27).

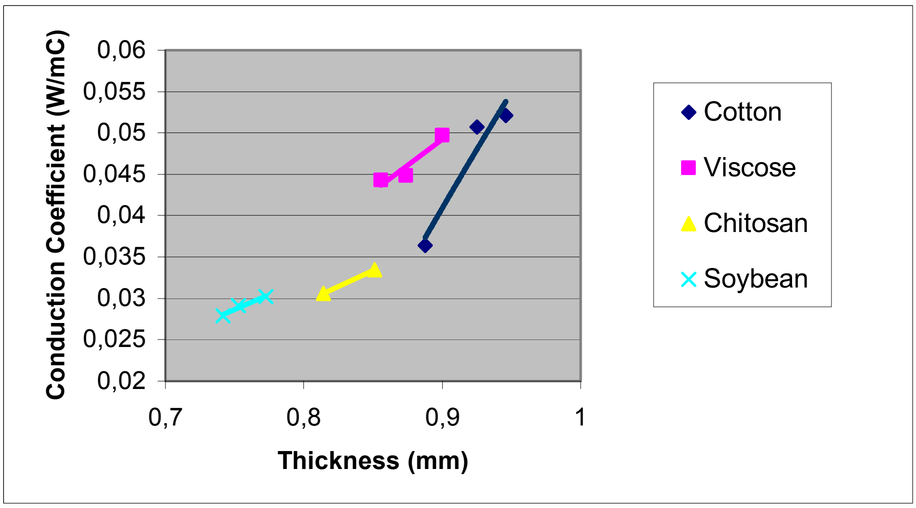


Figure 5.27: Thickness against conduction coefficient

The correlation between moisture regain and conduction coefficient of the samples are also tested and it is shown that there is a high correlation between these two parameters for bamboo (-0,708 p<0,05), viscose (-0,958 p<0,01), soybean (-0,746 p<0,05) and chitosan (0,997 p<0,01). However, for chitosan fabrics it is observed that the correlation is positive, which means conduction coefficient increases as moisture regain increases (see Figure 5.28).

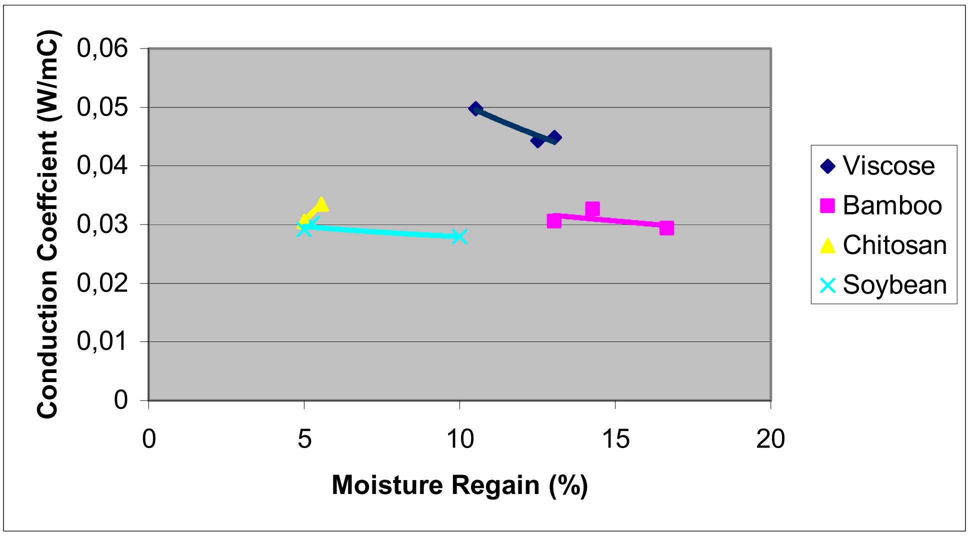


Figure 5.28: Moisture regain against conduction coefficient

In the light of the statistical analysis, there is a negative correlation between stitch density and conduction coefficients for modal (-0,983), viscose (-0,970), bamboo (-0,881) and soybean (-0,875) fabrics at 99 % significant level whereas for micro modal (0,735 p<0,05) and chitosan (0,999 p<0,01) fabrics, it is positive (see Figure 5.29).

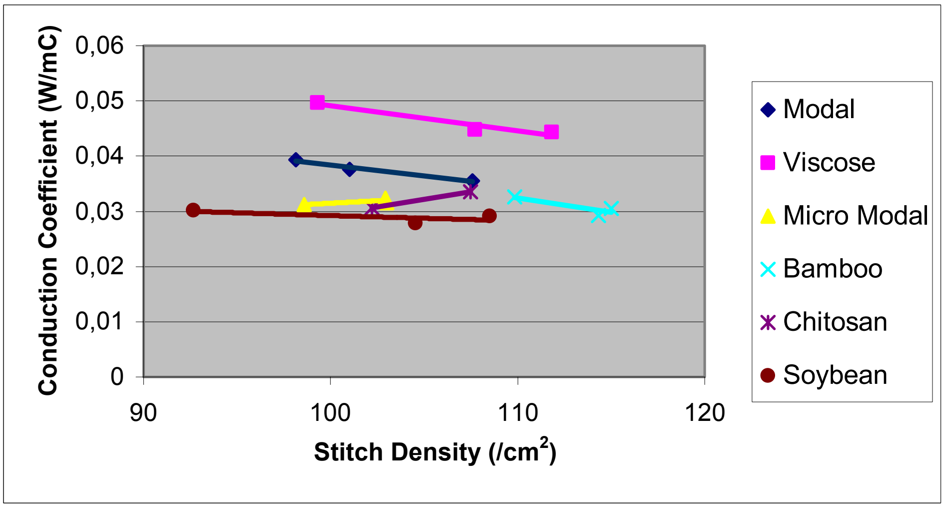


Figure 5.29: Stitch density against conduction coefficient

5.2.6.2. Convection Coefficients of Fabrics

Figure 5.30 and Table 5.14 reveal that cotton fabrics have the highest convection coefficient values whereas micro modal fabrics have the lowest ones. Cotton fabrics are followed by bamboo, modal and viscose fabrics in turn. For viscose, micro modal and chitosan fabrics, the convection coefficient increases as tightness factor increases, whereas, for soybean fabrics; values decrease as tightness factor increases.

Table 5.14: Convection coefficients of fabrics

Fabric Type	K_T (W/m.°C)x10^{-2}	R_T (m2.°C/W)x10^{-2}
11	8,7873	0,1138
12	10,3298	0,0968
13	8,2031	0,1219
21	8,5182	0,1174
22	9,0727	0,1102
23	8,8634	0,1128
31	8,2984	0,1205
32	8,5680	0,1167
33	8,6470	0,1156
41	7,2083	0,1387
42	8,3529	0,1197
43	8,5877	0,1164
51	8,9850	0,1112
52	8,8275	0,1133
53	9,2588	0,1080
91	8,0116	0,1248
92	8,9835	0,1113
101	8,5514	0,1169
102	8,1825	0,1222
103	7,8899	0,1267

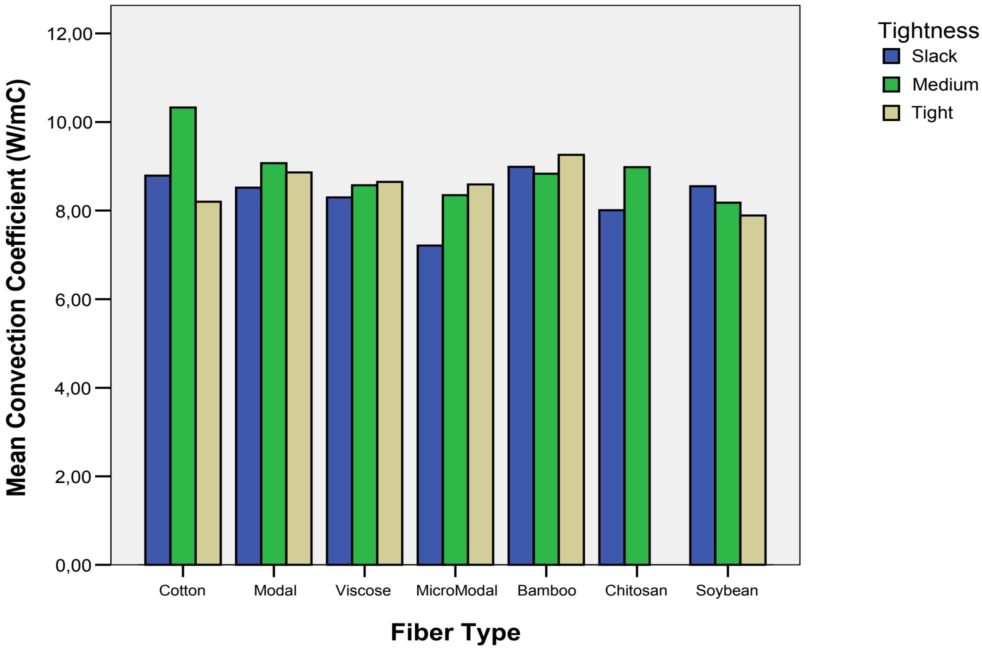


Figure 5.30: Convection coefficients of fabrics

ANOVA results:

1. Effect of fiber type

ANOVA results show that fiber type is an influential parameter for convection coefficients of fabrics [F(6,53)=5,634 p=0,000 95% significant level]. The effect size (eta squared) is 0,3893 which is high. For evaluating the difference between fibers, post hoc test has also been done. Chitosan-viscose (sig. 0,965) and cotton-bamboo (sig. 0,742) fabrics appear to present a similar pattern for the behavior of convection coefficients.

2. Effect of tightness factor

From the ANOVA results, it may be concluded that fabric tightness has a statistically significant effect on convection coefficients of fabrics [F(19,40)= 10918,089 p=0,00 95 % significant level].

Bivariate correlation analysis results:

Bivariate correlation analysis demonstrate that, there is a negative correlation between thickness and convection coefficients for cotton (-0,996), modal (-0,904) and viscose (-0,980) fabrics at 99 % significant level which means convection coefficient decreases as thickness increases. However, for soybean and chitosan fabrics, it observed that the correlation is positive, which means convection coefficient increases as thickness increases (Figure 5.31).

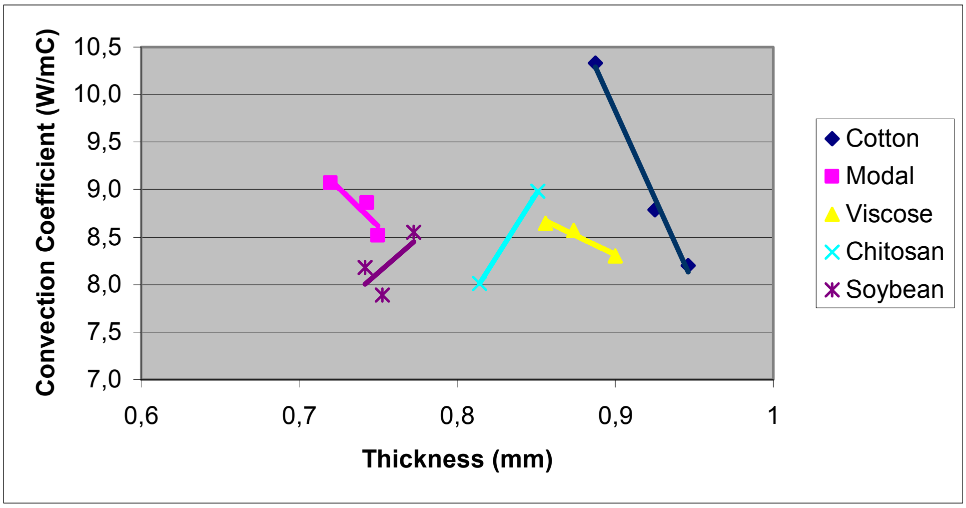


Figure 5.31: Thickness against convection coefficient

The correlation between air permeability and convection coefficient is tested and it is found that for cotton (0,784 $p<0,05$) and modal (0,843 $p<0,01$)fabrics convection coefficient increases as air permeability increases whereas for viscose (-0,887) and micro modal (-0,812) fabrics the negative correlation is observed at 99 % significant level (Figure 5.32).

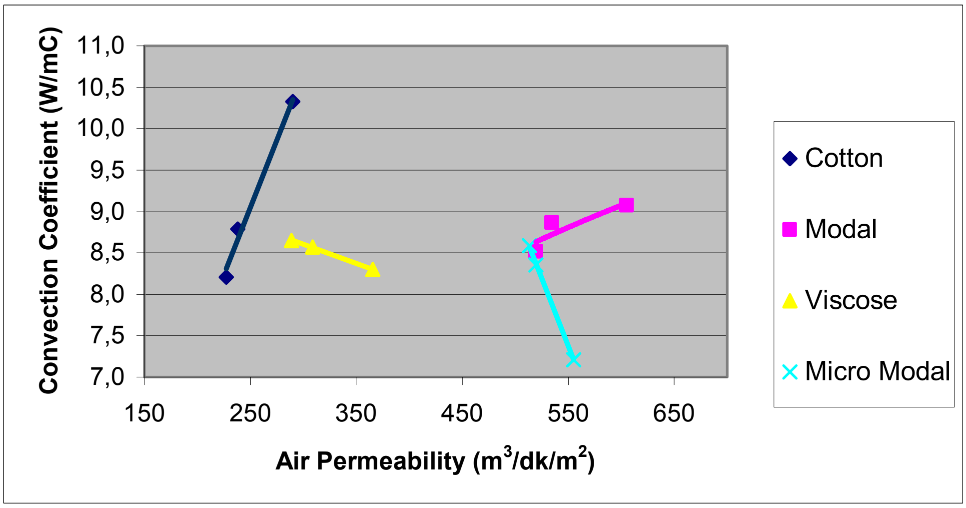


Figure 5.32: Air permeability against convection coefficient

Statistical analysis demonstrate that correlation between moisture regain and convection coefficient for viscose is 0,910 ($p<0,01$) whereas it is 0,790 ($p<0,05$) for modal fabrics. In the case of micro modal and chitosan fabrics, however, the relation between moisture regain and convection coefficient is different from the fabrics mentioned above such that convection coefficient decreases as moisture regain increases (see Figure 5.33).

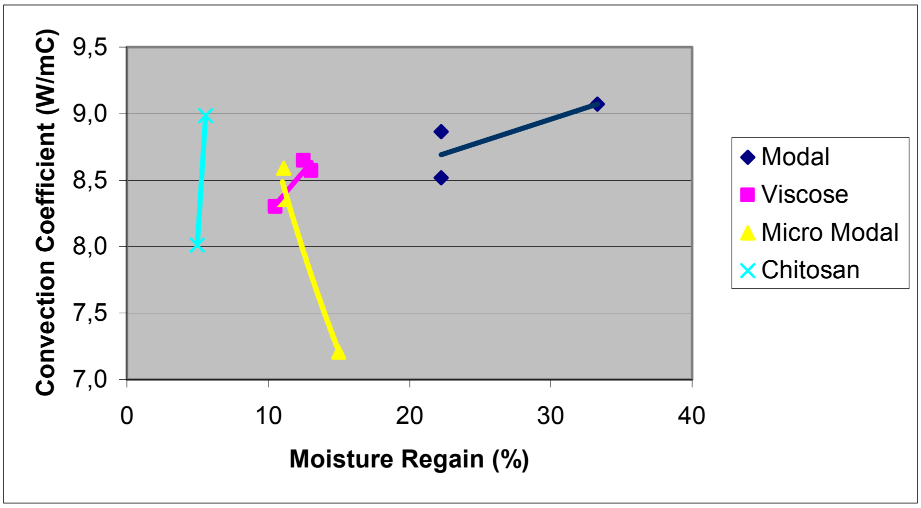


Figure 5.33: Moisture regain against convection coefficient

In accordance with correlation results, it is clear that there is a 0,900 correlation between stitch density and convection coefficients of fabrics at 95 % significant level which implies that convection coefficient increases as stitch density increases. Especially high correlation values are obtained at 99 % significant level for viscose (0,993), micro modal (0,984), chitosan (1.00) whose convection coefficient increases as stitch density increases while bamboo (-0,996), and soybean fabrics (-0,978) whose ones decrease as stitch density increases (Figure 5.34).

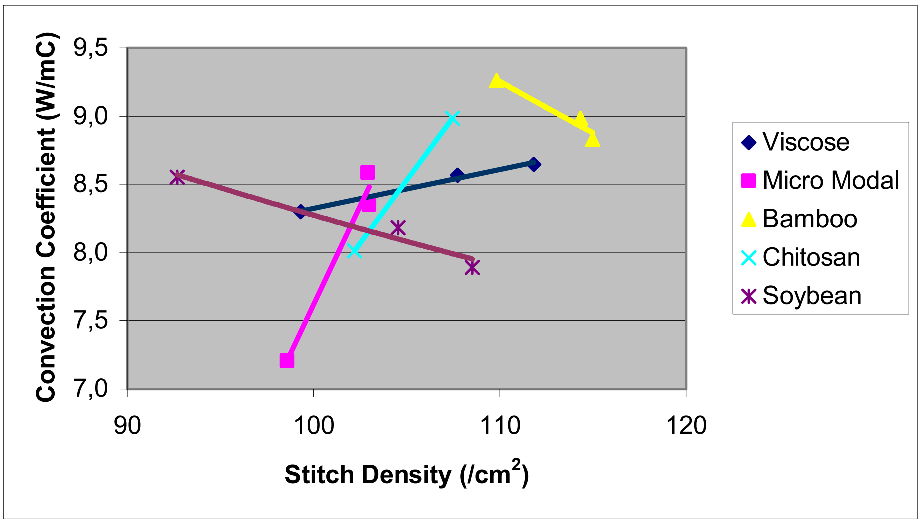


Figure 5.34: Stitch density against convection coefficient

6. MODELLING OF HEAT TRANSFER BEHAVIOR OF KNITTED FABRIC USING FEM

For simplicity reasons 12 sock made of cotton was selected for modeling the heat transfer behavior of the socks under discussion.

6.1. Drawing Part

Before the FEM analysis, CAD part of modeling has been completed. Since the base part of the sock has the largest contact area with the foot, the fabric structure for this part was selected for CAD modeling.

CATIA V5R16 was used to draw the knitting part. All the dimensions given for the model represent the realistic measurements taken from the sample.

In Figures 6.1, 6.2 and 6.3; the front, side and back view of the drawing can be seen.

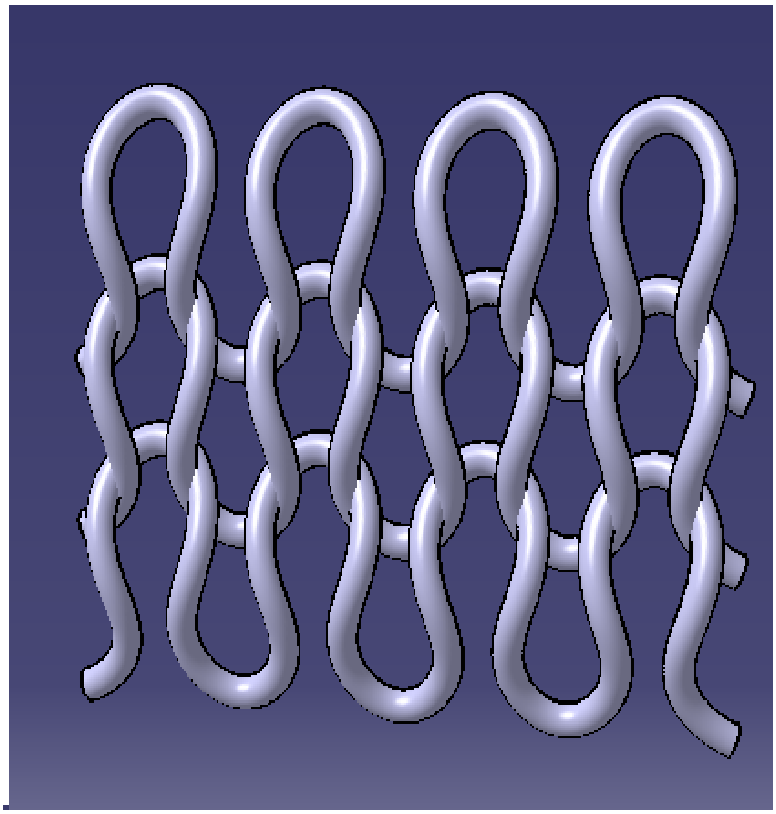


Figure 6.1: Front view of the knitting part

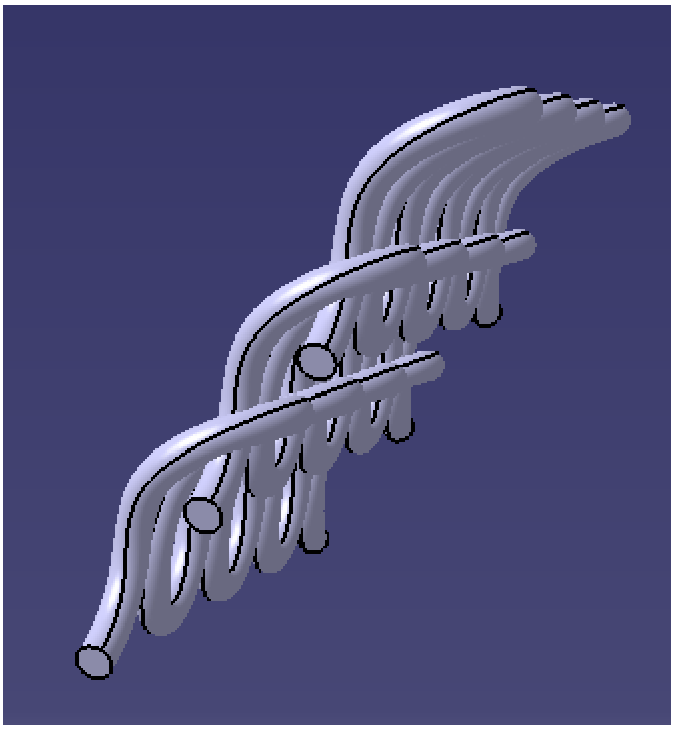


Figure 6.2: Side view of the knitting part

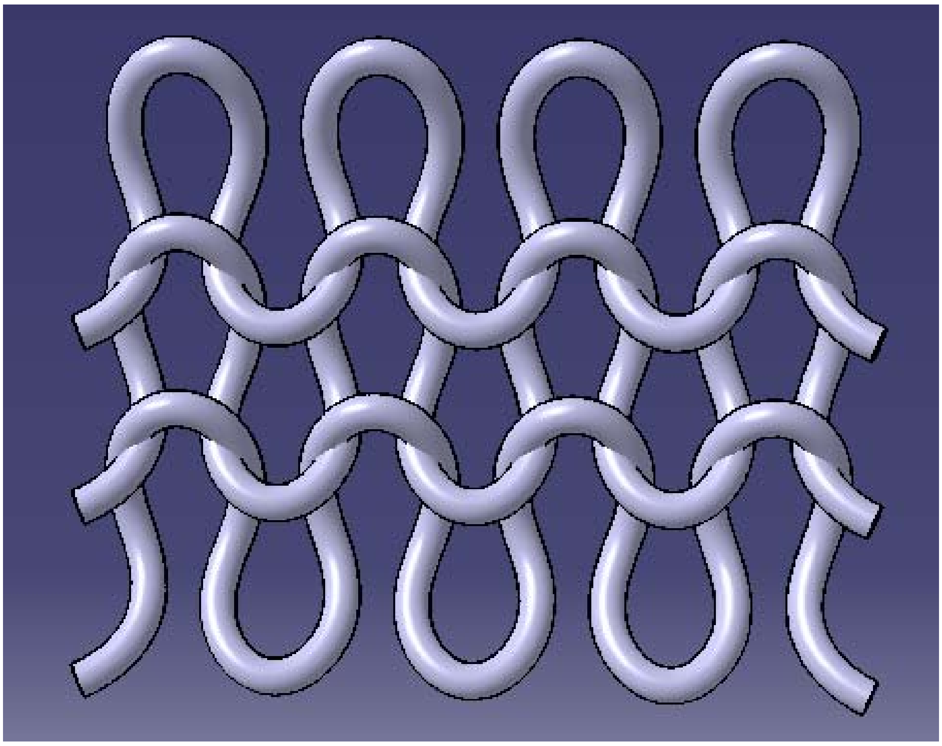


Figure 6.3: Back view of the knitting part

Having fabric modeling been completed, three plates were drawn; which of two show cold unit and one of them shows the hot unit. From Figure 6.4 and 6.5, the details of the whole system can be seen.

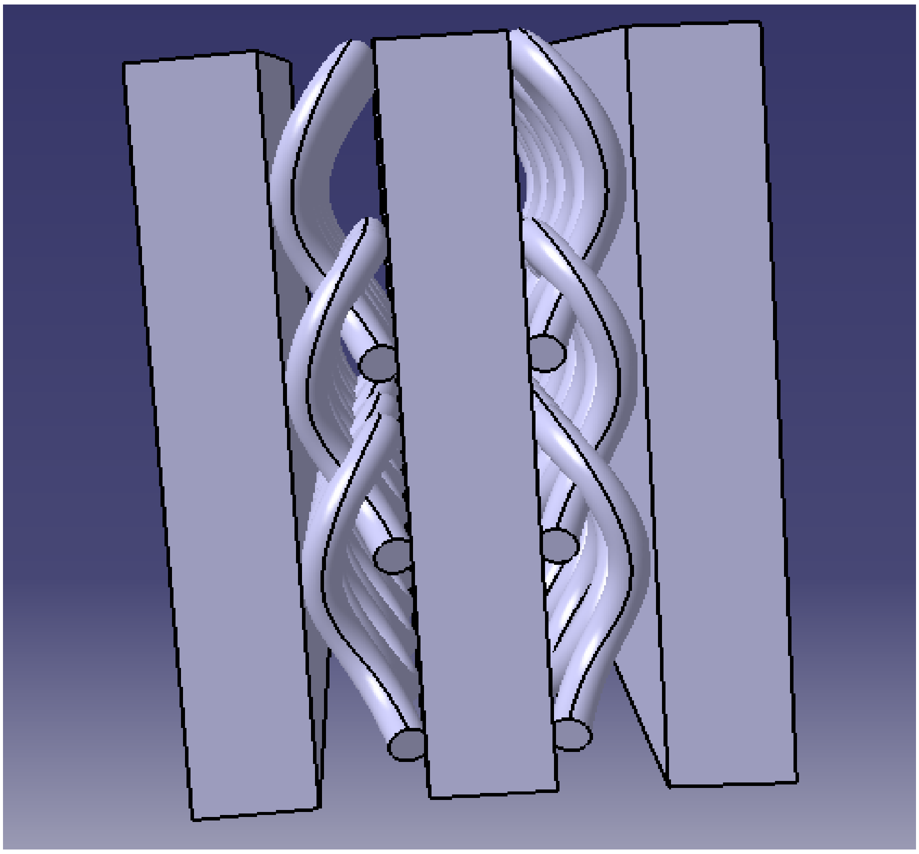


Figure 6.4: Front view of the system with plates

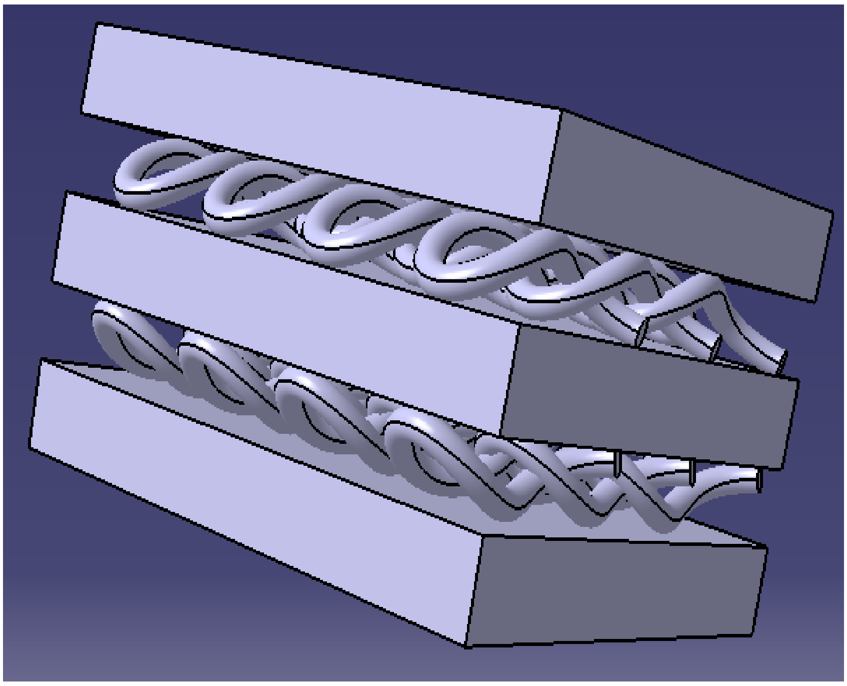


Figure 6.5: Side view of the system with plates

Following that, the unit was imported into ANSYS Workbench.

6.2 FEM Part

In ANSYS Workbench the program details regarding the contact points were also defined (see Figures 6.6 and 6.7).

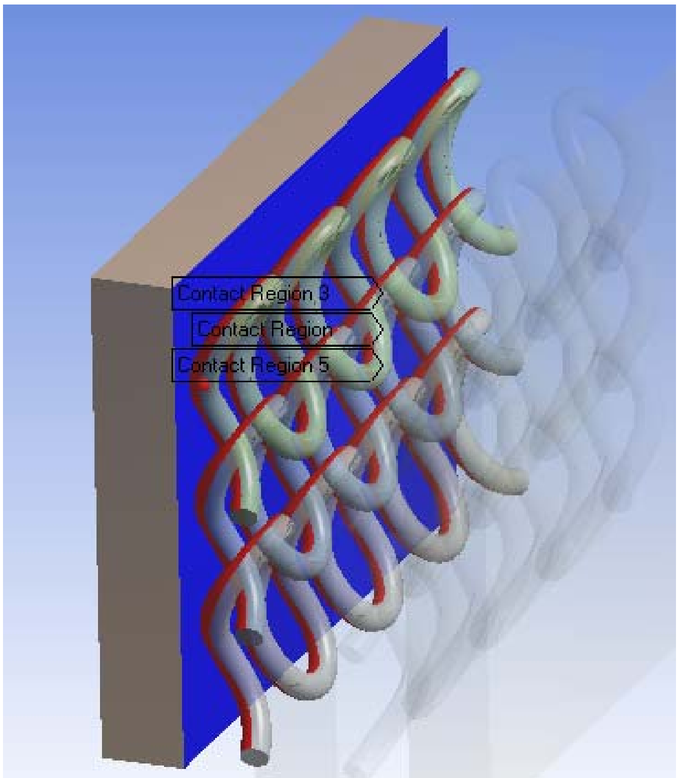


Figure 6.6: Contact regions between stitches and plate

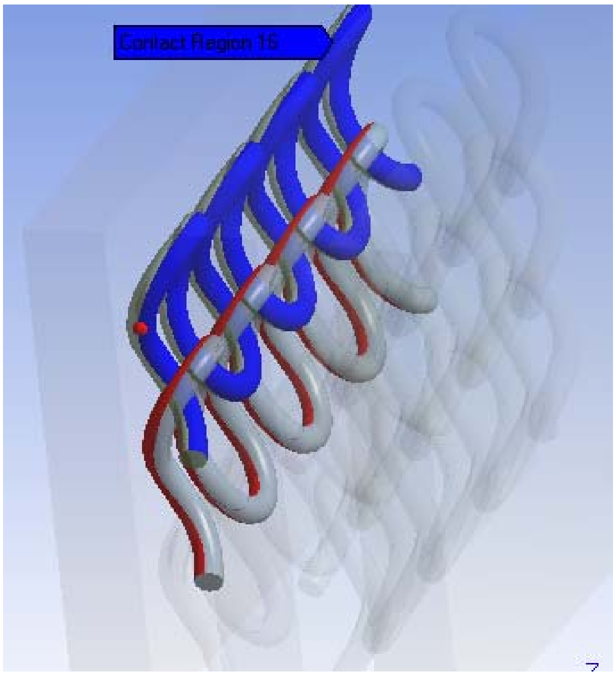


Figure 6.7: Contact regions between stitches

After the contact regions were defined to the system, it was ready for meshing. At first, mesh size was chosen with high values but the results were not satisfying. Then meshing was done with lower mesh size (see Figures 6.8 and 6.9).

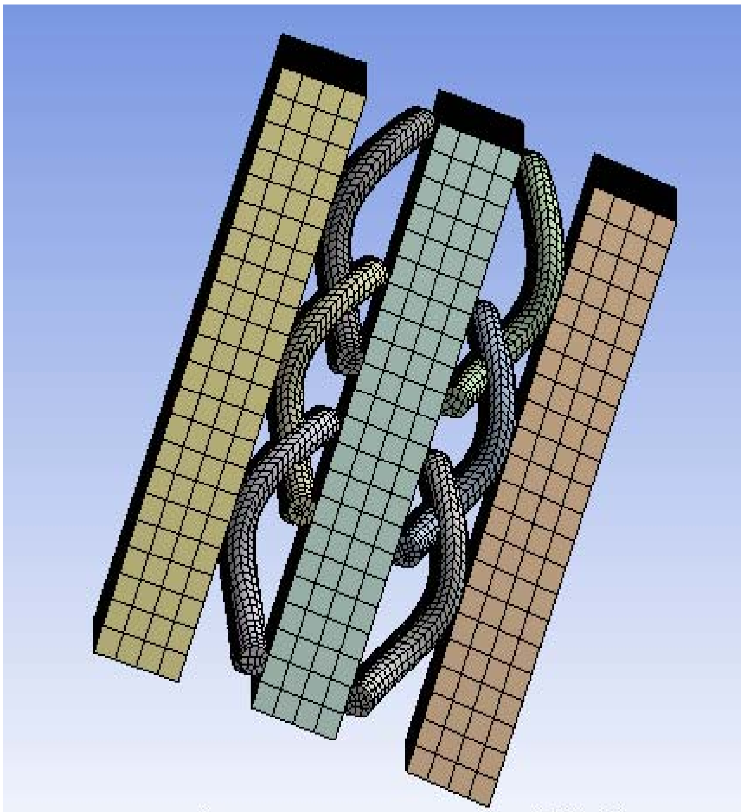


Figure 6.8: Meshed view of both plates and stitches

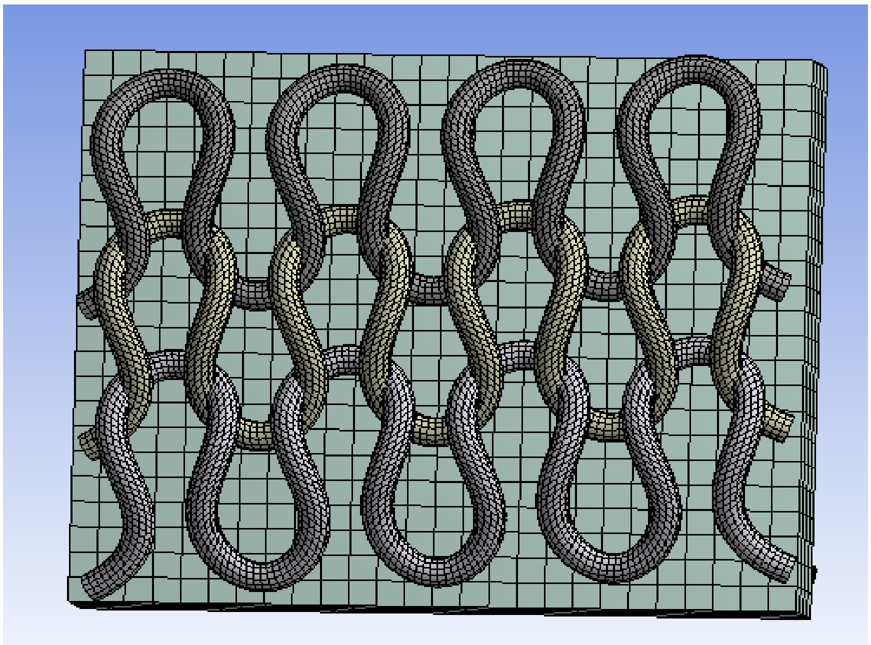


Figure 6.9: Front view of meshed stitches

Boundary conditions for temperatures of plates were needed to obtain the heat flux of the fabric model. The data obtained from the experimental study were fed to the environment menu of the program. The data is shown in Table 6.1 (see Figure 6.10 and 6.11).

Table 6.1: Temperatures of plates

Plates	Temperature (^{0}C)
Plate 1& 3	36.59
Plate 2	23.88

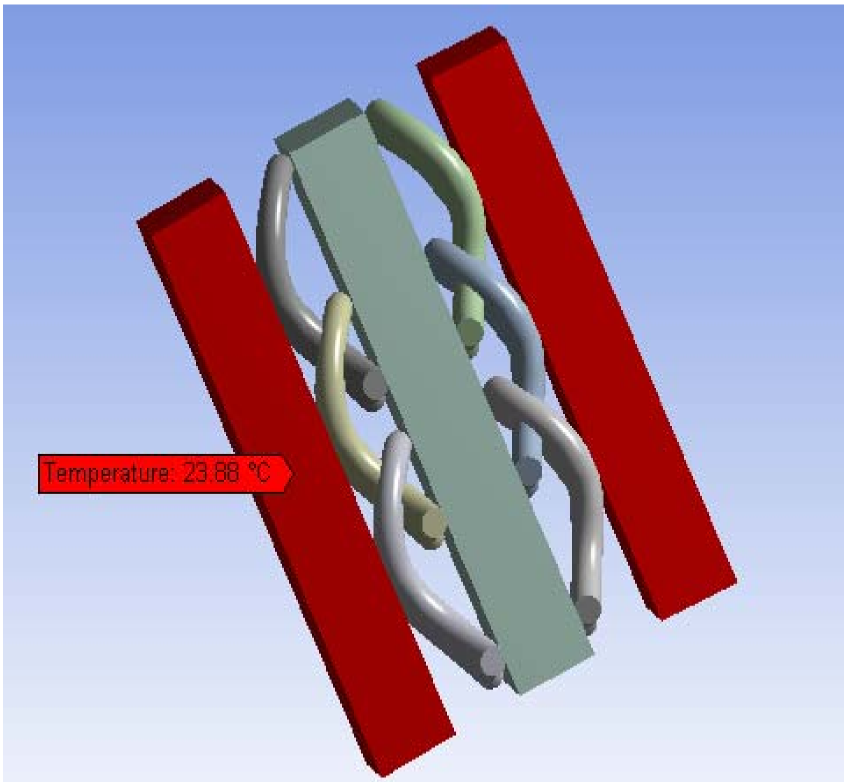


Figure 6.10: Boundary conditions for cooling plates

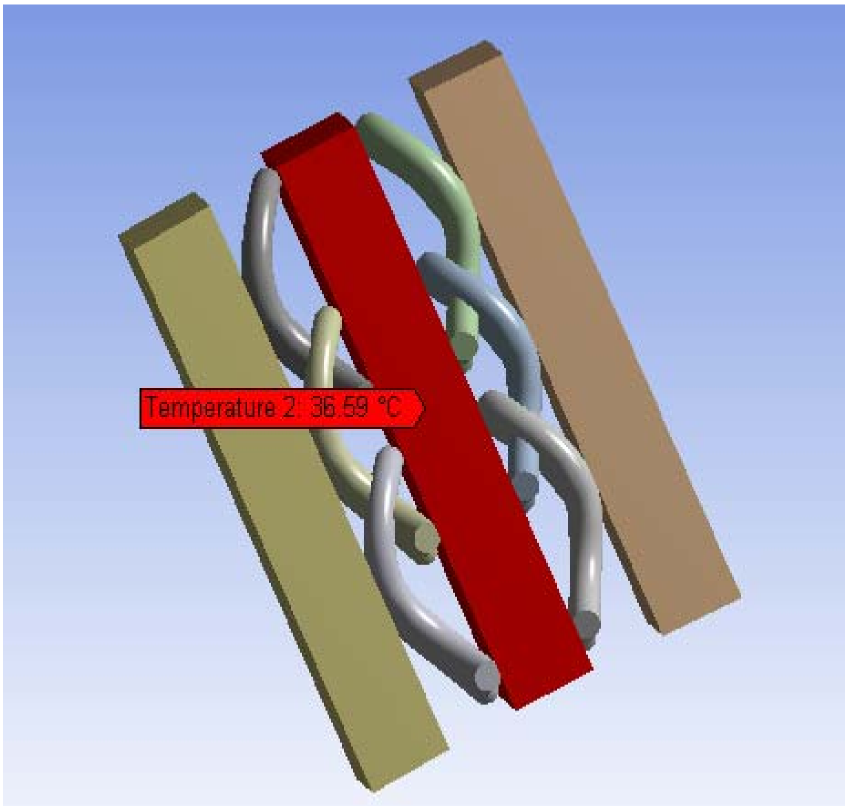


Figure 6.11: Boundary condition for heating plate

With reference to the literature, thermal conductivity of cotton fiber, which is 0.03 (W/mK) is accesed to the program [61].

6.3 FEM Results

In Figures 6.12 and 6.13; temperature distribution of the system is shown. As can be seen from these figures, the part of the fabric which is contact with the hot plate, has the highest temperature; whereas, the part contacting the cold plates has the lowest values.

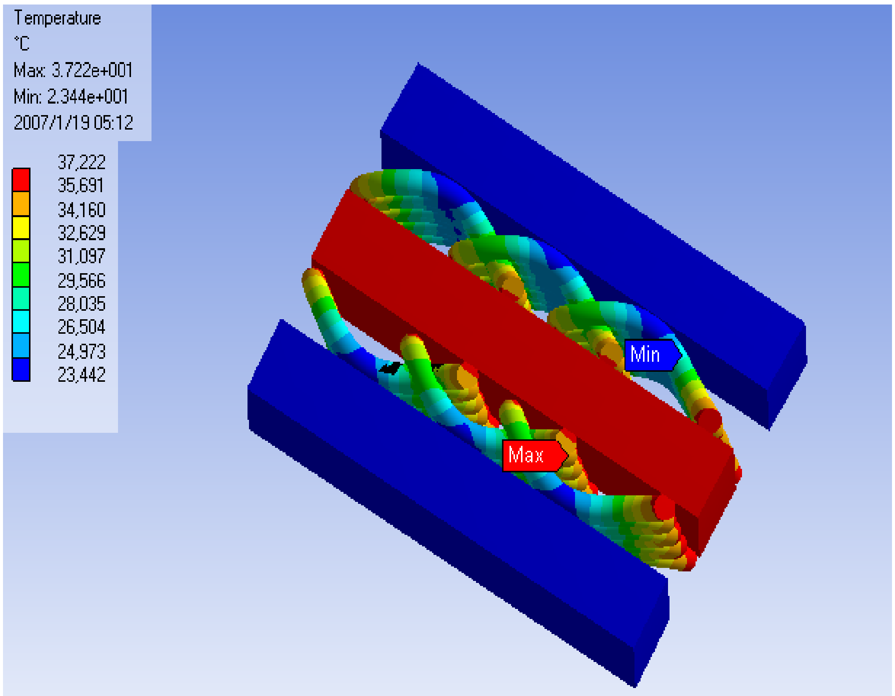


Figure 6.12: Temperature distribution of the system

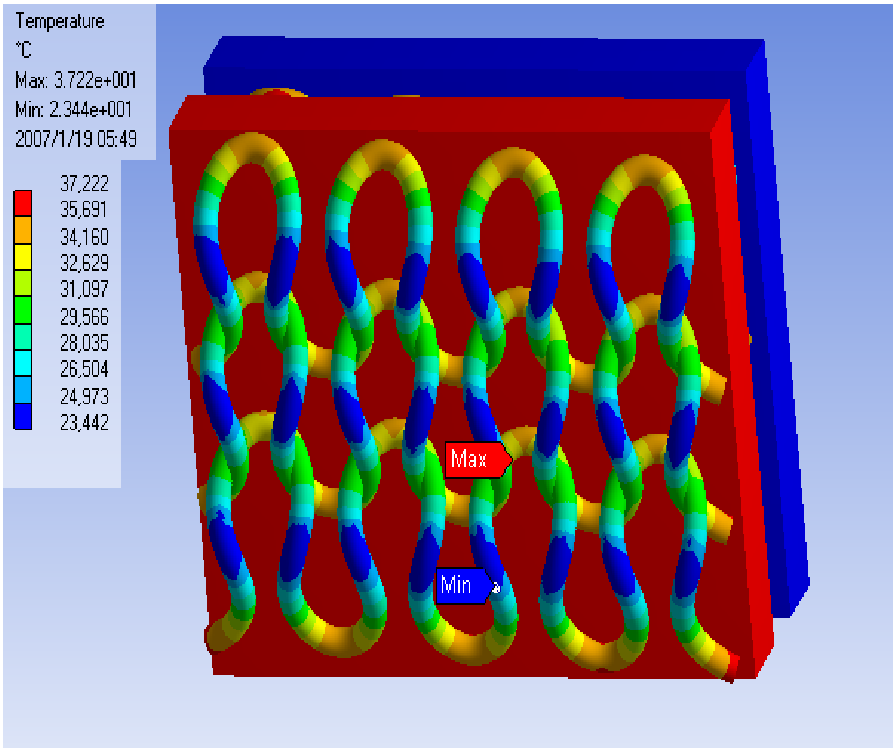


Figure 6.13: Front view of the temperature distribution of the knitting part

In Figures 6.14 to 6.16, total heat flux and heat flux in z direction are shown. As mentioned 4.1.1 heat flux and x and y directions, are omitted. It was observed that heat flux in the knitting part contacting the hot plate was at its minimum value. On the other hand, heat flux had its maximum values in the knitting parts contacting the cold plates.

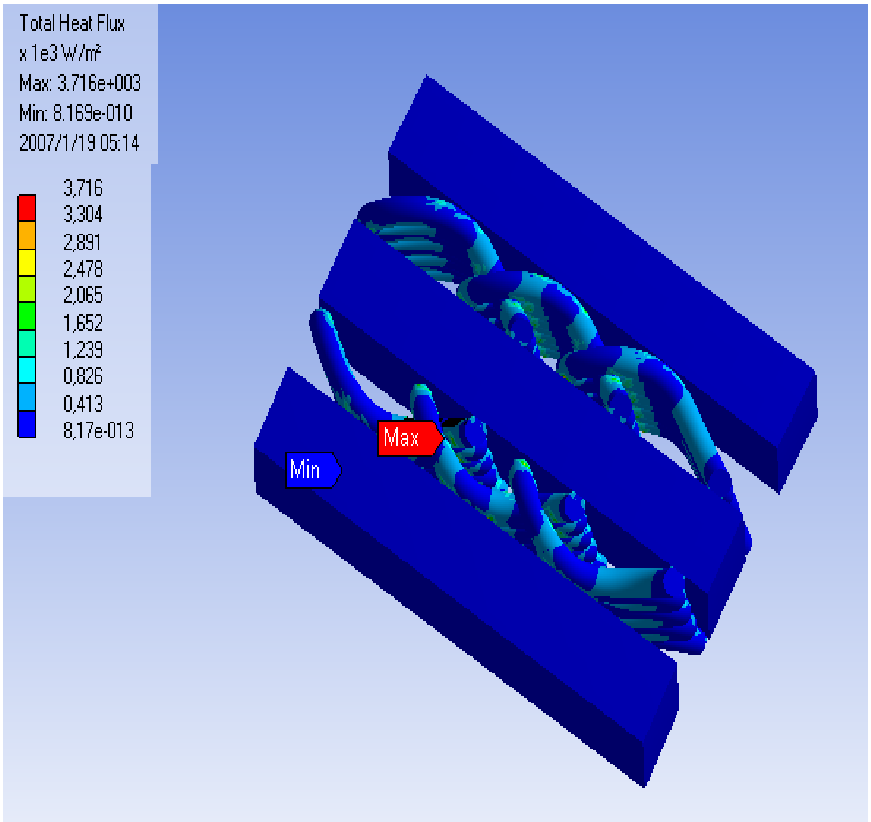


Figure 6.14: Total heat flux of the system

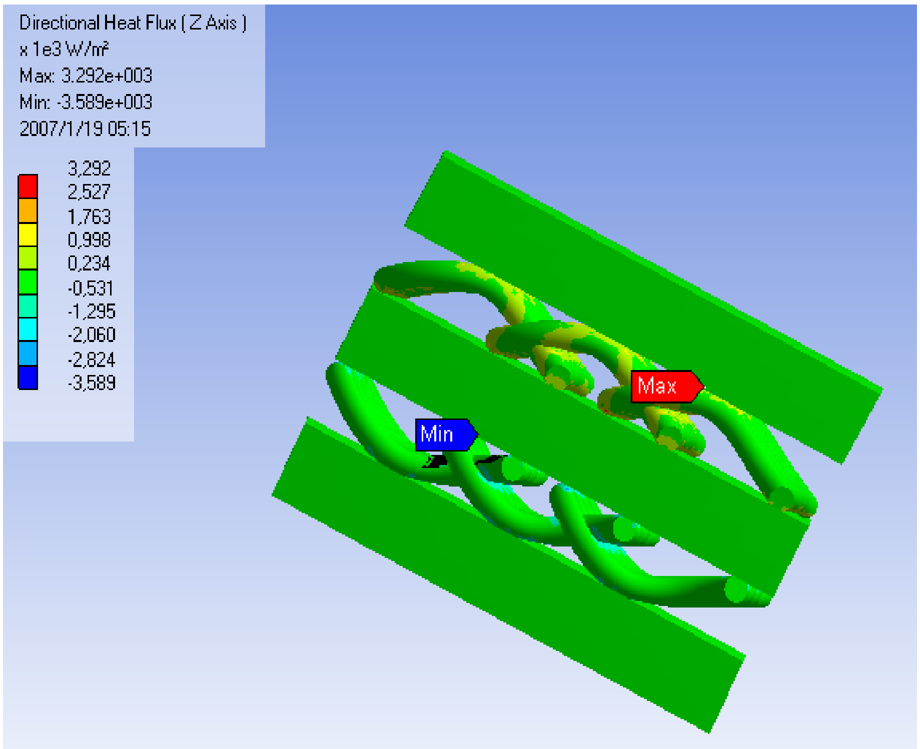


Figure 6.15: Directional (Z) heat flux of the system

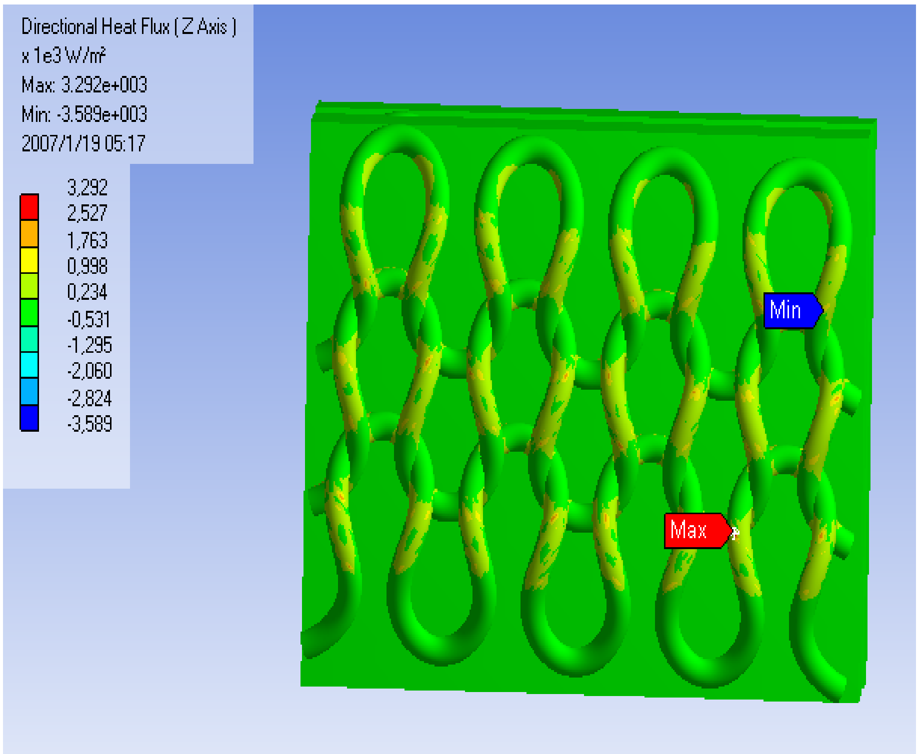


Figure 6.16: Front view directional heat flux of the system

Heat flux value (q^{II} =-0,531 $*10^3$) obtained from the FEM analysis was substituted into the equation 4.9 in an attempt to calculate the conduction coefficient of fabric (k). -0,531 $*10^3$ was used for calculations as this value corresponded to the most dominant heat flux distribution through the fabric. Finally, the conduction coefficient of the fabric calculated was 0,037. The coefficient obtained from the experimental result had been 0,0364. These results seem to be promising as the conduction coefficient calculated from FEM analysis and the one obtained from experiment are almost the same. This demonstrates that the model we have proposed can be used for other fiber types.

7. DISCUSSION

1. The most abraded fabric group is micro modal; whereas soybean fabrics are the least abraded samples. Statistically there is a significant difference between both fiber types and tightness factors. In general, abrasion resistance and thickness are negatively correlated. Also abrasion resistance decreases as yarn twist increases.

2. Moisture regain of modal fabrics tends to be higher, when compared to the other sample groups, whereas chitosan ones give the lowest moisture regain results. Both yarn twist and stitch density affect moisture regain negatively.

3. Bursting strengths of soybean fabrics are significantly higher when compared to the others whereas chitosan ones are lower. Both yarn twist and weight affect bursting strength positively.

4. There is a significant difference between widthwise shrinkage results of foot and neck while such a situation does not come to existence at lengthwise shrinkage results.

5. Cotton fabrics give the lowest air permeability values whereas modal fabrics have the highest values. Air permeability of fabrics are affected by thickness negatively while by moisture regain positively.

6. In general, it is possible to say that fabrics protein based fibers such as chitosan and soybean tend to dry faster, when compared to the other fabrics this can be explained with the lowest moisture regain of values of fabrics from these fibers. However, although it was expected from the modal fabrics to show slower drying rates when compared with the other fabrics due to their high moisture regain values, it has been the viscose fabrics which gave relatively slow drying rates. This might show that drying rates are not only

affected from moisture regain values of the fibers but also from the fabric properties as well.

7. The transfer wetting of cotton fiber differs from the other fibers and has the lowest value. On the other hand, the transfer wetting of micro modal fabric has the highest value. There is a negative correlation between transfer wetting rates both thickness, this relationship stands out with modal fabrics, and yarn twist.

8. Wicking of the cotton fabrics is the best. They are followed by chitosan, modal, soybean and micro modal in turn. Positive correlation comes to existence between wicking and both thickness and yarn twist whereas there is a negative correlation with transfer wetting.

9. Chitosan fabrics give the highest water vapor permeability values whereas cotton fabrics have the lowest values.

10. Cotton fabrics have the highest conduction coefficients values whereas soybean fabrics have the lowest ones. Statistically there is a significant difference between both fiber types and tightness factors. Conduction coefficient increases as both thickness and weight increase.

11. Like conduction coefficient results, cotton fabrics have the highest convection coefficients values. On the other hand, micro modal fabrics have the lowest ones. Statistically there is a significant difference between both fiber types and tightness factors. On the contrary to conduction coefficient, there is a negative correlation between thickness and convection coefficients for cotton, modal, and viscose fabrics. Moreover for cotton and modal fabrics convection coefficient increases as air permeability increases.

12. The conduction coefficient calculated from FEM analysis and the one obtained from experiment are almost the same. This result can be considered promising for further studies with other fiber types.

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APPENDIX

APPENDIX-A

Table A-1: Results of yarn hairness

YARN TYPE		MEAN
1	N1	12733,33
	N2	3032,00
	N3	1139,00
	S3	1957,67
2	N1	8940,33
	N2	2607,67
	N3	1026,67
	S3	1868,33
3	N1	9572,00
	N2	3148,00
	N3	1293,33
	S3	2450,00
4	N1	8589,67
	N2	1934,33
	N3	682,33
	S3	1086,00
5	N1	8462,67
	N2	2350,33
	N3	845,00
	S3	1434,67
9	N1	7776,00
	N2	2116,33
	N3	794,33
	S3	1449,67
10	N1	9415,33
	N2	2647,00
	N3	968,67
	S3	1791,33

APPENDIX –B

Table B-1: Results of yarn evenness

YARN TYPE	CV%	AVERAGE	NEPS 200%
1	17,13	87,7	165
2	15,09	94,3	10
3	15,02	92,9	36
4	11,36	98,6	26
5	14,78	101,2	17
9	14,69	71,4	99
10	13,04	81,5	28

APPENDIX –C

Table C-1: Results of yarn tension

YARN TYPE	RKM	EXTENSION (%)
1	12,55	7,176
2	21,75	12,707
3	11,25	7,493
4	22,5	11,018
5	14,45	18,563
9	12	9,663
10	16,8	17,007

APPENDIX –D

Table D-1: Results of yarn twist

YARN TYPE	TWIST (Rev/m)
1	769,6
2	715,9
3	763,1
4	678,5
5	717,7
9	764,3
10	798,9

BIOGRAPHY

Sena Cimilli, was born in 1982 in Erzurum. After she gratuated her secondary education from Erzurum Anatolian High School, she continued at Erzurum Science Lyceum and graduated from in 2000. At the same year, she won the İstanbul Technical University Department of Textile Engineering where she wants to be in since her childhood. In 2005, after graduating from Textile Engineering, she started her master thesis at the same place. Since December 2005, she works as a research assistant at ITU Textile Technology and Design Faculty.