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Factors affecting garment's thermophysiological properties in tropical weather countries

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ABSTRACT (ENGLISH)

This research was concerned with thermophysiological behavior analysis of garments made of classical cotton, and new functional materials like polypropylene, polyester cool max, viscose fiber made from bamboo plants and Merino wool, it aimed to find the best and optimal wear for the conditions in hot weather countries under different conditions of temperatures and humidity that actually exists in countries with hot weather like Egypt all around the year, and monitoring the factors that affects the comfortability of the garments used in that tropical weather. It is well know that cotton is a very good material for absorbing humidity and it is commonly used in tropical countries, but is it really the best material to be used?, what about using new functional materials like polyester cool max ,viscose fiber made from bamboo plants or Marino wool in these tropical weather? Will it be comfortable under these circumstances? And what about analyzing heat and moisture transport through these materials under these conditions which could reach to about 35 Celsius degrees and 80 % relative humidity. Answering these questions could lead us to achieve the maximum comfort properties, allowing us to understand the factors affecting the comfort properties in these conditions, leading us to develop garment properties that could be applied to enhance these properties.

The results show that viscose fiber made from bamboo plants garments achieved most of the special recommended thermophysiological properties. It is was found that viscose fiber made from bamboo plants doesn't adjust its temperature with the environment quickly as it will get heated quickly from the high temperature surrounding, as it will cause the body to feel the surrounding heat even without doing any effort and it has also acceptable water vapor resistance, water vapor permeability index and most of the desired required thermophysiological properties. Bamboo is available in such regions and it is also naturally anti-bacterial which is good to wear in those conditions where the human being releases a lot of sweat, where it is a good media for bacteria to grow. It is also UV protective and we can tell how important is this when it comes to that hot condition with long time of exposure to sun during long summer days, it is also green and biodegradable. The theoretical model shows that the total water vapor permeability becomes fewer as the water vapor resistance gets higher, leading to less comfort, and we can tell that the theoretical model used represents and clarifies the experimental results held for the different materials in the different experimental conditions, which will help in predicting the comfortability of the designed materials depending on the material specification.

ABSTRACT (CZECH)

Dizertační práce je zaměřena na analýzu termofyziologických vlastností u oděvů (prádla) vyrobených jednak z klasické bavlny, a jednak také z funkčních vláken , mezi které se řadí polypropylen, polyester cool max, viskózová vlákna vyrobená z bambusových rostlin a merino vlna. Cílem bylo nalézt nejvhodnější a optimální materiálové složení oblečení pro podmínky pobytu v zemích se subtropickým klimatem jako je např. Egypt. Oblečení bylo testováno při různých teplotách a vlhkostech, které jsou skutečně pro země v tomto podnebném pásu celoročně příznačné. Dále byly sledovány další faktory, které ovlivňují komfort těchto oděvů. Je známo, že bavlna je klasickým velmi dobrým materiálem, co se týče odvodu vlhkosti a je běžně používaná v tropických zemích. Je ale skutečně tím nejvhodnějším materiálem?

Zde také vyvstává otázka: „Jak nejlépe využít pro subtropické oblasti nové funkční materiály, mezi které patří polyester cool max, viskózové vlákno z vyrobené z bambusových rostlin nebo merino vlna". Budou tyto oděvy za těchto okolností mit dobrý oděvní komfort ?

Materiály byly testovány vlhko-tepelnému působení za podmínek 35°C a 80% RH. Výstupy z tohoto měření povedou ke konstrukci oblečení s maximálním oděvním komfortem, což nám umožní snáze pochopit faktory ovlivňující komfort v těchto podmínkách a nalézt řešení ke zlepšení těchto vlastností.

Výsledky ukazují, že viskózové vlákno dosahuje u oděvů maximálních doporučených vlhko-tepelných vlastností. Bylo zjištěno, že viskózové vlákno rychlou odezvu na změny teploty okolního prostředí. To je způsobeno tím, že tělo reaguje na okolní teplotu i bez fyzické zátěže. Textilie vyrobené z těchto vláken kladou přijatelný odpor vůči vodním parám (index paropropustnosti) a vyhovují požadovaným vlastnostem. V subtropických oblastech je viskóza – vyrobená z bambusu dostupnou surovinou, má přirozené antibakteriální účinky, tudíž oděvy z něj vyrobené dokážou lépe rozložit uvolněný pot pokožkou a zamezit tak růstu bakterií. Dále tato vlákna poskytují ochranu vůči UV záření, což je důležitým faktorem při dlouhém pobytu na denním slunci během letních dní, vlákna jsou rovněž snadno biologicky odbouratelná. Teoretický model ukazuje, že celková propustnost vůči vodním parám je nižší jakmile se vlhkost dostane do vnějších vrstev oděvu, což následně snižuje komfort nositele. Lze říci, že zde použitý teoretický model reprezentuje a objasňuje experimentální výsledky vztažené k různým materiálům za odlišných podmínek měření, které napomáhají projektovat komfort oděvů z navržených materiálů v závislostech na jejich specifických vlastnostech.

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Mohammad Motawe

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CHAPTER I

INTRODUCTION

1.1 Introduction

Clothing is one of the fundamental needs of the human being. It serves various and diverse purposes. Clothing selection is based on the needs and desires of the people. It may be to satisfy some aesthetic needs or to fulfill any particular demand of human being. People's selection of clothing depends upon their perception and feeling about the clothing. In some cases it is recommended to wear certain clothing and the selection is not possible, for example the suit of a firefighter, military uniform, etc.[1-3] However, it is very common that there is a dynamic and fundamental changes in the preferences of people with the change in the context; season, climate, age , type of activity, etc.

It is highly linked with the core requirement why a person is wearing any particular clothing. Moreover, clothing requirements are rather different depending upon the type of activities of any person. However, comfort is a basic requirement for people in all situations and it is considered an important factor in selecting clothes.

Comfort is difficult to explain since it is a complex and interdependent combination of physical, psychological and sensorial perceptions and highly depends of subjective evaluation of individuals. It is not possible that comfort level of people in the same situation could be same, since comfort can be changed by many parameters like temperature, air velocity and other parameters. However if more than 80% people feel comfort, then it can be said that such environment provides a comfort. Same is the case with clothing comfort.

Literature provides a number of mathematical models to predict comfort but still final decision is made based on subjective findings by using clothing in real world [1-3]. There is continues research to produce clothing which should be able to provide higher level of comfort. It is not possible to make clothing suitable for every situation. Industry is producing different designs, colors, and patterns to provide better look for wearers and at the same time functional clothing to fulfill certain demands i.e. water proof jackets, firefighting suits, etc.

As a consequence, the wearer of the breathable clothing outperforms the other, as it is possible to withstand high activity levels for a longer period of time. Hence, it is appropriate to describe wear comfort as the `physiological function' of outer wear.

The human body converts the energy provided by food into work and heat, depending mainly on the level of activity. To guarantee a constant body temperature within a narrow range, the heat has to be released to the environment. This process is controlled by signals, which are sent by the thermoreceptors of the skin and the hypothalamus, managing heat production and heat exchange using four different mechanisms: vasodilation, vaso-constriction, perspiration and shivering. The main part of the heat release occurs through the skin, only a small percentage accounts for the heat transfer via respiration. Since the skin is usually largely covered with clothing, the heat release of the human body is strongly influenced by the heat and moisture transfer through clothing.

Heat release via skin can be divided into dry heat losses and losses through evaporation. The former can be split into convection, conduction, and, additionally, the radiative exchange with the surrounding surfaces. Dry losses depend largely on the insulation of the clothing, which includes the insulation of the clothing itself and the insulation of the air layer between skin and clothing and respectively the air between different clothing layers.

The second, the evaporative heat exchange with the environment, is the removal of heat from the human body by the evaporation of sweat from the skin. This process is mainly driven by the thermoregulatory system, the permeation efficiency of the clothing and the surrounding air’s water vapor pressure. If the ratio of evaporated and produced perspiration is low, moisture accumulates in the clothing layer. This process influences the thermal characteristics of the garment due to swelling of the fibers causing changes in the size, shape and stiffness. Some scientists developed one of the first theories of coupled heat and moisture transfer through clothing considering accumulation effects [4]. Others proceeded with a steady-state model, which included both the convective and the diffusive transport mechanisms in the garment, along with phase change due to condensation and evaporation [5]. Since time-dependent modeling is necessary due to water accumulation, simple dynamic model was developed that included heat transport by conduction and radiation as well as moisture transport by diffusion [6].

Wear comfort is also a major sale’s aspect. According to the journal World Sports Active wear , comfort is the most important thing in clothing , and it is coming from sportswear where consumers have become accustomed to the comfort'). Ninety-four per cent of consumers would like their clothing to be comfortable, i.e. wear comfort is number one in consumer expectations consequently, and in a survey 98% of specialized German dealers believe wear comfort to be an important or very important property of clothing. [7-9]

After recognizing the importance of wear comfort and the physiological function of clothes, one should define in more detail what wear comfort entails. In fact, wear comfort is a complex phenomenon, but in general it can be divided into four different main aspects:

- The first aspect is denoted as Thermophysiological wear comfort, as it directly influences a person's thermoregulation. It comprises heat and moisture transport processes through the clothing. Key notions include thermal insulation, breathability and moisture management.

- The Skin Sensorial wear comfort characterizes the mechanical sensations, which a textile causes at direct contact with the skin. These perceptions may be pleasant, such as smoothness or softness, but they may also be unpleasant, if a textile is scratchy, too stiff, or clings to sweat-wetted skin.

-The Ergonomic wear comfort deals with the fit of the clothing and the freedom of movement it allows. The ergonomic wear comfort is mainly dependent on the garment's pattern and the elasticity of the materials.

-Last but not least the Psychological wear comfort is of importance. It is affected by fashion, personal preferences, ideology, etc. For example nobody will feel comfortable in a color he dislikes.

We can tell that the task of clothing is, besides fashionable embodiment and expression, the protection against harmful environmental stresses including the climatic conditions. On this account, wellbeing, health and productivity of humans largely depend on clothing. Humans usually wear clothing all day long - even in bed we are surrounded by textiles - therefore it is often characterized as a “second skin”. Except in tropical latitudes, a person needs constant protect to avoid simply freezing. But protection against cold is only one aspect of the physiological function of clothing. When the human body temperature rises above a certain level, an effective cooling is provided by the evaporation of sweat coming out of the glands. The type of clothing has a major impact on this process, since it is responsible for the diffusion of water vapor. Hence, clothing strongly influences the physiological operations including the temperature control of the human body. Detailed knowledge of the exact process, the importance of which should not be underestimated, is necessary to determine thermal comfort.

The wear comfort is an important quality criterion. It affects not only the well-being of the wearer but also their performance and efficiency. If, for example, an active sportsperson wears a clothing system with only poor breathability, heart rate and rectal temperatures will increase much more rapidly than while wearing breathable sportswear [10-11]. As a consequence, the wearer of the breathable clothing outperforms the other, as it is possible to withstand high activity levels for a longer period of time. Hence, it is appropriate to describe wear comfort as the physiological function of sportswear.

1.2 Research objective

This research work aims mainly to investigate the comfort properties of classic underwear and outer wear made from classical cotton, and comparing these fabrics with new functional materials for example polypropylene, polyester cool max, viscose fibers made from bamboo plants and Merino wool, and it aims to find the best and optimal wear for the conditions in hot weather countries.

Also it aims to measure the comfortability of these different materials under different conditions of temperatures and humidity that actually exists in countries with hot weather like Egypt all around the year, and monitoring the factors that affects the comfortability of the garments used in that tropical weather.

It is well know that cotton for example is a very good material for absorbing humidity , but when it absorbs this humidity it is not that easy to lose this humidity , so when using this material in practicing sports for example , it will be useful in the beginning because it will absorb sweat , but after a while it becomes saturated with this maximum amount of sweat it could absorb, it will not be comfortable anymore because it will not get rid of this sweat easily and it will lead to discomfort for the wearer , so the only way to be comfortable is to change this garment with another one , so what about using new functional clothes from new materials like polyester cool max or Marino wool in these tropical weather? Will it be comfortable under these circumstances? And what about using these new functional materials and analyzing the heat, moisture loss, heat and moisture transport through these fabrics under this hot condition which could reach to about 35 Celsius degrees and 80 % relative humidity.

Although a lot of studies have been done concerning the comfort properties of garments and a lot of mathematical models have been established to predict and to study the comfort properties, but a real study and a real application is needed to actually determine factors which affect the comfort properties in real conditions, this is the main aim for the research, to exercise and examine different materials with different structures and finishes under variation of heat , humidity and combination of heat and humidity which actually exists all around the year in countries with tropical weather and here the climate condition of Egypt is actually being achieved varying from summer to winter time as well as the humidity; to study the comfort properties of garments which could be used to achieve the maximum comfort properties ,and this will allow us to understand the factors which affect the comfort properties in these conditions, leading us to develop garment properties that could be applied to enhance these properties.

CHAPTER II

THEORY

2.1 Interaction of human, clothing and environment

People wear clothing to protect their body from environment. As clothing is being worn, the human body interacts dynamically with it and the surrounding environment. There are four processes occurring interactively that determine the comfort status of the wearer. The processes are: physical processes in clothing and surrounding environments, physiological processes in the body, neurophysiological and psychological processes [12].

These four types of processes occur concurrently. The laws of physics are followed by the physical processes in the environment and clothing, which determine the physical conditions for the survival and comfort of the body. The laws of physiology are followed by the thermoregulatory responses of the body and the sensory responses of skin nerve endings. The thermoregulatory and sensory systems react to the physical stimuli from clothing and the environment to create certain appropriate physiological conditions for the survival of the body and to inform the brain of various physical conditions that influence comfort status [12].

The psychological processes are the most complicated, the brain needs to formulate subjective perceptions from the sensory signals from the nerve endings in order to evaluate and weigh these sensory perceptions against past experiences, internal desires and external influences. Through these processes, the brain formulates a subjective perception of overall comfort status, judgments and preferences. Alternatively, 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 alter the physical processes in the clothing and external environment [12].

On the basis of integration of all of these physical, physiological, neurophysiological and psychological processes and factors, the comfort status as the subjective perception and judgment of the wearer is determined [12].

2.2 Thermophysiology of the human body

The human body has the ability to regulate its internal temperature with a certain level of accuracy under changes in external and internal conditions. The temperature regulation works through biological mechanisms – specific central and peripheral nervous systems continuously detect the temperature fluctuations in the body and attempt to keep them in balance by means of biological actions [13].

Physiological temperature regulation is described as a complex system containing multiple sensors, multiple feedback loops and multiple outputs. Figure 1.1 shows modified version of Hensel's model of autonomic temperature regulation in man. The control variable is an integrated value of multiple temperatures such as the central nervous temperature (*Tcn*), the extra-central deep body temperature (*Tdb*) and the skin temperature (*Tsk*). Hensel defined the 'weighted mean body temperature' (*Tnb*) as the controlled variable for practical purposes:

$$Tnb = a\ Ti + (1 - a)\ Tsk\ , \quad a < 1 \qquad (1)$$

Values of *a* were proposed between 0.87 and 0.9 by measuring *Ti* in the esophagus.

The rating ratio was assumed to be the relative contribution from *Tsk* and *Ti* in a linear control function.

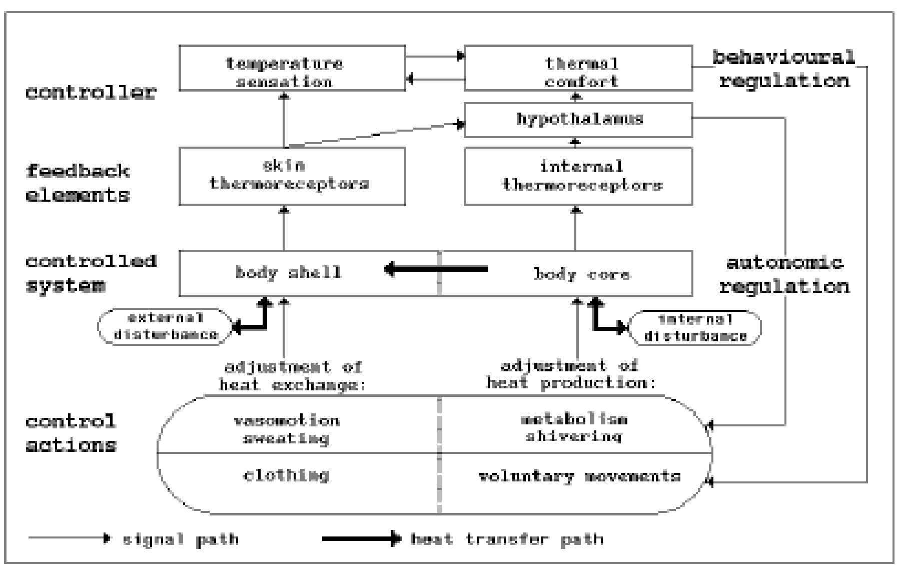


Figure 1.1 Schematic diagram of autonomic temperature regulation in man

The references (or set temperatures) for different control actions such as metabolism, and sweating might be different. The heat dissipation mechanisms such as sweating driven by warm receptors may have a higher set temperature than heat production mechanisms driven by cold receptors. Therefore, there is a zone of thermal neutrality in which no thermal regulation occurs. The thermal regulation mechanisms have been classified into three categories: autonomic regulation, behavior regulation and technical regulation [13].

The autonomic regulation responds to thermal disturbances from internal heat generated by exercise and environmental heat or cold. Thermoreceptors receive signals from the thermal disturbances and transfer them to the central nervous system via different nervous pathways. The receptors can respond not only to temperature but also much more effectively to temperature change. This means that rapid external cooling or warming may lead to a transient opposite change of internal temperature behavioral, thermoregulation in humans is related to conscious thermal sensations and emotional feelings of thermal comfort and discomfort. Behavioral thermoregulation in response to heat and cold modifies the need for autonomic thermoregulatory responses.

Various autonomic and behavioral components of temperature regulation were summarized [13]; technical thermoregulation can be considered an extension of the human regulatory system through technical inventions. Temperature regulation is shifted from the body to the environment using artificial sensors, controllers and effectors.

2.3 Comfort

2.3.1 Comfort definition

Many researchers have defined comfort in relation to clothing. According to some [14], comfort is not easy to define because it covers both quantifiable and subjective considerations. Comfort is a situation where temperature differences between body members are small with low skin humidity and the physiological effort of thermal regulation is reduced to a minimum. Comfort is not only a function of the physical properties of materials and clothing variables [1], but also must be interpreted within the entire context of human physiological and psychological responses. Personal expectation or stored modifiers that sort out or influence our judgment about comfort based on personal experiences must be also considered.

Comfort as wellbeing and fundamental to that wellbeing is the maintenance of the temperature of our vital organs within a few degrees of 37 ^{o}C for them to function properly, otherwise the metabolic system can be extensively disrupted and sustained abnormal temperature will lead to death [15]. Temperature control is achieved by changing skin temperature through changes to blood flow and by evaporation of water at the skin surface.

Various studies viewed comfort in a physical sense as the body being in a heat balance with the environment (thermal comfort), that the body is not being subject to pressure from narrow or badly designed clothing (movement comfort) and that skin irritation does not occur from unpleasant contact with clothing (sensorial comfort)[16].

Clothing comfort is governed by the interplay of three components: body, climate and clothing. The human body, its microclimate and its clothing form a mutually interactive system. The body and its microclimate are invariable; the clothing system is the only variable [17].

-Comfort is summarized into several components [18]:

-Comfort relates to subjective perception of various sensations.

-Comfort involves many aspects of human senses such as visual (aesthetic comfort), thermal (comfort and warmth), pain (prickling and itching) and touch (smooth, rough, soft and stiff).

-The subjective perceptions involve a psychological process in which all relevant sensory perceptions are formulated, weighed, combined and evaluated against past experiences and present desires to form an overall assessment of comfort status.

-The body–clothing interactions (thermal and mechanical) play important roles in determining the comfort status of the wearer.

-External environment (physical, social and cultural) has a great impact on the comfort status of the wearer.

2.3.2 Comfort aspects

As mentioned, wear comfort is a complex phenomenon but in general it can be divided into four main aspects [19]

-Thermophysiological wear comfort. This comprises heat and moisture transport processes through the clothing and directly influences a person's thermoregulation.

-Skin sensorial wear comfort. This deals with the mechanical sensations caused by textiles as it is in direct contact with the skin. Pleasant and unpleasant perceptions such as smoothness or softness, scratchiness, stiffness, or clinging to sweat-wetted skin may be created by textiles.

-Ergonomic wear comfort. This is characterized by the fit of the clothing and the freedom of movement it allows. The garment's construction and the elasticity of the materials are the main aspect of ergonomic wear comfort.

-Psychological wear comfort. This is of importance as well. It is affected by fashion, personal preferences and ideology.

2.3.2.1 Thermophysiological comfort

Thermophysiological wear comfort concerns the heat and moisture transport properties of clothing and the way that clothing helps to maintain the heat balance of the body during various levels of activity [20].

Thermophysiological comfort has two distinct phases. During normal wear, insensible perspiration is continuously generated by the body. Steady state heat and moisture vapor fluxes are thus created and must gradually dissipate to maintain thermoregulation and a feeling of thermal comfort. In this case the clothing becomes a part of the steady state thermoregulatory system. In transient wear conditions, characterized by an intermittent pulse of moderate or heavy sweating caused by strenuous activity or climatic conditions, sensible perspiration and liquid sweat occur and must be rapidly managed by the clothing. This property is important in terms of the sensorial and thermoregulatory comfort of the wearer. Therefore, heat and moisture transfer properties under both steady and transient conditions must be considered to predict wearer comfort [21]

2.3.2.2 Sensorial comfort

Sensorial comfort is the elicitation of various neural sensations when textile comes into contact with skin [19]. The skin sensorial wear comfort characterizes the mechanical sensations that a textile causes at direct contact with the skin. The perception may be pleasant, such as smoothness or softness, but it may also be unpleasant, if the textile is scratchy, too stiff or clings to sweat-wetted skin [22].

Sensorial comfort does not directly involve any temperature balance but is related to the way the person feels when clothing is worn next to the skin. Feeling wet and wet clinging can be a major source of sensorial discomfort in situations of profuse sweating [14].

Sensorial comfort is mainly determined by fabric surface structure and to some extent by moisture transport and buffering capacity. It is associated with skin contact sensation and is often expressed as a feeling of softness, smoothness, clamminess, clinginess, prickliness and the like. These descriptors can be related to specific, measurable fabric mechanical and surface properties including the number of surface fibers and contact points, wet cling to a surface, absorptivity, bending stiffness, resistance to shear and tensile forces, and coolness to the touch. These properties are mainly determined by fiber characteristics, yarn and fabric construction and fabric finish, but it is necessary to recognize that the extent of their relationship to comfort perception in clothing is also influenced by garment construction and properties [23]

2.3.3 Comfort and textiles properties

There are specific physical textile properties that may be measured in an effort to predict the comfort performance of fabric. Basically a textile material should be evaluated in terms of the most general functional properties: thickness, weight, thermal insulation, resistance to evaporation and air penetration. There are three clothing factors that relate directly to thermal comfort. First is the overall thickness of the materials and air spaces between the skin and environment. Second is the extent to which air can penetrate the clothing by wind or wearer motion. Third is the requirement that fabric does not restrict the evaporation of perspiration [21].

Important textile properties for comfort [24]:

-Intrinsic thermal insulation:

The intrinsic thermal insulation of a fabric can be determined by measuring its resistance to the heat transmission of heat by conduction. Intrinsic thermal insulation is proportional to the thickness of fabrics. It does not include the layer of air next to the fabric during use.

-Thermal insulation:

Thermal insulation is the resistance of a fabric and the layer of air next to it during use to dry or conductive heat loss. Unlike intrinsic thermal insulation, thermal insulation varies with the ambient wind speed. As the speed increases, the thermal insulation provided by the layer of air decreases.

-Resistance to evaporative heat loss:

Resistance to evaporative heat loss measures the ability of a fabric, together with the layer of air next to the fabric during use, to prevent cooling of the body by evaporation of heat generated during activity. Resistance to evaporative heat loss can be measured on either dry or damp fabrics.

-Thermal conductivity:

The thermal conductivity of a fabric is determined by the rate of transmission of heat through fabric. It is reciprocal of thermal insulation or thermal resistance.

-Moisture vapor permeability:

Moisture vapor permeability represents the resistance of a fabric to the transfer of water vapor, also known as insensible perspiration, released by body. Relative moisture vapor permeability is the percentage of water vapor transmitted through the fabric sample compared with the percentage of water vapor transmitted through an equivalent thickness of air. Low moisture permeability hinders the passage of perspiration through the fabric, leading to the accumulation of sweat in the clothing.

The rate of water vapor transmission through the fabric is also usually reduced by increasing the fabric thickness.

-Water absorption:

Water absorption is the capacity of a fabric to absorb the sweat generated by the body and the rate at which it is able to do so. To prevent wet clinging, the fabric's absorption should be low at the surface of the fabric which makes contact with the skin.

-Wicking:

Wicking is the capacity of a fabric to transport absorbed sweat away from the point of absorption, usually the skin and the rate at which it does so.

-Air permeability:

Air permeability is a measure of how air is able to flow through a fabric. It can be measured on either dry or damp fabrics. A fabric which has good air permeability, however, does not necessarily have good moisture vapor permeability. Air permeability is likely to be lower in fabrics where the absorption of water leads to swelling of the fiber and the yarn.

-Rate of drying:

The rate of drying is the rate at which water is evaporated from the outer surface of a fabric. The rate of drying must be sufficient to achieve continuous wicking and to prevent the fabric from becoming saturated with sweat.

-Wind proofing:

Wind proofing is a mechanism for reducing the heat loss from a garment by convection, thus improving the overall thermal insulation of clothing system.

-Surface coefficient of friction:

The surface coefficient of friction of a fabric contributes to its sensory comfort. The coefficient of friction usually increases significantly when a fabric has become wet, leading to rubbing or chafing of the skin. A low coefficient of friction is also essential when one layer of fabric is required to move freely against another layer.

-Handle:

The term handle describes the tactile qualities of a garment. It includes such properties as softness, compressibility, pliability and drape. These characteristics must not impair performance during sporting activity.

-UV resistance:

UV resistance can be vital for clothing exposed to high levels of sunlight. It is particularly important in ski wear, when the wearer may not always be fully aware of the degree of exposure to UV radiation.

-Anti-microbial, anti-bacterial and anti-odor properties:

Anti-microbial, anti-bacterial and anti-odor properties are important in garments which tend to remain in contact with sweat for long periods of time. Such items include sports socks, vests and underwear.

2.4 Thermal comfort

Thermal comfort, in simple words, implies the maintenance of the body temperature within relatively small limits. Under the conditions where the thermal comfort cannot be achieved by the human body's own ability (i.e. body temperature regulation), such as very cold or hot weather, clothing must be worn to support its temperature regulation by resisting or facilitating the heat exchange between the human body and the environment. The design of effective clothing for thermal comfort should be based on the understanding of the heat transfer through clothing.

The heat transfer through clothing is a very complicated phenomenon. Possible modes of heat transfer through clothing are conduction, convection, radiation and latent heat transfer by moisture transport. These modes of heat transfer are all affected by the geometries of human bodies and clothing systems which can never be exactly described. They are also affected by the conditions of human bodies such as skin temperature, skin wetness, and body movement, the conditions of environment such as wind, radiation, temperature and humidity, and physical properties of clothing and its constituents. The phenomenon may be further complicated by the buffering effect within clothing and condensation factors. In such a study, it may not be possible to consider all the factors at one time. Researches therefore are carried out by simulating the actual circumstances and taking into account the main human, clothing and environmental factors. Although much work has been done on this topic, the mechanisms under many circumstances are far from understood.

Thermal comfort is an emotional or effective experience referring to the subjective state of the observer under a thermal environment. According to Ashrae's definition, it is "that condition of mind which expresses satisfaction with the thermal environment" [25].

It has been found that the expression of thermal comfort strongly depends on the thermal physiological conditions of the subject. For a person under a long exposure, the physiological conditions for general thermal comfort can be specified as follows:

- The core temperature: the temperature of the deep central area including the heart, lungs, abdominal organs and brain within 36.6 °C to 37.1 °C

- The mean skin temperature: the surface area weighted average skin temperature within 33 °C to 34.6 °C for men and 32.5 °C to 35 °C for women.

- Local skin temperature within 32 °C to 35.5 °C

- Temperature regulation active and completely accomplished by vasomotor control of blood flow to the skin, i.e. no sweating and shivering present [26].

Among these four physiological conditions, the first one is the most important. The survival value of the consistency of the core temperature is very evident. Changes of more than 2 °C can be dangerous to human life. To achieve this consistency, heat production inside the human body and heat loss from the human body should be balanced. The human body's own ability to maintain this balance is by temperature regulation. In this process, heat lost from the human body is adjusted by changing skin temperatures or sweating rate, and heat production is modified by internal body activities. However, the effect of temperature regulation is limited, if changes of heat lost and heat production are beyond the limits which the body temperature regulation system can cope with, the core temperature cannot be maintained and life can be in danger. Such events are well known in severe weather conditions. In the sense of thermal comfort, therefore, clothing is used to help the body temperature regulation' by maintain the heat balance between the heat production and heat loss [26].

2.5 Modes of Heat Transfer

Heat can be transferred within the clothing system in the modes of conduction, radiation, convection and latent heat transfer by moisture transport.

2.5.1 Conduction

Conduction is a process in which heat is transferred through a body or from one body to another without appreciable displacement of the parts of the body. From the molecular point of view, the conductive heat is transferred from a faster moving molecule of higher temperature to a slower moving molecule of lower temperature.

The process can occur in either solid or fluid. Fourier's Law for the conduction of heat states that the instantaneous rate of heat flow dq is equal to the product of three factors: the area A of the section, taken at a right angle to the direction of heat flow, the temperature gradient $\frac{dT}{dX}$, which is the rate of change of temperature T with respect of the length path x, and a proportionality factor K, known as the thermal conductivity, i.e. $dq = -KA\frac{dT}{dX}$ .In clothing systems, all components of clothing such as air, fibers and moisture vapor are thermal conductors. The thermal conductivities of wool fibers are about 0.2 W/m/°C that of air is 0.026 W/m/°C.

2.5.2 Radiation

Radiation is the heat exchange between a hotter and a colder body by emitting and absorbing radiant energy. Heat exchange by radiation depends only on the temperature and the nature of the surface of the radiating objects.

The radiant heat can transfer directly through clothing spacing from the skin surface into the environment and between clothing materials. The emissivity of skin is about 0.95, that of textile fabrics, e.g. cotton, linen, wool lies between 0.95 and 0.90 [27].

2.5.3 Convection

Convection is the transfer of heat from one point to another within a fluid, gas or liquid, by the mixing of one portion of the fluid with another. The motion of the fluid may be entirely the result of differences of density due to the temperature differences, as in natural convection; or produced by an external force, as in forced convection. The rate of convection depends on the motion of the fluid and the temperature gradient.

The convection within clothing systems can be caused by the differences of air density at different places, external wind and body motion. When the human body is moving or in strong windy conditions, ventilation is an important way of convective heat transfer through clothing. Ventilation is the exchange of generally hot, wet air within a clothing system and cold, dry air in the environment without passing through fabric layers [28]. It could account for 75 % percent of the total heat loss from the human body when the wearer is walking in strong windy conditions [29].

2.5.4 Latent heat transfer

Latent heat transfer is a process in which heat is carried from one place to another by the movement of a substance which absorbs or dissipates heat by a change of phase. Latent heat transfer is the only way of body cooling when heat produced inside the human body cannot be totally lost by conduction, radiation and convection. In this case, sweat is produced at the surface of skin and heat is lost by evaporation of liquid sweat into moisture vapor which then passes into the environment.

2.6 Heat transfer through clothing

As already mentioned, heat can be transferred through clothing by conduction, radiation, convection and latent heat transfer by moisture transmission. Radiation, conduction and convection are dominated by the temperature difference between the skin surface and the environment, and are therefore grouped as dry heat transfer. On the other hand, latent heat transfer is achieved by moisture transmission which is drove by the difference in partial water vapor pressure between the skin surface and the environment [26-29].

2.6.1 Dry Heat Transfer through Clothing

The dry heat transfer through a clothing system can be described by

$$Hd=\frac{10.(Ts-Ta)}{Rc+Rs} \tag{2}$$

Where, Ts is the skin temperature (°C), Ta is the ambient temperature (°C), Hd is the rate of dry heat transfer through clothing (W/m^2), Rc is the thermal insulation of the clothing, and Rs is the the thermal insulation of the clothing surface. Rc and Rs are expressed in tog units [30]. 1 tog = 0.1 °C m^2/Watts (ISO unit). American counterparts would like to express the thermal insulation in Clo value. This is a unit which was developed based on human physiological factors. 1 Clo means the amount of clothing worn for a normal sitting-resting man to keep thermal comfort in a normal ventilated room. From biophysical data, a common conversion between Tog unit and Clo value is that, 1 Clo = 1.55 togs [31].

This formula only represents the main principles involved in the dry heat transfer through clothing. In actual circumstances, Rc and Rs are related to many factors within the human body-clothing-environment system.

2.6.2 Latent heat Transfer through clothing

The latent heat transfer through a clothing system can be described by

$$Hl=\frac{c.(Ps-Pa)}{Wc+Ws} \quad (3)$$

where, Hl is the rate of latent heat transfer through clothing (W/m^2), Ps is the partial water vapor pressure at the skin surface, Pa is the partial water vapor pressure in the environment, c is the evaporative heat at the skin temperature, C = 2.44 KJ/g at 35 °C, Wc is the resistance to water vapor transfer of the clothing, and Ws is the resistance to water vapor transfer of the clothing surface. The units of partial water vapor pressure and the resistance should be corresponding. Instead of the resistance to water vapor transfer, the permeability index was introduced to describe the water vapor transfer properties of clothing [32]. It can be defined as follows

$$i= \frac{C.R}{10.S.W} \quad (4)$$

Where, R is the total thermal insulation of the clothing system in tog unit, R = Rc + Rs, W is the total resistance to water vapor transfer, W = Wc + Ws. S is obtained from the temperature Tw of the wet bulb thermometer and is given by

$$S=\frac{Ts-Tw}{Pw-Ps} \quad (5)$$

Where, Pw is the saturated water vapor pressure at temperature Tw. At high wind velocities, S = 2.0 °C /mmHg, *i* was claimed as a dimensionless factor which described the efficiency of water vapor transfer through clothing, it ranges from 0, for a clothing system totally resistant to the water vapor transfer, to 1 for an ideally permeable clothing system which has no more impedance than the wet bulb thermometer at high wind velocities.

2.6.3 Simultaneous Dry and Latent Heat Transfer

When dry and latent heat transfer exist simultaneously, from formula (3), (4) and (5), the overall heat transfer H can be estimated by

$$H=\frac{10.(Ts-Ta)}{Rc+Rs}+\frac{C.(Ps-Pa)}{Wc+Ws} \quad (6)$$

In the above formula, dry and latent heat transfer are treated independently, and this only describes the main principles involved in the heat transfer through clothing. Under many circumstances, by using the above formula, the heat transfer may well be underestimated due to the effect of buffering and condensation [27].

Buffering happens when clothing materials absorb or desorb moisture vapor from the boundaries. The absorption or desorption involves heat lost to or gain from the boundary. The effect can increase the thermal comfort of a wearer when his environmental condition changes, e.g. moving from dry, warm indoor into cold, wet outdoor, or he starts sensible perspiration.

Condensation happens when the partial water vapor pressure within the clothing is higher than the saturated one which is determined by the local temperature. The condensation of water vapor into liquid water will release latent heat of vaporization which is 2.44 KJ/g of vapor. In contrast, the evaporation of the condensed water will absorb heat. Supposing moisture is condensed in the central layers of clothing, some of this condensed moisture may wick back to the Inner, warmer layers where it can be re-evaporated at the expense of its latent heat. This water vapor will later re-condense in the cooler layers giving up its latent heat at a place further away from the skin. This cycling of moisture between warmer and cooler parts of the clothing provides an extra mode of heat transfer between the body and the environment [33]. Condensation can result in extra chill for a person working in a cold environment, and therefore should be eliminated as much as possible.

2.7 Factors Related to the Heat Transfer through Clothing

2.7.1 Human Factors

2.7.1.1 Body Posture

The heat transfer through clothing is influenced by body posture by changing the effective surface area, the geometry of the clothing and the entrapped air layers. For standard clothing, with measurements on a thermal manikin, it was found that the clothing thermal insulation of a sitting person was 8-18% lower than that when standing [34]. Similar results were also reported from the measurements from wearer trials [35].

2.7.1.2 Body Motion

Body motion sets up convection currents within the clothing system, and therefore increases heat flow rate through clothing and reduces the clothing thermal insulation. "Bellows action", "pumping effect" and "ventilation" are common terms to describe the exchange of the hot air within the clothing and cold air in the environment, which is induced by body motion. The effects of body motion have been recognized. From the studies on two human subjects at the Harvard Fatigue Laboratory, it was reported that the thermal insulation value of an Arctic Uniform was reduced from 2.7 Clo with the subjects standing, to 1.3 Clo for level walking at 6.4 km/hr [36]. However, little additional work was conducted until recently, when the need for such data became essential to improve the modeling techniques for predicting environmental stress and tolerance for active men.

In recent years, clothing insulation values during bicycling and walking were studied by several workers [37]. Much of this work is just data capturing, and the understanding of the mechanism of the effect of body motion on the heat transfer through clothing was limited.

2.7.1.3 Body Geometry

The curvature of the body surface can affect the clothing thermal insulation. By considering a cylinder covered with insulating materials, it was found that the effective thermal insulation provided by a given material of a given thickness becomes smaller as the radius of the cylinder is reduced [33]. This explained the greater difficulty in keeping the arms and legs warm compared with the trunk in cold weather. The shape of the human body can also affect the effective area of the radiant heat lost from the body [38].

2.7.1.4 Skin Wetness

The latent heat loss is affected by the skin wetness. The following formula was suggested to account this effect [28]. That is

$$HI=\frac{d(Pss-Pa)}{W} \qquad (7)$$

where, HI is the latent heat transfer by evaporation, Pss is the saturated water vapor pressure at the skin surface, Pa is the ambient partial water vapor pressure, W is the resistance to water vapor transfer of the clothing system, and d is a so-called "perspiration discomfort factor', d is directly related to the skin wetness. It was assumed that d= 0.1 when the perspiration is insensible, and d=1.0 when the skin is totally wetted. The skin wetness can also affect the dry heat transfer, since the absorption of liquid sweat or moisture by clothing materials can change the thermal properties of the materials, and can induce a buffering effect and even condensation under certain conditions.

2.7.1.5 Skin Temperature

The skin temperature is a governing factor in the heat transfer through clothing. The changes in its magnitude and distribution around the body surface regulate the heat lost from the human body. However, its effect on the thermal insulating properties of clothing is small due its small variability.

2.7.2 Clothing Factors

2.7.2 .1 Fiber Type

Textile clothing materials whether of woven, knitted or non-woven construction are disperse systems consisting of textile fibers, air and moisture. Air has a very low thermal conductivity and offers a high resistance to conductive heat transfer. Textile fibers are much better conductors of heat than air - the thermal conductivity of wool fibers is about 10 times and of cotton fibers about 25 times that of air. Because the fibers occupy only a small fraction of the total volume in a textile fabric except for very tight fabrics, the differences in fiber type are of minor importance for the dry heat transfer and the thermal insulation [33]. Comparatively, the effect of fiber type is more evident for pile fabrics than others, since in pile fabrics heat is transferred in parallel with the fiber arrangement [39, 40].

As far as the latent heat transfer is concerned, clothing materials made of hygroscopic fibers behave differently from those clothing materials made of hydrophobic fibers due to the buffering effect. Thickness, compression resistance of clothing materials, the relationship between the thickness of clothing materials and the thermal insulation have been investigated by many workers [41]. It has been universally agreed that the thermal insulation of clothing materials are proportional to their thickness. On this basis, the compression of clothing materials will reduce the thermal insulation due to the loss of thickness. The thermal insulation of polyester battings under different pressures was investigated [41]. It was found that the rate of reduction of the thermal insulation with increasing pressure was the maximum at the lowest pressure, and minimal at the highest pressure. Clothing such as sleeping bags are subjected to compression in use, the compression resistance of clothing materials is thus very important to retain the thermal insulating properties of clothing.

2.7.2.2 Air Permeability of Clothing Materials

The air permeability of clothing materials is directly related to the resistance to water vapor transmission. When latent heat transfer is important for thermal comfort, clothing made of materials of low air permeability is not desirable. However, the air permeability is also directly related to the resistance to air penetration in windy conditions. To minimize the heat lost by air penetration, clothing for use in cold and windy conditions should have an outer cover of as low permeability as possible [42].

2.7.2.3 Bulkiness of Clothing Materials

Many workers [43] have examined the effect of bulk density on the thermal insulation of clothing materials. It has been agreed that, in order to obtain the maximum thermal insulation, the structure of clothing materials should be neither so open that it allows too much radiation and convection or so close that it allows too much conduction.

2.7.2.4 Clothing Design and Fit

When fabrics are made into clothing and worn on the body, there are air gaps between layers of fabrics and openings around the body depending on the design and fit of the clothing. It has been reported that as much as 75% of the total heat can be lost through openings at the places like the neck, the waist, the wrists and ankles by bellows action when the body is moving in windy conditions [29]. This heat lost can be reduced for well-designed and fitted clothing, and this is important for clothing used in cold environment. The effects of openings and fit of clothing on the thermal insulation of clothing in windy conditions were studied on a cylindrical apparatus [44]. It was shown that the thermal insulation of a fabric system increases when a 'seal" was formed at the bottom opening of the system. This finding was further proved by the comparative tests on a manikin with an open clothing system and a closed clothing system [45].

2.7.3 Environmental Factors

2.7.3.1 Environmental Temperature

The environmental temperature is a governing factor of heat transfer through clothing. Apart from that, it can also affect the clothing thermal insulation. This is because, first, the conductivities of fibers and air are related to the temperature; second, the proportion of the radiant heat transfer over the total varies with the temperature difference between the skin and the environment. In addition, in a cold environment, condensation is likely to occur, and this can also reduce the thermal insulation of clothing [46].

2.7.3.2 Humidity

The humidity of the environment is a very important factor in determining the latent heat transfer by moisture transmission through clothing. This is because the driving force of the water vapor transmission is the difference between the water vapor pressure at the skin surface and that in the environment which is strongly related to the relative humidity by the relation RH=Pa/Pss , where Pa is the partial water vapor pressure in the environment and Pss is the saturated partial water vapor pressure at the environmental temperature. So, the increase in the humidity in the environment can reduce the latent heat transfer through clothing.

The ambient humidity can also influence the dry heat transfer by increasing the moisture or water content in the clothing. It has already been shown that the thermal insulation of clothing materials markedly reduces when the moisture content in the clothing materials Increases from 0 to 75% [47].

2.7.3.3 Wind

Wind can have the most destructive effect on the thermal insulation of a clothing system by air penetration, compression of the clothing materials and the removal of the surface still air layer. The effects of streamlined and turbulent air flow on the surface thermal insulation of different fabrics placed on a hot plate was examined [48]. It was found that the reduction in the surface thermal insulation was proportional to the wind velocity to the power of 0.7 in the case of turbulent air flow, and to the square root of the wind velocity in the case of streamlined air flow. The case of the turbulent air flow was regarded to be similar to the case of a clothed man in wind.

The surface thermal insulation of a clothed man in wind was investigated [49], and a useful empirical formula was given, i.e.

$$Rs = \frac{1}{0.61+0.19V} \text{ Clo} \qquad (8)$$

Where, Rs is the surface thermal insulation in Clo value, V is the wind velocity in cm/sec. The effect of air penetration on the clothing thermal insulation was studied and a series of experiments were conducted of clothing assemblies, which consisted of a layer of wind resistant outer fabric and a layer of thick underlying fabric, with a hot plate method in a wind tunnel. It was found that the air penetration had little effect at low wind velocities but was important at high wind velocities [42]. Later the mechanism of wind penetration was studied, and it was found that an air space between the outer wind break layer and the inner clothing would allow air that penetrates the wind break layer in the windward side to lose its momentum and drift to the leeward without penetrating the inner clothing[44].

Air motion significantly affects body heat transfer by convection and evaporation. Air movement results from free (natural) and forced convection as well as from the occupants' bodily movements. The faster the motion; the greater the rate of heat flow, by both convection and evaporation. When ambient temperatures are within acceptable limits, there is no minimum air movement that must be provided for thermal comfort. The natural convection of air over the surface of the body allows for the continuous dissipation of body heat. When ambient temperatures rise, however, natural air flow velocity is no longer sufficient and must be artificially increased, such as by the use of fans. Typical human responses to air motion are shown in Table 1 [44].

Table 1 Subjective response to air motion

Air Velocity fpm	m/s	Occupant Reaction
0 to 10	0 to 0.05	Complaints about stagnation
10 to 50	0.05 to 0.25	Generally favorable (air outlet devices normally designed for 50 fpm in the occupied zone)
50 to 100	0.25 to 0.51	Awareness of air motion, but may be comfortable, depending on moving air temperature and room conditions
100 to 200	0.51 to 1.02	Constant awareness of air motion, but can be acceptable (e.g., in some factories) if air supply is intermittent and if moving air temperature and room conditions are acceptable
200 (about 2 mph) and above	1.02 and above	Complaints about blowing of papers and hair, and other annoyances

In general, insufficient air motion promotes stuffiness and air stratification. Stratification causes air temperatures to vary from floor to ceiling. When air motion is too rapid, unpleasant drafts are felt by the room occupants. The exact limits to acceptable air motion in the occupied zone are a function of the overall room conditions of temperature, humidity, along with the temperature and humidity conditions of the moving air stream. A noticeable air movement across the body when there is perspiration on the skin may be regarded as a pleasant cooling breeze. When the surrounding surface and room air temperatures are cool, however, it will probably be considered a chilly draft. The neck, upper back, and ankles are most sensitive to drafts, particularly when the entering cool air is 1.5 °C or more below normal room temperature.

Every 15 fpm increase in air movement above a velocity of 30 fpm is sensed by the body as one degree temperature drop. Air systems are usually designed for a maximum of 50 fpm in the occupied zone, but that is typically exceeded at the outlet of air registers. Cool air can impinge on an occupant in two general cases: Air that is warm when introduced into the room may cool off before reaching the occupant, or the air is intended to cool the occupant under overly warm ambient conditions.

In either case, when the temperature of the air impinging on an occupant is below the ambient temperature, the individual becomes more sensitive to air motion and may complain of drafts. Therefore, careful attention must be given to air distribution as well as velocity. The tendency of warm air to rise can greatly affect occupant comfort due to convective air motion, and thus influences the correct placement of the heat source in a room.

2.7.3.4 Ambient Radiation

Men are in a thermal radiant environment. Thermal radiation not only comes from the sun or a radiator, but from any heated objects such as the ground surface, a wall, boiler, etc. The radiant field around a clothed man is an important factor in determining the heat lost from the human body. It was found that the heat gain from the direct and reflected radiation at the South Pole was up to 200-400 kcal/m^2hr, and was equivalent to raising temperature of the environment by 8 - 20°C, depending on the wind [50]. The radiant heat lost from the clothing surface can be estimated by

$$\mathrm{Hr} = \mathrm{A}.\varepsilon.\sigma.(\mathrm{Tc}^4 - \mathrm{Tmr}^4) \qquad (9)$$

where, A is the effective radiant surface area, ε is the emissivity of the clothing surface, σ is the Stefen-Boltzman's constant, Tc is the surface temperature of the clothing, Tmr is the mean radiant temperature of the environment. Hr is the radiant heat lost (watts). Tmr can be assessed by using a globe thermometer.

2.8 Moisture transmission through textiles

Moisture transmission through textiles has a great influence on the thermo-physiological comfort of the human body which is maintained by perspiring both in vapor and liquid form. The clothing to be worn should allow this perspiration to be transferred to the atmosphere in order to maintain the thermal balance of the body. Diffusion, absorption-desorption and convection of vapor perspiration along with wetting and wicking of liquid perspiration play a significant role in maintaining thermo-physiological comfort. The scientific understanding of the processes involved in moisture transmission through textiles and the factors affecting these processes are important to designing fabrics and clothing assemblies with efficient moisture transfer in different environment and workload conditions.

In a regular atmospheric condition and during normal activity levels, the heat produced by the metabolism is liberated to the atmosphere by conduction, convection and radiation and the body perspires in vapor form to maintain the body temperature. However, at higher activity levels and/ or at higher atmospheric temperatures, the production of heat is very high and for the heat transmission from the skin to the atmosphere to decrease, the sweat glands are activated to produce liquid perspiration as well. The vapor form of perspiration is known as insensible perspiration and the liquid form as sensible perspiration [51]. When the perspiration is transferred to the atmosphere, it carries heat (latent as well as sensible) thus reducing the body temperature. The fabric being worn should allow the perspiration to pass through; otherwise it will result in discomfort. The perception of discomfort in the active case depends on the degree of skin wetness. During sweating, if the clothing moisture transfer rate is slow, the relative and absolute humidity levels of the clothing microclimate will increase suppressing the evaporation of sweat. This will increase rectal and skin temperatures, resulting in heat stress [52].

It is also important to reduce the degradation of thermal insulation caused by moisture build-up. If the ratio of evaporated sweat and produced sweat is very low, moisture will be accumulated in the inner layer of the fabric system, thus reducing the thermal insulation of clothing [52] and causing unwanted loss in body heat. Therefore, both in hot and cold weather and during normal and high activity levels, moisture transmission through fabrics plays a major role in maintaining the wearer’s body at comfort. Hence, a clear understanding of the role of moisture transmission through clothing in relation to body comfort is essential for designing high performance fabrics for particular applications.

2.8.1 Processes involved in moisture transmission through textiles

The process of moisture transport through clothing under transient humidity conditions is an important factor which influences the dynamic comfort of the wearer in practical use. Moisture may transfer through textile materials in vapor and in liquid form, as outlined below.

2.8.1.1 Water vapor transmission

Water vapor can pass through textile layers by the following mechanisms:

• Diffusion of the water vapor through the layers.

• Absorption, transmission and desorption of the water vapor by the fibers.

• Adsorption and migration of the water vapor along the fiber surface.

• Transmission of water vapor by forced convection.

2.8.1.2 The diffusion process

In the diffusion process, the vapor pressure gradient acts as a driving force in the transmission of moisture from one side of a textile layer to the other. The relation between the flux of the diffusing substance and the concentration gradient was first postulated by Fick [53].

$$J_{Ax}=D_{AB}\frac{dCA}{dX} \qquad (10)$$

Where, J_{Ax} is the rate of moisture flux; $\frac{dCA}{dX}$ is the concentration gradient; and D_{AB} is the diffusion coefficient or mass diffusivity of one component, diffusing through another media. Water vapor can diffuse through a textile structure in two ways, simple diffusion through the air spaces between the fibers and yarns and along the fiber itself [54, 55]. In the case of diffusion along the fiber, water vapor diffuses from the inner surface of the fabric to the fibers' surface and then travels along the interior of the fibers and its surface, reaching the outer fabric surface. At a specific concentration gradient the diffusion rate along the textile material depends on the porosity of the material and also on the water vapor diffusivity of the fiber. The moisture diffusion through the air portion of the fabric is almost instantaneous whereas through a fabric system is limited by the rate at which moisture can diffuse into and out of the fibers, due to the lower moisture diffusivity of the textile material [56].

In the case of hydrophilic fiber assemblies, vapor diffusion does not obey Fick's law. It is governed by a non-Fickian, anomalous diffusion [57, 58]. This is a two stage diffusion process. The first stage corresponds to a Fickian diffusion but the second stage is much slower than the first, following an exponential relationship between the concentration gradient and the vapor flux [59-61]. This diffusion process can be explained by swelling of the fibers. Due to the affinity of the hydrophilic fiber molecules to water vapor, as it diffuses through the fibrous system, it is absorbed by the fibers causing fiber swelling and reducing the size of the air spaces, thus delaying the diffusion process [62, 63]. Some scientists [64] have explained this reduction in the diffusion rate, as caused by the stress relaxation of the fiber after swelling. Others [65] have given an account to this phenomenon; the heat of sorption produced increases the temperature of the fibrous assemblies, which in turn affects the rate of moisture transmission.

The moisture diffusivity of a textile material is influenced by a number of factors. It decreases with an increase in the fiber volume fraction of the material. As the fiber volume fraction increases, the proportion of air in the fibrous assembly decreases, reducing the total diffusivity. The moisture diffusivity through the fabric decreases with an increase in the flatness of the fiber cross section [66]. With an increase in fabric thickness, the porosity of the material is reduced, thus reducing the diffusion rate [67]. Water vapor diffusion is highly dependent on the air permeability of the fabric [68]. Air permeability increases as the porosity of the fabric increases; which also results in higher moisture through the air spaces within the fabric. The type of finish applied (i.e. hydrophilic or hydrophobic) to a fabric has no great effect on the diffusion process [69].

2.8.1.3 The sorption-desorption process

Sorption-desorption is an important process to maintain the microclimate during transient conditions. A hygroscopic fabric absorbs water vapor from the humid air close to the sweating skin and releases it in dry air. This enhances the flow of water vapor from the skin to the environment comparatively to a fabric which does not absorb and reduces the moisture built up in the microclimate [70-72]. In the absorption-desorption process an absorbing fabric works as a moisture source to the atmosphere [73].

It also works as a buffer by maintaining a constant vapor concentration in the air immediately surrounding it, i.e. a constant humidity is maintained in the adjoining air, though temperature changes due to the heat of sorption. The magnitude of the differences in moisture transport caused by fabric sorption was examined [74], and the perception of these differences. Adsorption of water molecules takes place below a critical temperature, due to the Van der Waal's forces between the vapor molecules and the solid surface of the structure. The higher the vapor pressure and the lower the temperature, the higher is the amount absorbed. In a thermodynamic equilibrium the chemical potential of the vapor is equal to that of the absorbed film. An increase in vapor pressure causes an imbalance in chemical potential, and more vapor transfers to the absorbed layer to restore the equilibrium [63]. The amount of water vapor which can be absorbed by the materials is dependent on the fiber regain and the humidity of the atmosphere (%). In the case of absorbent fibers, e.g. cotton, rayon, the moisture sorption is not only dependent on regain and humidity, but also on the phenomena associated with sorption hysteresis, the effect of heat, dimensional changes and elastic recovery effects, due to the reduced swelling of the fibers. During swelling, the fiber macro-molecules or micro-fibrils are pushed apart by the absorbed water molecules, reducing the pore size between the fibers as well as the yarns, thus reducing the water vapor transmission through the fabric. As swelling increases the capillaries between the fibers get blocked, resulting in lower wicking. Also, the distortion caused by swelling sets up internal stresses which influence the moisture sorption process. The mechanical hysteresis of the fibers accentuates the adsorption hysteresis [63]. The adsorption hysteresis increases with an increase of the fiber hydrophilicity.

2.8.1.4 Convection process

Convection is a mode of moisture transfer that takes place while air is flowing over a moisture layer. This is known as the forced convection method. The mass transfer in this process is controlled by the difference in moisture concentration between the surrounding atmosphere and the moisture source. The process is governed by equation (11) [75].

$$Qm = -A\,hm(Ca - C\propto) \qquad (11)$$

Where Qm is the mass flow by convection through area A of the fabric along the direction of the flow, C_{a} is the vapour concentration on the fabric surface and $C_{\propto}$ is the vapor concentration in the air. The flow is controlled by the concentration difference (C_{a} - $C_{\propto}$) and the convective mass transfer coefficient h_m, which depends on the fluid properties as well as on its velocity. In a windy atmosphere the convection method plays a very important role in transmitting moisture from the skin to the atmosphere [76, 77]. Evaporation and condensation also have a noteworthy effect on moisture transmission. Evaporation and condensation depend on the temperature and moisture distribution in porous textiles at the time of moisture transfer [78]. During the evaporation of liquid perspiration, latent heat is taken from the body, cooling it down. The role of evaporative heat transfer in maintaining thermal balance becomes more crucial with an increase in the surrounding atmospheric temperature. In this case, due to the low temperature gradient between the skin and the environment, conduction and convection heat transfer are reduced [79]. When a negative temperature gradient exists between the skin and the environment, evaporative heat transfer becomes the only way to cool down the body temperature. Since the latent heat of water is quite large (2500 kJ/kg), even a small amount of evaporation adds significantly to the total heat flow [80]. Wind enhances the evaporative heat transfer and results in additional cooling that is desirable in periods of peak performance. In the steady state, the latent heat lost by water due to evaporation is equal to the heat that comes to the water from the surrounding air, making it cooler. In that case the energy balance equation at the air-water interface [53] is as follows:

$$Q_{conv} = Q_{evap} \tag{12}$$

Where Q_{conv} is the convective heat transfer from the surrounding air to the water and Q_{evap} is the heat taken from the water due to evaporation. Condensation is a direct result of a fabric being saturated by liquid perspiration [57]. It occurs within the fabric whenever the local vapor pressure rises to saturation vapor pressure at the local temperature [81]. Condensation normally occurs when the atmospheric temperature is very low. When the warm and moist air from the body meets the fabric, it works as a cold wall, and condensation occurs. The results presented from laboratory testing and field trials have confirmed that condensation occurs at atmospheric temperatures below 100°C [82]. In the case of fabrics where the water vapor can diffuse from the skin to a part of the fabric layer more easily than from the fabric layer to the atmosphere, such as in the case of water proof fabrics, the probability of occurrence of condensation is very high.

Condensation in an initially dry porous material takes place in three stages [83]. First of all, velocity, temperature and vapor concentration fields are developed within the material and condensation begins. In the second stage, the liquid content increases gradually, but it is still too low to move and finally, as the liquid content increases further and goes beyond a critical value, the pendulum like drops of condensate coalesce and begin to move under surface tension and gravity. When the vapor concentration at the two faces of the fabric, are at the saturation level, condensation occurs throughout the entire thickness of the fabric. If the vapor concentration at the two faces is bellow saturation for the local temperature, condensation occurs only over a region within the fabric. In this case, condensation occurring in the fabric forms a wet zone, separated by two dry zones [82, 83]. The extent of the wet region increases with the increase in condensation. The extension of condensation develops mainly in the direction of the hot side rather than that of the cold side. In the case of a waterproof breathable fabric, the extent of condensation is very high.

2.9 Liquid water transmission: Steady state flow

The flow of liquid moisture through textiles is caused by fiber-liquid molecular attraction at the surface of the fiber materials, which is mainly determined by the surface tension and the effective capillary pore distribution and pathways [78]. Liquid transfer through a porous structure involves two sequential processes – wetting and wicking. Wetting is the initial process involved in fluid spreading. In this process the fiber-air interface is replaced with a fiber-liquid interface as shown in (Figure 1.2 a). The forces in equilibrium at a solid-liquid boundary are commonly described by the Young-Dupre equation, given below [84]:

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos\theta \qquad (13)$$

Where, γ represents the tension at the interface between the various combinations of solid (S), liquid (L) and vapor (V), and θ is the contact angle between the liquid drop and the surface of the solid to be wetted. In the case of a textile material, the fiber represents the solid portion.

There are several factors influencing the wettability of the material. The contact angle is a direct measurement of the fabric wettability. A low contact angle between the fiber and the liquid means high wettability [85]. The wettability also increases, as the surface tension between the solid and the liquid interface diminishes. With an increase in the temperature of the liquid, its surface tension is reduced, resulting in higher wetting [63]. Also, with an increase in the liquid's density and viscosity, the surface tension of the material increases, thus reduces wettability. With an increase in surface roughness, the spreading of water along the surface becomes faster due to the troughs offered by rough surfaces as the apparent wetting angle is decreased. The wettability of the material also changes with the chemical nature of the surface and so with an increase in hydrophilicity, the contact angle is reduced, thus increasing the surface wettability [86]. As the roundness and the diameter of the fibers are reduced, the cosine values of the advancing angle increase, thus increasing the surface wettability.

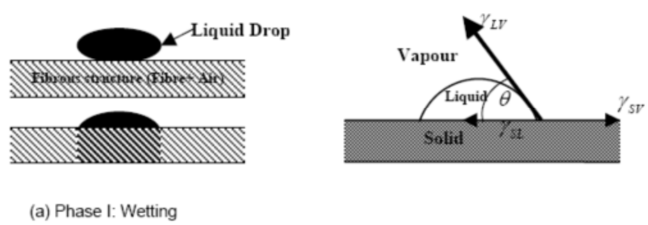


Figure 1.2 (a) The liquid transfer processes through a porous media

In sweating conditions, wicking is the most effective process to maintain a feel of comfort. In the case of clothing with high wicking properties, moisture coming from the skin is spread throughout the fabric offering a dry feeling and the spreading of the liquid enables moisture to evaporate easily. When the liquid wets the fibers, it reaches the spaces between the fibers and produces a capillary pressure. The liquid is forced by this pressure and is dragged along the capillary due to the curvature of the meniscus in the narrow confines of the pores as shown in (Figure 1.2 b).

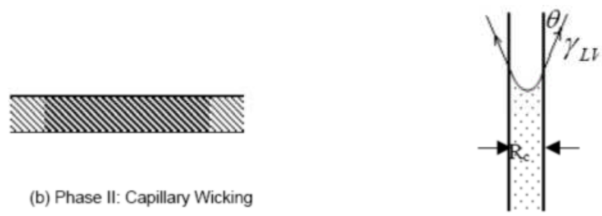


Figure 1.2 (b) The capillary wicking through a porous media

The magnitude of the capillary pressure [63] is given by the Laplace equation:

$$P = \frac{2\gamma LV \cos\theta}{Rc} \tag{14}$$

Where P is the capillary pressure developed in a capillary tube of radius Rc. A difference in the capillary pressure in the pores causes the fluid to spread in the media. Hence, a liquid that does not wet the fibers cannot wick into the fabric [87]. The ability to sustain the capillary flow is known as wickability [88]. The distance travelled by a liquid flowing under capillary pressure, in horizontal capillaries, is approximately given by the Washburn-Lukas equation [85]:

$$L = \sqrt{\frac{Rc\,\gamma\cos\theta}{2\eta}}\,t^{\frac{1}{2}} \tag{15}$$

Where, L is the capillary rise of the liquid in time t and η is the viscosity of the liquid. The amount of water that wicks through the channel is directly proportional to the pressure gradient. The capillary pressure increases as both the surface tension in the solid-liquid interface and the capillary radius decrease. A textile material consists of open capillaries, formed by the fibers walls [89]. From the Lukas-Washburn equation, it is expected that capillary rise at a specific time will be faster in a medium with larger pore size. However, using a comparative wicking study [90], it was shown that this is not always the case. It was found that higher initial wicking through the capillaries with bigger diameter has been overtaken with time by the capillaries with smaller diameter. A larger amount of liquid mass can be retained in larger pores but the distance of liquid advancement is limited. This may be explained by the Laplace equation, as the radius of the capillary decreases, the pressure generated in the capillary will be higher, causing faster flow through the capillary. The model developed by Rajagopalan and Aneja [91] also predicts that at a constant void area, increasing the perimeter of the filaments increases the maximum height attained by the liquid. Conversely, increasing the void area at a constant perimeter decreases the final height attained, but increases the initial rate of liquid penetration. With the increase in the packing coefficient of the yarn, the fibers come closer to each other introducing a greater number of capillaries with smaller diameter likely to promote liquid flow. In any system where capillarity causes relative motion between a solid and a liquid, the shape of the solid surfaces is an important factor, which governs the rate and direction of liquid flow [92]. The shape of the fibers in an assembly changes the size and geometry of the capillary spaces between the fibers and consequently the wicking rate. With an increase in the non-roundness of a fiber, the specific area increases, thus increasing the proportion of capillary wall that drags the liquid.

The tortuosity [93] of the pores has a great influence on the wicking process. It depends on the alignment of the fibers as well as on irregularities in the fiber diameter or shape along the pores. With an increase in the tortuosity of the pores, its wicking potential is reduced [94]. For instance, yarns spun with natural fibers have very irregular capillaries due to various factors such as fiber roughness, cross-sectional shape and limited length, which interrupt the flow along the length of the yarn [95]. In the case of textured filament yarns, as the number of loops in the yarn increases, the continuity of the capillaries formed by the filaments decreases as the filament arrangement becomes more random. Under these conditions wicking is reduced. The same explanation is also applicable to the slower wicking found in twisted yarns. During the spinning process, at higher twist levels, slow migration of fibers takes place along the yam structure, changing the packing density and resulting in disruption of the continuity, length and orientation of the capillaries. The twist direction has no significant effect on the yarn wicking performance. The presence of a wrapper filament also retards wicking as the volume of liquid in the capillaries is reduced [96].

2.10 Combined liquid transmission and vapor

In a humid transient condition, moisture is transported through textiles both in liquid and vapor form. It was identified that the transportation of moisture in humid transient conditions happens in three different stages [78]. The first stage is dominated by two fast processes - water vapor diffusion and liquid water diffusion in the air filling the inter fiber voids, which can reach a new steady state condition in a fraction of a second. During this period, water vapor diffuses into the fabric due to the concentration gradient across the two surfaces. Meanwhile, the liquid water starts to flow out of the regions of higher liquid content to the drier regions, driven by surface tension. During the second stage, the moisture sorption of the fibers is much slower than during the first stage, and takes a few minutes to a few hours to complete, depending on the heat transfer processes. In this period, sorption of water into the fibers takes place as the water vapor diffuses into the fabric, which increases the relative humidity at the fiber surfaces. After liquid water diffuses into the fabric, the surfaces of the fibers are saturated due to the film of water on them, which enhances the sorption process. Finally, the third stage is reached as a steady state, in which all forms of moisture transport and heat transfer become steady and the coupling effect between them becomes less significant. In this condition, distributions of temperature, water vapor concentration, fiber water content, liquid fraction volume and evaporation rate become independent of time. With liquid water evaporation, liquid water is drawn from the capillaries to the upper surface. Combined liquid water and water vapor transmission along the fabric is very important in the case of sweat. The liquid transport (i.e. liquid diffusion or capillary wicking) is very small compared with the vapor diffusion at low moisture content, whereas at saturation, capillary wicking is the major mechanism of moisture transport [97].

2.11 Combined heat and mass transmission

Moisture transmission through a textile material is not only associated with the mass transfer processes, but heat transfer must also be taken into account. Heat and moisture absorption in hygroscopic materials are inseparably interrelated. During the transmission of water molecules through textile materials, they are absorbed by fiber molecules due to their chemical nature and structure. Absorption of water is followed by the liberation of heat, known as heat of absorption. The amount of heat produced is dependent on the absorption capacity of the material. Due to the production of heat, as the temperature is increased on the surface of the material, the rate of moisture vapor transmission is reduced [59, 60]. During the investigation of the wool-water system, It was observed that in a textile material, immersed in a humid atmosphere, the time required for the fibers to come to equilibrium with the atmosphere is negligible compared with the time required for the dissipation of heat generated and absorbed by the fibers when regain changes [98]. With an increase in humidity, the heat transfer efficiency of the material increases. The heat transfer process also comes into play during the moisture transportation, under dynamic conditions, due to phase change of the water molecules. Thus, during the transient stages of moisture sorption and diffusion, the heat transfer process is coupled with four different forms of moisture transfer due to the heat released or absorbed during sorption/ desorption and evaporation/ condensation which in turn are affected by the efficiency of heat transfer and the length of the transient stage is dependent on the heat transfer process [99].

The coupling effect, between moisture diffusion and heat transfer depends on a number of properties, such as the moisture of sorption capacities, the fiber diameter, the water vapor diffusion coefficient, the density and the heat of sorption [100]. The heat of wetting of cellulosic fibers depends to some extent on the moisture regain and the crystalline structure, and it decreases proportionally with an increase in the degree of crystallinity of the fibers [101].

Two transient phenomena, buffering and chilling, are associated with the simultaneous heat and moisture vapor transport through fiber assemblies [99]. The cooling effect or buffering effect is experienced due to perspiration in hot climates and the chilling effect is associated with the after exercise sweating in cool climates. At a sudden increase in relative humidity in the climate, fabrics absorb moisture maintaining a microclimatic condition and generating heat. This gives rise to a thermostatic or buffering action for the person wearing the fabric in clothing [71]. The cooling effect was first postulated by Spencer-Smith [102], who postulated that there would be a cooling effect at the onset of perspiration in hot climates, whereas in the case of cold climates it would result in a ‘post exercise chilling effect [103]. It reduces the working performance, even causing hypothermia. When water vapour (vapour perspiration) comes into contact with a cold wall (clothing), it condensates, thus reducing the thermal insulation of clothing. Both these phenomena are extremely dependent on atmospheric temperature and humidity conditions.

2.12 Methods for the Study of Heat Transfer through Clothing

2.12.1 Experimental Simulations

The full understanding of the phenomenon of the heat transfer through clothing requires the knowledge of the thermal behavior of the clothing materials and clothing systems as a whole. The simplest experimental approach to this problem is by using a flat plate method in which clothing materials or simple clothing assemblies are covered on a heated flat surface and the heat transfer through the materials or assemblies are observed. Because the geometry of a flat surface is very simple, these methods have the advantage in evaluating the thermal properties of the materials or assemblies, but have problems in applying the results to the actual clothing systems in use. For this reason, various cylindrical methods were developed, which take into the consideration that a human body approximately consists of many cylindrical forms. Hence, the cylindrical methods provide better simulations than flat plate methods. Yet, the findings from these cylindrical methods are still unable to analyse the heat transfer between different parts of a clothed human body, and heat transfer induced by the body motion. Based on the above considerations, in recent years, manikins have been developed and applied.

2.12.1.1 Flat Plate and Cylindrical Methods

The earliest version of this kind of method which has been applied to clothing materials was developed and it consisted of a flat cylindrical vessel [104], a plate at the bottom of the vessel, and a plate hung below the vessel. The temperature within the flat vessel was controlled at 100 °C by passing steam through it. Samples were sandwiched between the upper and lower plates. Temperatures at the lower surface of the upper plate and the upper surface of the lower plate were measured with thermometers.

The thickness of the sample was obtained by measuring the distance between the pegs projecting from the edges of these two plates. This method was later improved [105], and became well known as the Lees' disc method by which thermal conductivities of various materials were evaluated.

When the Lees' disc method was applied to textile fabrics, the contact thermal insulation between the fabric and the discs, and the pressure applied on the fabrics could affect the final results. This problem was noted [106], and it was tackled by using multiple fabric layer techniques and specifying the pressure applied on the fabrics.

In the Lees' disc method, no guard ring was used to prevent heat loss in the directions other than through the sample. This might be reasonable in his work, since the discs and the samples were thin and the surface area was large. However, this was not satisfactory in later work a new disc method with a guard ring on it was invented. In addition, Lee’s method employed only one single hot plate, the sample was exposed to the conditioned air and the temperature of the hot plate was controlled at body temperature. This arrangement was regarded as a good simulation of actual clothing in use and was recommended as a standard.

Later, in order to take the water vapor transmission into account, methods which allow simultaneous dry and latent heat transfer through clothing were developed. A flat plate method was developed in which fabrics were placed on a hot, porous plate which was covering on a water dish. Modern versions of this kind were developed throughout the world after that.

In the above methods, heat transfer through the clothing was measured in the same way, i.e. measuring the power input into the testing system. However, Niven's flat plate method [108] is very different in this aspect. His method combined the flat plate guard ring technique and the cooling principle. The time taken for the hot plate which covered the specimen to drop its temperature from 50 °C to 49.5 °C was chosen as a measure of the rate of heat transfer through the specimen.

The most commonly used flat plate method nowadays is the disc Togmeter, which was first developed by Clulow and Rees [30]. The Togmeter used a standard plate of known thermal insulation in between the hot plate and the specimen so that the thermal insulation of the specimen could be determined by comparing the temperature difference across the specimen and across the standard plate. This method was adopted as a British Standard in 1971 (BS. 4745).

The simplest method of this kind may be the use of a Kata-thermometer upon which the specimen is wrapped. The time taken for a definite temperature drop is a measure of the thermal insulating properties of the specimen or the heat transfer through the specimen. This method was used by Bachmann [109]. The problem of the use of a Kata-thermometer is that the surface area is too small to obtain a reliable and consistent measurement.

In fact, before this method, some cylindrical methods of bigger sizes than a Kata-thermometer had already been developed [110]. These methods employed the same cooling method because of its simplicity. However, since the 1930s, most cylindrical methods have used the constant temperature method, in which the temperature of the cylindrical body was controlled at a constant level similar to the human body temperature, and the heat supplied to maintain the constant temperature was measured. These methods were used by several scientists [111,112].

A new apparatus was developed [113] which used a heated cylinder-like zinc tank with two convex and two concave sides to simulate the shape of the human body. Clothing specimens were used to the tank. The results were expressed as the percentage insulation (PI) which was defined as follows.

$$\mathrm{PI} = \frac{\mathrm{t}}{\mathrm{T}} \mathrm{X}\ 100\% \qquad (16)$$

Where, *T* is the temperature drop between the hot water inside the tank and the other surface of the tank when the tank is not covered with the specimen, and *t* is the temperature drop when the tank is covered with the specimen. In order to study the latent heat transfer, sweating cylindrical apparatus were also developed [114]. The cylindrical apparatus was covered with a layer of linen which was kept wet by absorbing water from a water reservoir. Specimens were wrapped on the layer of linen. The moisture transfer properties of the specimen were expressed in a Permeability Index.

More recently [41], the advantage of the disc Togmeter design was taken, and it was applied in the development of a cylindrical Togmeter. This cylindrical apparatus had an internally heated cylinder and an enclosing layer of known thermal conductivity on which the specimen was covered. The thermal insulation of the specimen as a function of the angular position could be evaluated. This apparatus was especially useful for studies in windy conditions. The only criticism of his cylindrical Togmeter was that the size was too small and the heat loss from the ends of the cylindrical apparatus was not prevented.

A new system was developed [115] which measure thermal properties of the fabric to determine the thermal properties of different textile materials. The computer controlled instrument is called Alambeta calculates all the statistic parameters of the measurement and exhibits the instrument auto-diagnostics, which avoids faulty instrument operation. The whole measurement procedure, including the measurement of thermal conductivity, thermal resistance, sample thickness and the results evaluation, lasts less than 3 -5 min.

The above mentioned measuring instrument consists of metal block with constant temperature which differs from the sample temperature. When the measurement starts, the measuring head goes down and touches the planar measured sample which is located on the instrument base under the measuring head. In this moment, the surface temperature of the sample suddenly changes and the instrument registers the heat flow course. Simultaneously, sample thickness is measured. All the data are then processed in the computer according to an original program.

Due to the fast response of the apparatus and within various research projects the thermal-insulation and thermal-contact properties of most of the common textile products were experimentally investigated [116].

The sweating guarded hot plate [117] is widely recently used to measure the thermal resistance R_{ct}, the apparatus consists of the measuring unit, temperature controller and water supply unit. The measuring unit, fixed to a metal block with heating element, is a square porous metal plate with 3mm thickness. The test section in the center of the plate is surrounded by the guard heater, which prevents lateral heat leakage from the edges of the specimen which was a defect in most of the measuring methods. The bottom heater beneath the test section can prevent the downward heat loss from the test section and guard heater section. This arrangement drives heat to transfer upward only along the specimen thickness direction.

The tested fabrics are mounted on the square porous plate that is heated to a constant temperature that approximates body skin temperature (i. e. 35 °C). The plate temperature is measured by the sensor sandwiched directly underneath the plate surface. The electrical power is recorded. The whole apparatus is housed in a chamber so that the environmental conditions can be carefully controlled [117, 118].

2.12.1.2 Manikins

The total number of existing manikins is still small because of their high cost. The earliest manikin, who can be found in the literature, was employed by the Royal Air Force Institute of Aviation Medicine [119]. It consisted of sixteen independently controlled sections. Each section was arranged to reproduce the skin temperature. Heat lost from the manikin due to forced ventilation was investigated. Later in the U.S. Army Research Institute of Environmental Medicine [120], a similar heated sectional copper manikin was also developed. With this manikin, sweating was also simulated by wearing a coverall type of "skin" which was made of "T-shirt" material and wetted in advance. The uneven wetness of the "skin" after a period of testing was a problem for such sweating simulation. The above two manikins cannot simulate walking and were regarded as of the first generation.

The second generation movable manikins were later developed in Germany, Denmark and Japan [121]. Amongst them, copper manikin "Charlie" in the Hohenstein Institue in Germany was the most famous one. However, none of these manikins was successful in simulating sweating. Manikins of the third generation, which are aimed to simulate sweating and sophisticated body motions, are being developed.

2.12.1.3 Theoretical Simulations

The fundamental feature of the theoretical simulations is that it applies physical principles in a mathematical model which takes into account some or many characteristics of actual clothing in use. With the worldwide application of computers, these research methods have a great potential in the further advance of this area.

Many theoretical models have been developed for the solution of heat transfer through clothing over last few years. A model of the combined conductive and radiative heat transfer through fibrous insulating materials was presented [6]. By comparing the theoretical results with the experimental ones, convective heat transfer through low density battings in still air was found to be of little importance. Later another model was developed for the heat transfer by conduction, radiation and vapor transport in multi-layered clothing assemblies. This model was applied to display the effects due to condensation or evaporation of water within clothing and absorption or desorption by hygroscopic materials. More recently, attempts have been made to develop models which consider the main features of the human body-clothing-environment system [122, 123]. Results from such models can directly analyze the contribution of clothing to body thermal comfort.

More recently in the last 40 years, numerous studies have focused on the heat transfer from human body to surrounding air. A considerable amount of papers have considered modeling heat transfer from human body to the surrounding air [6, 124, 125].

These models are capable of predicting human physiologic response to transient, non-uniform thermal environment [126]. A computer model of human thermoregulation for a wide range of environmental conditions was presented. The numerical formulation of the passive system was verified by comparison with the known analytic solutions for conduction in cylinders. Further, the active system was presented and was compared with the model predictions, the experimental data and the predictions by other models. The active system known as a dynamic model is capable of predicting human thermal responses in cold, cool, neutral, warm, and hot environments.

On the other hand, a numerical model was developed to predict skin burn injury resulting from heat transfer through a protective garment worn by an instrumental manikin exposed to laboratory-controlled flash exposures [125]. This model incorporated characteristics of the simulated flash fire generated in the chamber and the heat-inducted changes in fabric thermophysical properties. The model proved to be a powerful tool for engineering thermally protective garments.

Although the models mentioned are fairly complex, a greater part of them have not yet gained widespread use. Reason for this may include lack of confidence in the predictive abilities, limited range applicability and many times deficient modeling of the heat exchange with the environment.

2.12.1.4 Wearer Trials

Various methods can be used to evaluate or predict clothing comfort [127]. The thermal insulation properties of clothing can be defined through physical measurement using thermal manikins or through wear trials using human test subjects. User tests or trials are the only way to provide realistic and comprehensive evaluations of the performance of clothing. However, it is infeasible to use these to test a variety of clothing systems because they are costly and it is difficult to control variables to determine where the subjective sensations come from. When tests are used for extreme conditions, the difficulty of these problems becomes more serious [128]. A wide range of environmental conditions cannot be tested with human subjects for safety reasons, even though consumers can actually be exposed to such conditions. Therefore, it is important to use information from laboratory levels in the planning of test a field level.

Wearer trials can be used for studying different properties of clothing by means of subjective judgments or objective measurements. When these methods are applied to the study of heat transfer through clothing, results are determined objectively. The rate of dry heat transfer (Hd) from the human body is determined by solving the heat balance equation, i.e.

$$\text{Hd} = \text{M-W-C}_r\text{-E}_r\text{-E-S (watts/m}^2\text{)} \tag{17}$$

Where, M is the body metabolism which can be determined from oxygen uptake, W is the external work, C_r and E_r are the respiratory heat loss by convection and evaporation respectively, E is the skin evaporative heat loss which can be determined from the body weight loss and S is the body heat storage. The thermal insulation of the clothing (Rc), clothing surface (Rs) and the clothing system (R) can be calculated as:

$$\text{Rc} = \frac{\text{Ts} - \text{Tc}}{\text{Hd}} \tag{18}$$

$$\text{Rs} = \frac{\text{Tc} - \text{Ta}}{\text{Hd}} \tag{19}$$

$$\text{R} = \frac{\text{Ts} - \text{Ta}}{\text{Hd}} \tag{20}$$

Where, Ts is the mean skin temperature, Tc is the mean temperature of the clothing surface, and Ta is the ambient temperature. If the partial water vapor pressure at the skin surface, at the clothing surface and in the environment can be measured, the resistance to water vapor transfer of the clothing (Wc), the clothing surface (Ws) and the system (W) can also be calculated:

$$\text{Wc} = \frac{\text{Ps} - \text{Pc}}{\text{E}} \tag{21}$$

$$\text{Ws} = \frac{\text{Pc} - \text{Pa}}{\text{E}} \tag{22}$$

$$\text{W} = \frac{\text{Ps} - \text{Pa}}{\text{E}} \tag{23}$$

Where, Ps and Pc are the mean partial water vapor pressure at the skin surface and the clothing surface, and Pa is the, ambient partial water vapor pressure [127, 128].

2.13 Methods for the Study of Moisture Transfer through Clothing

Water vapor can be transferred through textile layers by different processes, e.g. diffusion, absorption-desorption and forced convection. The route of diffusion through a layer can be described by the following mechanism: (a) molecular diffusion through solid (polymeric phase), (b) surface diffusion of adsorbed molecules along the fibers and (c) molecular diffusion through the air spaces of the fabric [73]. A vapor is diffused from one side of a fabric to the other in response to a difference in the pressure gradient. The diffusion process through a porous material is governed by Fick’s law [53], as shown below

$$J_{Ax}=D_{AB}\frac{dC_A}{dx} \text{ in g cm}^{-2}\text{sec}^{-1} \qquad (24)$$

Where, J_{Ax} is the rate of moisture flux, $\frac{dC_A}{dx}$ is the concentration gradient, and D_{AB} is known as the diffusion coefficient or the mass diffusivity of one component diffusing through another media as mentioned before. The absorption-desorption process plays a major role in vapor transport through hygroscopic materials. In the presence of air flow, the forced convection process plays a significant part in carrying moisture from the skin to the atmosphere, through the fabric layers, especially in the case of highly porous textile layers. In the case of a windy atmospheric condition or movement of air under clothing, corresponding to an “inner wind” due to body movement (known as pumping effect), the amount of moisture transferred by convection increases. The confined air layer close to the skin does not behave as a passive barrier. This is a place where strong convective movements take place, due to its vertical dominant disposition and by the separation of a few centimeters between two surfaces (skin and internal fabric) with sufficient amount of pressure gradient.

The measurement of water vapor permeability is a slow and somewhat delicate operation. However, it can be carried out quite effectively. The different methods used for determining the water vapor permeability of textile assemblies are as follows:

The evaporative dish method or control dish method (BS 7209), the upright cup method or Gore cup method (ASTM E 96-66), the inverted cup method, the desiccant inverted cup method (ASTM F 2298), the dynamic moisture permeable cell (ASTM F 2298), and the sweating guarded hot plate method, knowing as the skin model (ISO 11092) [129, 130].

In different methods, different terms are used to express the water vapor permeability of a material [62]. Results obtained from the different available methods are not always comparable due to the different testing condition and the units used in the measurements. The most common units used for the measurement of the water vapor permeability of fabrics are listed below [19, 130, 131, 132]:

• The Percentage Water Vapor Permeability Index, (WVP %) is used in the evaporative disc method (BS 7209); this method uses water at 20°C and an atmospheric condition of 20°C and 65% relative humidity; this standard is based on the control dish method (CAN2-4.2-M77) and the Gore modified disc method .

• The Moisture Vapor Transmission Rate (in g m^{-2} Day^{-1}) is used in the cup method (ASTM E96-66); it uses air at relative humidity of 50% and a recommended water temperature of 32.2 °C or a desiccant.

• The Resistance to Evaporative Heat Transfer, Ret (in m^2Pa/W) is used in the sweating guarded hot plate (ISO 11092:1993, EN 31092); it is an indirect method of measuring the vapor transmission property of a fabric. In this test method, the experiment is carried out at isothermal condition at standard atmospheric condition.

• The Resistance, in cm, of equivalent standard still air is used in the holographic visualization method; in this method it is possible to measure the resistance offered by the fabric layer and the air layer separately. The resistance of the fabric (cm) can be expressed in terms of the standard still air providing the same vapor resistance. ISO 7933 and ISO 9920 refer to two methods of determination of the evaporative resistance of a clothing assembly [79]:

• The use of Fpcl, which is a reduction factor for evaporative heat loss with clothing, compared to the nude body.

• The use of Im, the permeability index of clothing, which provides a relation between evaporative and dry heat resistance of clothing items or systems.

According to ISO 7933, the clothing vapor resistance is calculated using Fpcl as a reduction factor for the latent heat exchange of the clothed person compared to the nude situation, using the following equation:

$$RT= \frac{1}{(he \text{ X } Fpcl)} \text{ m}^2 \text{ kPa W}^{-1} \qquad (25)$$

Where:

he is the evaporative heat transfer coefficient for the nude person, given by:

he = 16.7 × hc W m^{-2} kPa^{-1}) the constant 16.7 is the Lewis number (°C.kPa^{-1}) and hc is the convective heat transfer coefficient (W.m^{-2}. °C $^{-1}$)

The humid heat transfer energy (E) is written in the following form:

$$E = heFpcl\ (Pskin\text{-}Pair)\ \text{Joule} \qquad (26)$$

Where, Pskin and Pair are the moisture pressure at the skin and ambient air respectively; he is the evaporative heat transfer coefficient. Clothing can also absorb liquid sweat by capillary action or wicking, and therefore not all the latent heat of evaporation is available for cooling the skin. Fpcl goes from zero to unity; Zero means that the fabric is completely impermeable and unity is used for the absence of clothing. The thickness and porosity of a given textile affects its Fpcl and if the textile is wet, the porosity decreases while the heat loss from the body increases by direct conduction, thus decreasing the thermal resistance and increasing the Fpcl. The definition of the relation between RT, im and IT is given in ISO 9920 [133]:

$$i_m = \frac{I_T}{L\ X R_T} = \frac{h_e}{L\ X\ h_{tot}}\ \text{KPa/°C} \qquad (27)$$

Where Im is the index for vapor permeability, h_{tot} is the total radiation and convective heat transfer coefficient of clothing, including air layers, and L is the Lewis number.

The sweating guarded hot plate apparatus or “Hohenstein” skin model [131, 133] is used to measure the thermophysiological comfort of clothing. It simulates the moisture transport through textiles and clothing assemblies when worn next to the human skin. This model measures the water vapor resistance of the fabric by measuring the evaporative heat loss in the steady state condition. The temperature of the guarded hot plate is kept at 35°C (i.e. the temperature of the human skin) and the standard atmospheric condition for testing (65% R.H. and 20 °C) is used.

A new fast response measuring instrument (skin simulator) was developed, the Permetest [134], for measuring of the water vapor permeability of textile fabrics, garments, nonwoven webs and soft polymer foils, by measuring the evaporative heat resistance. It works on the principle of heat flux sensing. The temperature of the measuring head is maintained at room temperature for isothermal conditions. The heat supplied to maintain the temperature of the measuring head, from where the supplied water gets evaporated, is measured. The heat supplied to maintain a constant temperature with and without the fabric mounted on the plate is measured. This instrument provides the relative water vapor permeability (%) of the fabric in the steady state isothermal condition.

Relative water vapor permeability (%) =

$$\frac{\text{Heat lost when the fabric is placed on the measuring head}}{\text{Heat lost from the bare measuring head}} \text{ X100} \qquad (28)$$

The Permetest can be used according to both BS 7209 and ISO 9920 standard. If the ring above the measuring head is used, a separating air layer will be created between the measuring head (simulated skin) and the fabric layer, thus providing the measuring condition according to BS 7209. On the other hand, if the ring above the measuring head is not used, the fabric will be in direct contact with the measuring head, i.e. according to the conditions used for the ISO 9920 standard.

In the dish method, the water vapor permeability of the fabric is measured by a gravimetric method. The specimen under test is sealed over the open mouth of a dish containing water and placed in the standard atmosphere for testing. After a period of time used to establish equilibrium, successive weighing of the dish is made and the rate of water vapor transfer through the specimen is calculated. In this method, the steady state water vapor permeability is also measured. The relative permeability of the sample is calculated comparing it with a reference fabric.

$$\text{Water vapor permeability (WVP)} = 24M / A.t \text{ (g } m^{-2} \text{ day}^{-1}) \qquad (29)$$

$$\text{Relative water vapor permeability index\%} = (WVP)f \times 100 / (WVP)r \qquad (30)$$

Where:

M is the loss in mass, g

t is the time between weightings in h

A is the internal area of the dish, m^2

(WVP)f and (WVP)r are the water vapor permeability of the test fabric and reference fabric respectively. In the case of the upright cup method the fabric is placed and sealed above a cup, 2/3rd of which is filled with water and then the cup is placed in a wind tunnel at a standard atmosphere on a weighing balance and the change in mass of the fabric at a time interval is measured. In the case of the inverted cup method the cup with the fabric is placed in such a way that the fabric will be in the lower side of the water. The inverted cup method is designed for use with waterproof samples, because the fabrics which allow the passage of liquid water may not be inverted as they will leak [129].

The Grace, Cryovac Division has developed a Moisture Vapor Transmission Cell (MVTR cell), which offers a faster and more simplified method for measuring the water vapor transmission behavior of a fabric. In principle, the cell measures the humidity generated under controlled conditions as a function of time. The change in humidity at a time interval gives the moisture vapor transmission rate (T) of the fabric.

$$T = (269 \times 10^{-7}) \left(\Delta\%\text{RH X } \frac{1440}{\text{Time Interval}} \right) \text{ g in}^{-2} \text{ day}^{-1} \qquad (31)$$

Li and Holcombe [60] have set up an experimental apparatus, known as the sorption cell to measure moisture transfer through a textile material by the sorption process. The temperature and humidity of the cell is simultaneously controlled by immersing it in a hot water bath and feeding dry and wet nitrogen according to the required proportion. The sorption capacity of the fabric is measured from the reading obtained from the balance, from which the fabric has been hung. The temperature change due to water vapor sorption was measured by inserting a fine thermocouple into the surface layer of the fabric. A sorption cell gives the transient moisture content of the fabric sample and the moisture flux across the fabric, thus measuring the moisture sorption of the fabric and the moisture flux simultaneously in a transient condition [54, 73]. A dynamic moisture permeable cell (DMPC) was developed [135], which is capable of evaluating the transport properties of textiles under various conditions such as pure diffusion, combined diffusion as well as convection and pure convection. The convective flow has been evaluated by measuring the relative pressure drop at the bottom outlet. The convective flow through hygroscopic porous materials is complicated, due to the tendency of the fibers to take up water vapor and experience fiber swelling. The change in the fabric connective flow properties has been taken as a function of relative humidity. The increment in the Darcy´s flow resistance with relative humidity is much less in the case of hydrophilic materials [77]. The DMPC can be used to obtain both steady state and dynamic state data.

The resistance to the water vapor transfer depends on the resistance of the air layer and the outer clothing. The resistance offered by the fabric layer in vapor transmission from the skin to the atmosphere is much lower than that offered by the external boundary air layer, and often much lower than that of the inner confined air layer between the skin and the fabric. So, in order to measure the flow resistance of a textile, we also need a precise determination of the surrounded air layers. From comparative studies of the different methods used for water vapor permeability determination, it is concluded that the average reading for all fabrics were lowest when measured with the upright cup, followed by the DMPC, and finally by the inverted cup method. The upright cup test and the dynamic moisture permeation cell were very highly correlated, and the desiccant inverted cup test and the sweating hot plate test were also highly correlated [129]. An inverse relationship exists between the resistance to evaporative heat loss and the water vapor permeability index of the fabric [130]. Both the water vapor permeability (Wd) and the water vapor transmission (WVT) have a direct relationship with the water vapor transfer across the fabric. The water vapor permeability (Wd) indicates the quantity of water vapor that has been moved through a unit area of the sample material in a certain point in time as a result of the pressure gradient between the two sides of the sample. The water vapor transmission value (WVT) also indicates the water vapor flow through the sample within a given time interval, but without reference to the water vapor pressure difference exerted during the measurement. The water vapor resistance (Ret) describes a material's resistance to moisture or evaporative transport through the material; therefore it is inversely proportional to the other two values. From the experimental analysis of water vapor permeability of 30 different fabrics, using different available methods, It was found that there are good correlations for the Control Dish using BS 7209 (0.979), the Skin Model (0.925) and the Gore Cup (0.995) methods as shown in (Figure1.3) , despite the differences in measuring techniques [136].

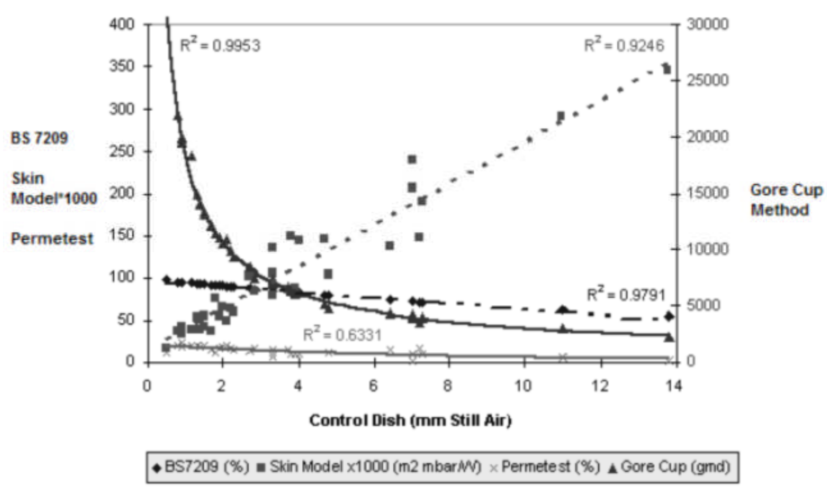


Figure1.3 Comparison between different methods of measuring water vapor permeability

2.14 Methods used to determine the wettability of a textile material

Fabrics wettability is measured with different ways like Tensiometry and Goniometry i.e.

i. Tensiometry – The Processor Tensiometer has been developed to measure the wettability of the fabric by measuring the wetting force by the Wilhelmy method. In this method the wetting force (force applied by the surface, when the liquid comes in contact with it) is measured. The contact angles are calculated indirectly from the wetting force when a solid is brought in contact with the test liquid using the Wilhelmy principle [137].

ii. Goniometry - in this method the wettability of a material is measured by measuring the contact angle between the liquid and the fabric by an image processing method [138]. The developments of Automated Contact Angle Tester (ASTM D 5725-99), HTHP contact angle tester and drop analyzer tester have been based on this principle. In the case of the drop analyzer tester two processes are used, namely the static wetting angle measurement and the dynamic wetting angle measurement [139].

An experimental apparatus was set to measure the wettabillity of filament specimens using a liquid membrane technique [140]. The force exerted by the liquid membrane on the filament specimen, as the ring with a liquid membrane moves up or down the filament specimen is evaluated by this instrument, thus measuring the wetting force. The University of Manchester developed the UMIST wettability tester, which gives the wettability as well as initial wicking rate of the fabric.

The skin dynamic wetness is a very important factor determining the contact comfort feeling of the skin. The clothing vapor resistance has been related with skin wetness and metabolic rate by the following equation [141]

$$W = \frac{Esw}{Emax} + 0.06 \qquad (32)$$

Where E_{sw} is the regulatory sweat evaporation rate, E max is the maximal evaporation rate possible in the ambient climate with the present clothing and skin temperature for a totally wet skin and 0.06 is the minimal skin wetness (or moisture evaporation) due to diffusion through the skin. ISO 7730 is used to determine skin temperature, sweat rates and ambient temperatures for comfort at various metabolic rates. In ISO 7730, the required sweat evaporation at comfort is given as a function of the metabolic rate [142]:

$$Esw = 0.42\ (M\text{-}58)\ ,\ watt/m^2 \qquad (33)$$

Where M is the metabolic rate.

A new technique was developed to measure fabric dynamic wetness [143]. In this it was possible to observe the dynamic moisture change in the fabric by treating it with cobaltous chloride before the experiment and observed the change in the color due to the absorption of moisture during the test.

2.15 Methods used to determine wicking through a textile material

After wetting the fiber, the liquid reaches the capillary, and a pressure is developed which forces the liquid to wick or move along the capillary. This capillary penetration of a liquid may occur from an infinite (unlimited) or a finite (limited) reservoir [84]. The different forms of wicking from an infinite reservoir are transplanar or transverse wicking, in-plane wicking and vertical or longitudinal wicking. A spot test is a form of wicking from a limited reservoir [137]. In the case of a vertical capillary rise, the effect of gravity slows down the flow rate before equilibrium is reached.

There are different standards to determine the wickability (vertical wicking) of fabrics [144]:

1-BS 3424:1996, Method 21 – specifies a very long time period (24 hours) and is intended for coated fabrics with very slow wicking properties.

2-DIN 53924, 1978 – specifies a much shorter time of 5 minutes maximum and is therefore more relevant to the studies of clothing comfort involving the transfer of perspiration. Testing is undertaken at the standard atmospheric condition of 20°C temperature and 65% relative humidity.

Normally the terms and units used for measuring absorption and wicking of fabrics are:

A. For bulk absorption:

1. Bulk material absorption (BMA) – records the total absorption capacity of the fabric.

2. Bulk absorption rate (BAR) – calculates the amount of water absorbed vertically by 1 gram of fabric.

3. Bulk absorption time (BAT) – records the time in seconds it takes for the water to be absorbed vertically into the fabric.

B. For wicking:

1. Amount of water wicked (AWW) – determines the wicking capacity of the fabric away from the absorption zone.

2. Surface-water transport rate (SWTR) – calculates the amount of water wicked by 1 gram of fabric per second.

3. Wicking time (WT) – is the time in seconds for the water to wick across a specified distance (3.25 cm).

2.16 Measurement of combined heat and moisture transfer

Three methods are available for testing heat and moisture comfort of textiles: the micro climate method, the thermal manikin method, and the wear trial method. The micro climate method is used to evaluate the heat and moisture comfort of fabrics, whereas the thermal manikin method is used for clothing and wear trial method for subjective measurement. The evaluating methods of heat and moisture comfort of clothing are more complex than those used for fabrics. To evaluate the heat and moisture comfort of clothing, it is required to consider the human body, the clothing to be worn, the environment, and the other factors [145]. The thermal manikin has been developed to simulate the human body. The manikin acts as a heat transfer sensor that mimics a real three-dimensional body. It senses the difficult-to-model local sweat evaporation, convection and radiation processes that are highly dependent on local microclimate. The manikin is also used to accurately depict the sweat transport of a clothed human and analyze other effects of clothing.

Manikins are usually designed with the following capabilities and characteristics:

• Detailed spatial and rapid temporal control of surface heat output and sweat rate.

• A surface temperature response time approaching that of the human skin.

• A human like geometry and weight with prosthetic joints to simulate human motion

• Breathing with inflow of ambient air and outflow of warm humid air at realistic human respiration rates.

Two types of manikins are normally available: the sweating manikin and the dry manikin. With the dry manikin it is only possible to measure the dry heat flow, both in transient and steady condition. With the sweating manikin it is possible to measure the evaporated heat loss and the dry heat loss in both transient and steady state conditions [146].

The results obtained from thermal manikin testing are useful for [147]:

• Detailed assessment of thermal stress in environments with human occupancy;

• Determination of heat transfer and thermal properties of clothing;

• Prediction of human responses to extreme or complex thermal conditions;

• Validation of results from human experiments regarding thermal stress;

• Simulation of responses in humans exposed to thermal environments.

The thermal resistance of textile materials is measured in terms of S.I. units in degrees Kelvin meters square per watt (Km^2/W), defined as the ratio of the temperature difference between the two faces of the material to the rate of heat transfer per unit area of the material, normal to the faces. The Tog is an European unit of thermal insulation, and is one tenth of the S.I. unit. Another commonly used unit is the clo, which is approximately equal to 1.55 togs, and is defined as the resistance of clothing which provides comfort to a sitting – resting subject in a standard ventilated room at 21 °C [56].

The International Standards Organization (ISO) has produced an integrated series of international standards for the assessment of human responses to thermal environments, which include standards for the assessment of thermal comfort, heat stress and cold stress. ISO 7243 is used for the monitoring and control of hot environments. ISO 7933 is used to analyze the heat exchange between a worker and his or her environment. ISO 9886 is used in the establishment of personal monitoring systems of workers exposed to hot environments. ISO 9886 provides guidance on physiological measurement and interpretation. The ISO system therefore covers almost all exposures to hot environments [148].

CHAPTER III

EXPERIMENTAL WORK

Transport of heat and moisture through clothing material is a very complicated question dependent of various parameters like:

Body temperature

Human activity

Number of clothing layers

Environmental conditions

3.1 Aim of work

We can assume that the transport is a dynamic process, which is possible to be described as heat conduction and moisture transport in porous bodies. Apparels materials used in hot weathered countries must fulfill demands on a good organism protection against high temperatures and allow good air permeability, water vapor permeability on the other side it should also be absorbable for the moisture and also to get rid of the moisture easily.

This research work aims mainly to investigate the comfort properties of classic wear made from classical cotton and functional materials like polypropylene, polyester cool max and Merino wool, and it aims to find the best and optimal wear for the conditions in hot weathered countries.

Also it aims to measure the comfortability of these different materials under different conditions of temperatures and humidity that actually exists in countries with tropical weather all around the year, and monitoring the factors that affects the comfortability of the garments used in this tropical weather.

Although a lot of studies have been done concerning the comfort properties of garments and a lot of mathematical models have been established to predict and to study the comfort properties, but a real study and a real application is needed to actually determine factors which affect the comfort properties in real conditions, this is the main aim for the research, to exercise and examine different materials with different structures and finishes under variation of heat , humidity and combination of heat and humidity which actually exists all around the year in countries with tropical weather and here the climate condition of Egypt is actually been achieved varying from summer to winter time as well as the humidity; to study the comfort properties of garments which could be used to achieve the maximum comfort properties ,and this will allow us to understand the factors which affect the comfort properties in these conditions, leading us to develop garment properties that could be applied to enhance these properties.

The average weather in Egypt due to the Egyptian meteorologist institute varies between 15 °C to 35 °C all around the year during the four seasons, and with humidity from 40% to 80%, and in this work, the actual weather conditions were achieved and the properties under research where investigated.

3.1.1 Design of the experiments

In this work the different comfort properties like the thermal effusivity (e) ($Ws^{1/2}/m^2K$), thermal conductivity (K) (W/mK), thermal resistance (Rct) (m^2Kw^{-1}), thermal diffusivity (m^2/s), air permeability (m/sec), water vapor resistance (Ret) (m^2Pa/W) and water vapor permeability index (I_{mt}) for these garments have been measured under the mentioned different conditions to determine the comfort properties of each type and to see the effect of each of the humidity and the temperature which actually exists in tropical countries on the comfort properties of these fabrics.

3.1.1.1 Thermal effusivity (e) ($Ws^{1/2}/m^2K$)

Thermal effusivity is a heat transfer property present in all materials in all formats – solid, liquid, pastes, powder and gas. Effusivity is the property that dictates the interfacial temperature when two semi-infinite objects at different temperature touch. Effusivity combines thermal conductivity, density and heat capacity into one value

$$e = (k\rho c_p)^{\frac{1}{2}} \qquad (34)$$

Where k is the thermal conductivity, ρ is the density and c_p is the specific heat capacity. The product of ρ and c_p is known as the volumetric heat capacity.

A material's thermal effusivity is a measure of its ability to exchange thermal energy with its surroundings [149].

If two semi-infinite bodies initially at temperatures T1 and T2 are brought in perfect thermal contact, the temperature at the contact surface Tm will be given by their relative effusivities.

$$Tm = T1 + (T2 - T1)\frac{e2}{(e2+e1)} \qquad (35)$$

Thermal effusivity is a surface property [150], and therefore the finishing processes can change it. This parameter allows assessment of the fabric's character in the aspect of its 'coolwarm'' feeling. Fabrics with a low value of thermal effusivity give us a ''warm'' feeling, in this investigation the thermal effusivity was measured by TCI apparatus [151], and the mean of 10 experiments was taken.

3.1.1.2 Thermal conductivity (K) (W/mK)

Thermal conductivity K, is a physical property of a material that characterizes the ability of that substance to transfer heat [150]. The value of thermal conductivity determines the quantity of heat passing per unit of time per unit area at a temperature drop of 1 degree ^{o}C per unit length. In the limit of infinitesimal thickness and difference in temperature, the fundamental law of heat conduction is:

$$Q = K\,A\,{}^{dT}/_{dX} \qquad (36)$$

Where:

Q Is a measure of the heat flow

A Is the cross sectional area

${}^{dT}/_{dX}$ Is the temperature / thickness gradient

K is defined as the thermal conductivity. Materials having a large thermal conductivity value are good conductors of heat; one with a small thermal conductivity value is a poor heat conductor i.e. good insulator. Hence, knowledge of the thermal conductivity value (W/mK) allows for quantitative comparisons to be made between the thermal insulation efficiencies of different materials, in this investigation the thermal conductivity was measured by TCI apparatus [151] and the mean of 10 experiments was taken.

3.1.1.3 Thermal resistance (Rct) (m^2Kw^{-1})

Thermal resistance is a very important parameter from the point of view of thermal insulation [152], and is proportional to the fabric structure. In this investigation the thermal resistance was measured by the Sweat Guarded Hot Plate system and the mean of 10 experiments was taken.

Clothing insulation can be described in terms of its Clo value. The Clo value is a numerical representation of a clothing ensemble's thermal resistance. Thermal resistance is connected with fabric thickness by the relationship:

$$Rct = \frac{h}{K} \quad , m^2KW^{-1} \qquad (37)$$

Where:

h : fabric thickness

K: thermal conductivity

3.1.1.4 Thermal diffusivity (m^2/s)

Thermal diffusion is defined by the relationship:

$$a = \frac{k}{pc} \qquad (38)$$

Where:

p Fabric density,

c Specific heat of fabric,

K Thermal conductivity.

Thermal diffusion is an ability related to the heat flow through the fabric structure. Substances with high thermal diffusivity rapidly adjust their temperature to that of their surroundings because they conduct heat quickly in comparison to their volumetric heat capacity or 'thermal bulk' and they generally do not require much energy from their surroundings to reach thermal equilibrium [153, 154]. In this investigation the thermal diffusivity was measured by TCI apparatus [151], and the mean of 10 experiments was taken.

3.1.1.5 Air permeability (m/sec)

Air permeability is defined as the volume of air in milliliters, which is passed in one second through l00 mm^2 of the fabric at a pressure difference of 10 mm head of water. In the British Standard test, the airflow through a given area of fabric is measured at a constant pressure drop across the fabric of 10 mm head of water. The specimen is clamped over the air inlet of the apparatus with the use of rubber gaskets and air is sucked through it by means of a pump. The air valve is adjusted to give a pressure drop across the fabric of 10 mm head of water and the airflow is then measured using a flow meter. [155, 156] In this investigation the air permeability was measured by SDL M0215 according to the relevant standards [157] and the mean of 10 experiments was taken after leaving each of the samples in every climatic condition for 48 hours.

3.1.1.6 Water vapor resistance (Ret) (m^2Pa/W)

Water vapor resistance (Ret) is water-vapor pressure difference between the two sides of specimen divided by the resultant evaporative heat flux per unit area in the direction of the gradient. In this work the Water vapor resistance was measured by Sweating Guarded Hot Plate system [152], and the mean of 10 experiments was taken. Water-Vapor Resistance [m^2 pa/w] is calculated as:

$$Ret = \Delta P \frac{A}{H-\Delta He} \qquad (39)$$

Where:

Δ p difference of partial pressure between two sides of specimen

A area of the measuring unit (plate), m^2;

H heating power supplied to the measuring unit (plate), W;

Δ He correction term, W.

3.1.1.7 Water vapor permeability index (I_{mt})

I_{mt} is the ratio of thermal resistance and the water vapor resistance in accordance with this equation:

$$i_{mt} = S\frac{R_{ct}}{R_{et}} \qquad (40)$$

Where S equals 60 Pa/K, I_{mt} is dimensionless and has values between 0 and 1. A value of 0 implies that the tested fabric is water vapor impermeable, that is, it has infinite water vapor resistance, and a material that has a value of 1 has both the water vapor resistance and the thermal resistance of an air layer with the same thickness. The water vapor permeability index was measured according to the relevant standards [158].

3.2 Materials used

In this work eight different types of garments with plain structure and very limited variation of weight and thickness were used varying from classical cotton with core yarn with different spandex ratios and new functional materials like polypropylene, polyester cool max, polyester thermolite, viscose fiber made from bamboo plants and Merino wool. Cotton is being commonly used in Egypt , but the new functional material are not in common use , it is well known that the cotton is very good in absorbing moisture but in the same time it is not that easy to get rid of it , so after a short while of wearing it will be wet and in this case it will cause uncomfortable and unpleasant feeling for the wearer , so the new materials are being investigated to notice the behavior of these material in such conditions, Table 2; shows the specification of the used materials.

Table 2 Specification of materials under investigation

No	Sample	Yarn count, Tex	Loop length, cm	Course count per cm	Wale count per cm	Thickness, m	Weight, g/m^2
1	96%Cotton 4%Lycra	19.6	0.253	23	11.5	0.00109	152.9
2	94%Cotton 6%Lycra	19. 6	0.29	24	11.6	0.00113	155.78
3	92%Cotton 8%Lycra	19.6	0.246	24	12.1	0.00115	161.38
4	Polypropylene	19.82	0.274	22	12.3	0.00102	148.72
5	Merino wool	19.78	0.38	22	12.2	0.00097	146.22
6	95%Viscose fiber made from bamboo plants, 5%Lycra	19.74	0.34	20	11.3	0.00093	143.8
7	62%PE Coolmax 32%PE micro 6%Lycra	19.81	0.275	22	11.6	0.00094	144.72
8	94%PE 6%Lycra	19.75	0.268	23	11.4	0.00103	150.48

3.3 Climatic conditions used in investigating the thermophysiological properties:

Nine different test conditions were held for each of the samples varying between 15 °C then 25 °C then 35 °C with combination with the humidity from 40% then 60% and then 80 % to actually represent all the weather combinations conditions in the tropical condition under investigation. Table 3 shows the design of experiments used to achieve the different climatic conditions under investigation.

Table 3 Climatic experimental design

Humidity % \ Temperature °C	15	25	35
40	√	√	√
60	√	√	√
80	√	√	√

3.4. Image analysis for material under investigation:

In this research, image analysis was used in two phases, the first one is to calculate the pore percentage of each material, where photos were captured after leaving each of the samples in each of the climatic conditions for 48 hours then the pictures were taken then processed within the Matlab system to get the pore ratio. The measurement system was constructed on the basis of a computer and a camera. The image was processed by transferring it to a digital image which is composed of pixels which can be thought of as small dots on the screen.

A digital image is a way of how to color each pixel, the image was transferred into a grey scale on and then to a binary image. The output image replaces all pixels in the input image with luminance greater than level with the value 1 (white) and replaces all other pixels with the value 0 (black). Where level in the range (0,1) were specified. This range is relative to the signal levels possible for the image's class. Therefore, a level value of 0.5 is midway between black and white, regardless of class. So the areas which contain yarns was presented as black dots, while areas that presented pore spaces was presented as white dots, and grey values are areas within between. Following that, area of pores was calculated as a percentage comparing to areas that contain yarns.

The second phase was to calculate the yarn diameter, which was used in the theoretical model; it was measured as well within the same procedure using Image analysis system [159]. Twenty-five measurements were taken on each of the samples in every condition. The system consists of microscope, monitor and image processing system. The image analysis system was calibrated using special graph grade. The image of the fabric was displayed on a monitor. The fabric was placed under the microscope and it was adjusted to display the portion of the yarn on which the diameter measurements were to be carried out. The diameter of that portion of the yarn was read directly from the calibrated scale on the screen. This was done 25 times on several loops from different locations on each fabric to assure that we get the average reading which refers to nearly the whole fabric.

3.5. Wearer trials and thermal photos:

In this stage the 25 °C with 40% humidity was taken as the neutral condition related to the other conditions and wearer trial have been accomplished, a trial was done by a healthy human being and photos with thermal camera were taken after forty minutes of continuous normal cycling, this was to see which of the fabric will maintain the best thermoregulation properties compared with the other samples.

3.6. Data analysis

The multiple linear regression is being used to analyze the data obtained from the experiments, the general formula was used, where $j = \sum a_i f_i \ (x_1 \ldots\ldots x_p)$, different formulas were used for analysis i.e. :

$$Yi = \beta_0 + \beta_1 X_{i,1} + \beta_2 X_{i,2} + \ldots\ldots + \beta_{p-1} X_{i,p-1} + \varepsilon_i \ \text{for } i = 1,2,\ldots,n \qquad (41)$$

Where:

Y_i is the value of the response variable for the $_i$th case

β_0 is the intercept

$\beta_{1,}$ $\beta_{2,}$ ...., β_{p-1} are the regression coefficients for the explanatory variables

$X_{i,k}$ is the value of the K_{th} explanatory variable for the $_i$th case

Parameters as usual include all of the β's as well as σ^2. These need to be estimated from the data. And it can be analyzed to obtain the effect of each parameter on the physiological property of the measured garments under study:

$$\mathbf{X} = \begin{bmatrix} 1 & X_{1,1} & X_{1,2} & \cdots & X_{1,p-1} \\ 1 & X_{2,1} & X_{2,2} & \cdots & X_{2,p-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & X_{n,1} & X_{n,2} & \cdots & X_{n,p-1} \end{bmatrix} \quad (42)$$

Coefficient matrix β:

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_{p-1} \end{bmatrix} \quad (43)$$

In the data analysis and the following graph figures it was referred to the conditions as -1, 0, and 1 for each of the temperature 15 °C, 25 °C and 35 °C, for the humidity 40%, 60%, 80% respectively, and X for temperature and Y for humidity which refers to the different climatic conditions. And the blue grid is for the temperature, the green for the humidity and the red for the property under investigation.

CHAPTER IV

RESULTS AND DISCISSION

In this investigation the mentioned comfort properties like the thermal effusivity, thermal conductivity, thermal resistance, thermal diffusivity, air permeability, pores ratio, water vapor resistance and the water vapor permeability index are held in due with the mentioned climatic factorial design at the specified temperatures and the specified humidity with combination of them to achieve the real weather conditions in hot weathered countries and the following results were obtained.

4.1 96%Cotton 4%Lycra

The thermal comfort properties of the produced 96%Cotton 4%Lycra garments were investigated in the different climatic conditions that exist in hot countries. It is clear from Table 4.1 how the thermophysiological properties for the material under study acts in the different simulated hot weather conditions.

Table 4.1 96% Cotton 4% Lycra Thermophysiological properties in different weather conditions

Climatic Condition	Effusivity (Ws½/m²K)	k (W/mK)	Rct (m^2Kw^{-1})	Diffusivity (m^2/s)	Air permeability m/sec	Pores %	Ret m²Pa/W	I_{mt}
15°C+40%ϕ	125.08	0.061	0.0157	2.41	0.0186	0.15	5.4	0.17
15°C+60%ϕ	133.15	0.062	0.0155	2.18	0.0183	0.14	6.4	0.15
15°C+80%ϕ	139.98	0.066	0.0145	2.25	0.0173	0.07	9.6	0.09
25°C+40%ϕ	129.86	0.063	0.0153	2.36	0.0181	0.14	5.6	0.16
25°C+60%ϕ	148.57	0.064	0.0150	1.86	0.0176	0.12	6.5	0.14
25°C+80%ϕ	160.08	0.072	0.0135	2.00	0.0164	0.04	9.8	0.08
35°C+40%ϕ	135.58	0.064	0.0150	2.25	0.0172	0.14	6.1	0.15
35°C+60%ϕ	151.42	0.066	0.0145	1.92	0.0153	0.11	6.7	0.13
35°C+80%ϕ	168.12	0.075	0.0128	1.99	0.0112	0.02	10.1	0.08

4.1.1 Effusivity (Ws½/m²K)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.1, for analysis of the results, the following equation was obtained:

$$\text{Effusivity} = 146.17 + 9.48\,X + 12.94\,Y - 3.95\,X^2 + 4.4\,XY \qquad (44)$$

From the R-squared = 98.6217 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0006.

From the above equation the factors affecting Effusivity (Ws½/m²K) behavior in 96% Cotton 4%Lycra fabrics can be concluded. It is clear that humidity has the highest positive effect and the temperature has the second highest effect as well as the interaction between the humidity and the temperature. (Figure 4.1) and (figure 4.2) show the Effusivity (Ws½/m²K) behavior in that fabric.

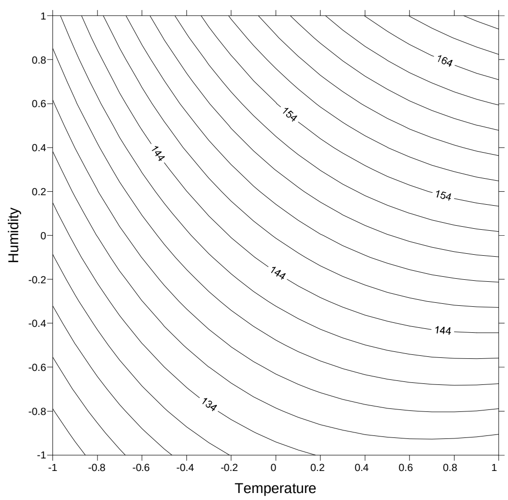


Figure 4.1 Contour lines showing the Effusivity (Ws½/m²K) behavior with in the different climatic conditions.

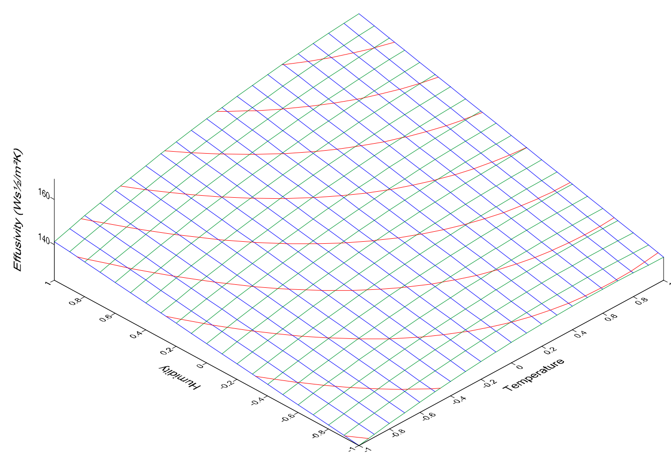


Figure 4.2 The effect of Temperature and Humidity on the Effusivity (Ws½/m²K).

Due to the high temperature and the high humidity, the Effusivity (Ws½/m²K); which assess the fabric's character in the aspect of it's ‘coolwarm'' feeling , is getting higher , and we can tell that the Fabrics with a low value of thermal Effusivity (Ws½/m²K) gives us a ‘‘warm'' feeling and vise versa.

4.1.2 Thermal conductivity (K) (W/mK)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.1, for analysis of the results, the following equation was obtained:

$$k = 0.064 + 0.0026\,X + 0.004Y + 0.002\,Y^2 + 0.001\,XY \qquad (45)$$

From the R-squared = 99.1446 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0002.

From the above equation the factors affecting K (W/mK) behavior in 96% Cotton 4%Lycra fabrics can be concluded. It is clear that humidity has a positive effect and the temperature has also a positive effect as well as the interaction between the humidity and the temperature. (Figure 4.3) and (Figure 4.4) show the K (W/mK) behavior in that fabric under study.

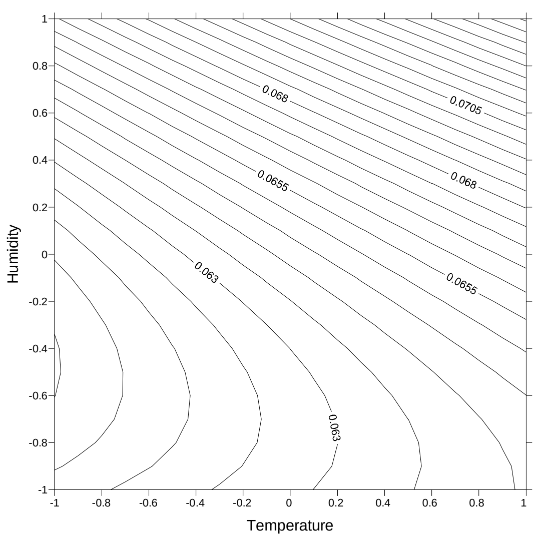


Figure 4.3 Contour lines showing the Thermal conductivity (W/mK) behavior with in the different climatic conditions.

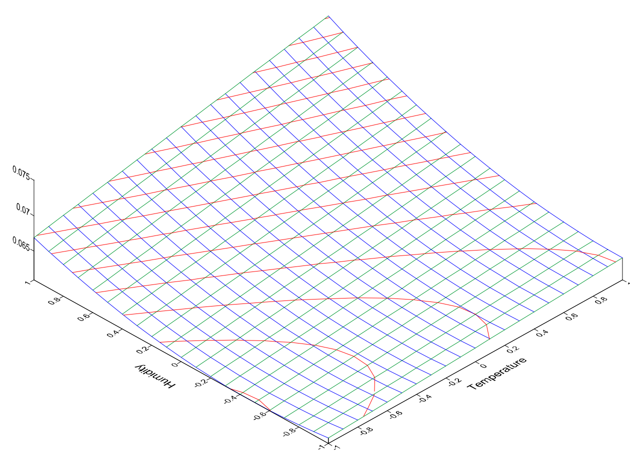


Figure 4.4 The effect of Temperature and Humidity on the Thermal conductivity (W/mK)

Fabrics having a large thermal conductivity value are good conductors of heat; one with a small thermal conductivity value is a poor heat conductor and it can be a good insulator. Hence, we are stimulating the hot condition we need fabrics that easily release the heat from the body, knowledge of the thermal conductivity value allows for quantitative comparisons to be made between the thermal insulation efficiencies of different fabrics.

4.1.3 Thermal resistance (Rct) (m^2Kw^{-1})

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.1, the following equation was obtained:

$$Rct = 0.015 - 0.00056\ X - 0.0008\ Y - 0.0005\ Y^2 - 0.0002\ XY \quad (46)$$

From the R-squared = 99.3085 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0001.

From the above equation the factors affecting Rct (m^2Kw^{-1}) behavior in 96% Cotton 4%Lycra fabrics can be concluded. It is clear that both humidity and the temperature have a negative effect with their increase, as well as the interaction between both of them. (Figure 4.5) and (Figure 4.6) show the Thermal resistance (m^2Kw^{-1}) behavior in the fabric under study.

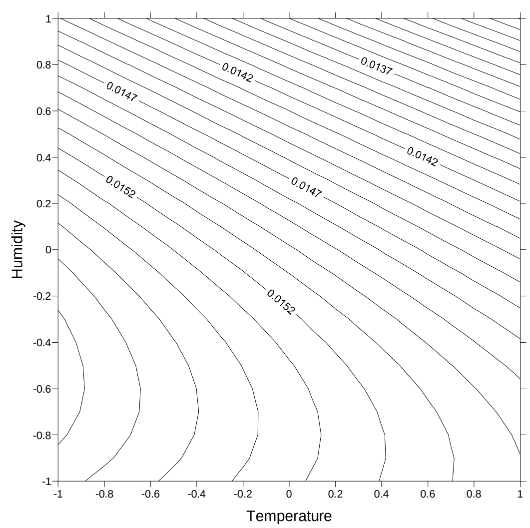


Figure 4.5 Contour lines showing the Rct (m^2Kw^{-1}) behavior with in the different climatic conditions

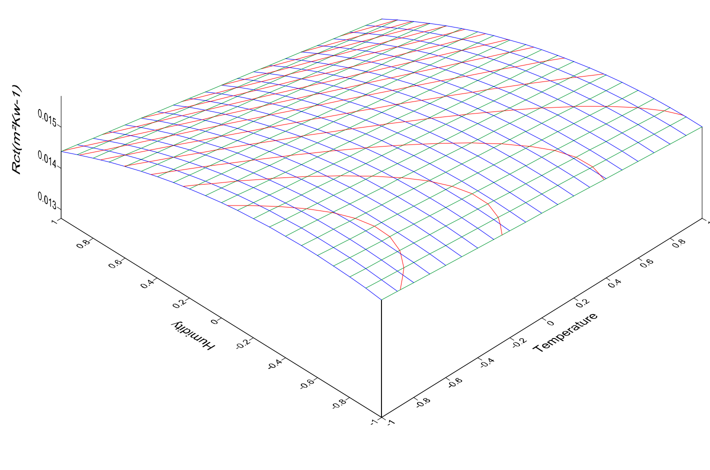


Figure 4.6 The effect of Temperature and Humidity on the Rct (m^2Kw^{-1})

Due to the high temperature and the high humidity, Rct (m^2Kw^{-1}) which is a very important parameter from the point of view of thermal insulation and which is proportional to the fabric structure is getting lower mainly because of the water content increasing, and in such hot condition with higher temperature and higher humidity, it is desirable for the human being to wear something that is easy to release body temperature, in a way to feel cooler.

4.1.4 Diffusivity (m^2/s)

The multiple linear regression is being used to analyze the data for the Diffusivity obtained from Table 4.1, for analysis of the results, the following equation was obtained:

$$\text{Diffusivity} = 1.98 - 0.112\,X - 0.12\,Y + 0.22\,Y^2 \qquad (47)$$

It is concluded from R-squared that the equation represents 88.43 percent of the results model and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0089.

From the above equation the factors affecting Diffusivity (m^2/s) behavior in 96% Cotton 4%Lycra fabrics can be concluded. It is clear that humidity and temperature have a negative effect on it. (Figure 4.7) and (Figure 4.8) show the Diffusivity (m^2/s) behavior in that fabric.

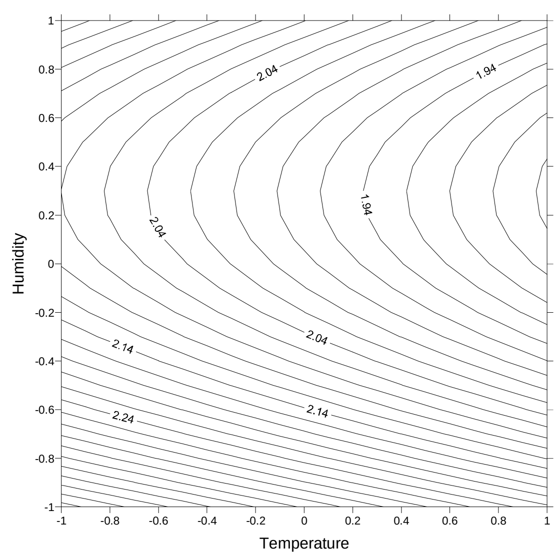


Figure 4.7 Contour lines showing the Diffusivity (m^2/s) behavior with in the different climatic conditions.

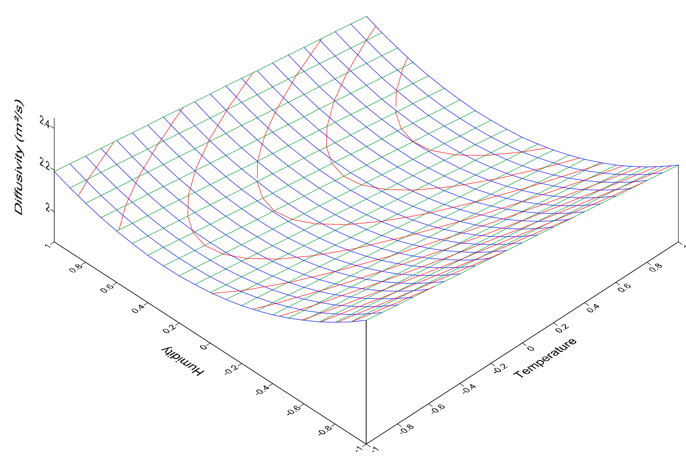


Figure 4.8 The effect of Temperature and Humidity on the Diffusivity (m^2/s)

Due to the high temperature and the high humidity, Diffusivity (m²/s) which is the ability related to the heat flow through the fabric structure is getting lower. fabrics with high thermal diffusivity rapidly adjust their temperature to that of their surroundings because they conduct heat quickly in comparison to their volumetric heat capacity ,and it is noticed that with the increase in the moisture content that ability in the fabric is getting lower, but on the other side it is desired in such tropical condition to wear a material that can release heat from the body to make the wearer more cooler, so such information could lead in helping in the design of such fabrics that could adapt in the hot weather countries.

4.1.5 Air permeability (m/sec)

The multiple linear regression is being and the following equation was obtained:

$$\text{Air permeability} = 0.016 - 0.0017\, X - 0.0015\, Y - 0.00117\, XY \qquad (48)$$

From the R-squared = 89.3822 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0072.

From above, it is clear that humidity and temperature have negative effect as well as the interaction between the humidity and the temperature. (Figure 4.9) and (Figure 4.10) show the Air permeability (m/sec) behavior in that fabric.

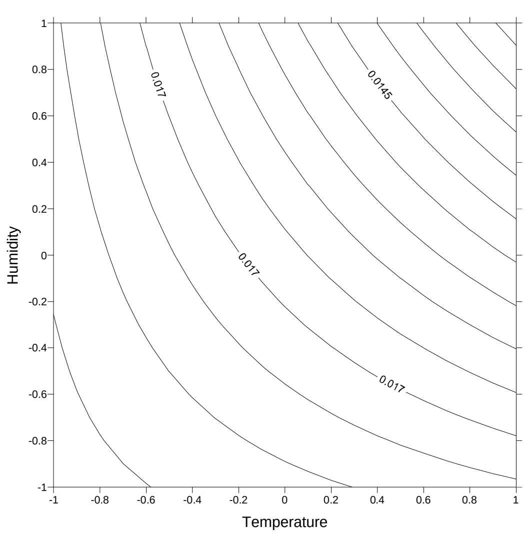


Figure 4.9 Contour lines showing the Air permeability (m/sec) behavior with in the different climatic conditions

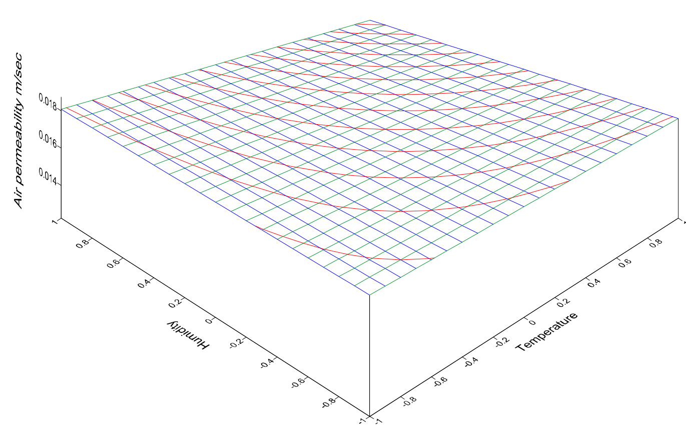


Figure 4.10 The effect of Temperature and Humidity on the Air permeability (m/sec)

Air permeability (m/sec); which is a dominant factor in water vapor transfer is dramatically decreasing with the increase of humidity, it could be referred to the cotton structure, which when absorbs water, causes the fibers to swell leading to minimizing the pores with in the fabric causing more air resistance and less air permeability.

4.1.6 Pores ratio

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.1, for analysis of the results, the following equation was obtained:

$$\text{Pores ratio} = 0.13 - 0.012\,X - 0.048\,Y - 0.043\,Y^2 - 0.0098\,XY \qquad (49)$$

From the R-squared = 99.4931 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0001.

From the above equation the factors affecting Pores ratio behavior in 96% Cotton 4%Lycra fabrics can be concluded. It is clear that humidity has the highest negative effect and the temperature has the second highest negative effect as well as the interaction between the humidity and the temperature. (Figure 4.11) and (Figure 4.12) show the Pores ratio behavior in that fabric.

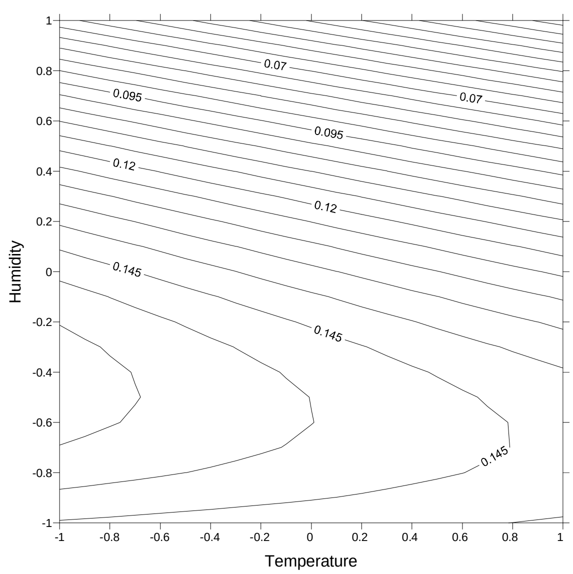


Figure 4.11 Contour lines showing the Pores ratio behavior with in the different climatic conditions.

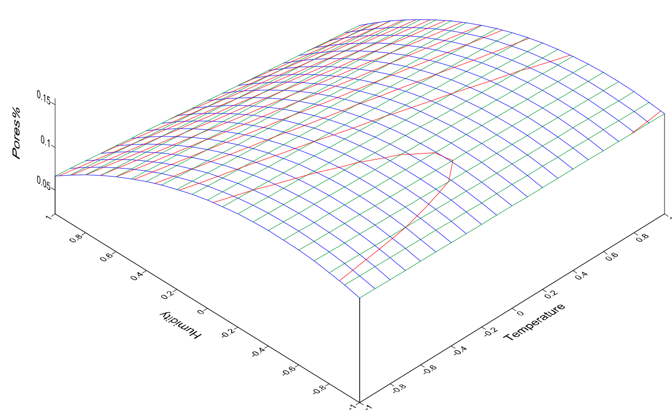


Figure 4.12 The effect of Temperature and Humidity on the Pores ratio

Due to the high temperature and the high humidity, the Pores ratio; which is a dominant factor in air permeability and water vapor transfer is dramatically decreasing with the increase of humidity, it could be referred also to the cotton structure, which when absorbs water, causes the fibers to swell leading to minimizing the pores with in the fabric causing more air resistance and less air permeability.

4.1.7 Water vapor resistance (Ret) (m^2Pa/W)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.1, and the following equation was obtained:

$$Ret = 6.4 + 0.25\ X + 2.06\ Y + 0.08\ X^2 + 1.23\ Y^2 - 0.05\ XY \qquad (50)$$

From the R-squared = 99.8816 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0001.

From the above equation the factors affecting Ret (m^2Pa/W) behavior in 96% Cotton 4%Lycra fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it causes more resistance to the water vapor. (Figure 4.13) and (Figure 4.14) show the Water vapor resistance (m^2Pa/W) behavior in that fabric.

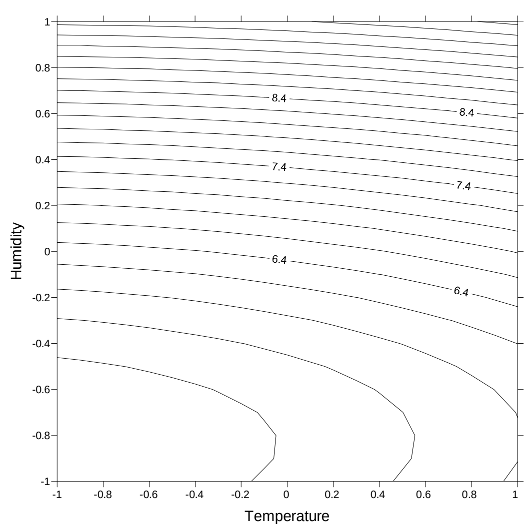


Figure 4.13 Contour lines showing the Ret (m^2Pa/W) behavior with in the different climatic conditions.

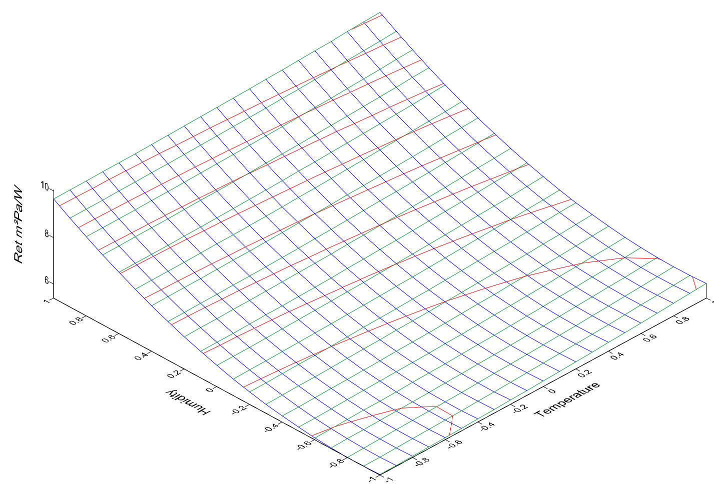


Figure 4.14 The effect of Temperature and Humidity on the Ret (m^2Pa/W)

With the increase of temperature and humidity, the cotton absorbs that humidity causing the fibers to swell affecting the Pores ratio with in the fabric and minimizing it; and the water vapor normally transfers from regions with high water vapor pressure to others with low water vapor pressure going through the pores in the fabric, so the transfer is difficult because of the reduced pores areas and at the same time because of the higher humidity existence, leading to higher water vapor resistance and less wear comfort in that tropical condition.

4.1.8 Water vapor permeability index (I_{mt})

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.1, and the following equation was obtained:

$$I_{mt} = 0.13 - 0.01\,X - 0.03\,Y - 0.015\,Y^2 + 0.003\,XY \qquad (51)$$

From the R-squared = 99.8394 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0000.

From the above equation the factors affecting Water vapor permeability index behavior in 96% Cotton 4%Lycra fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it leads to significant negative change in the water vapor permeability index. (Figure 4.15) and (Figure 4.16) show the water vapor permeability index behavior.

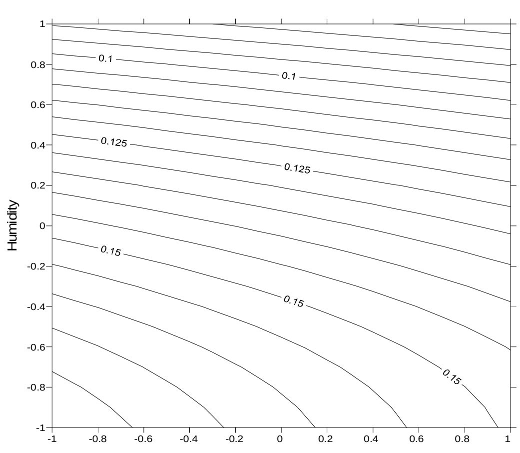


Figure 4.15 Contour lines showing the I_{mt} behavior

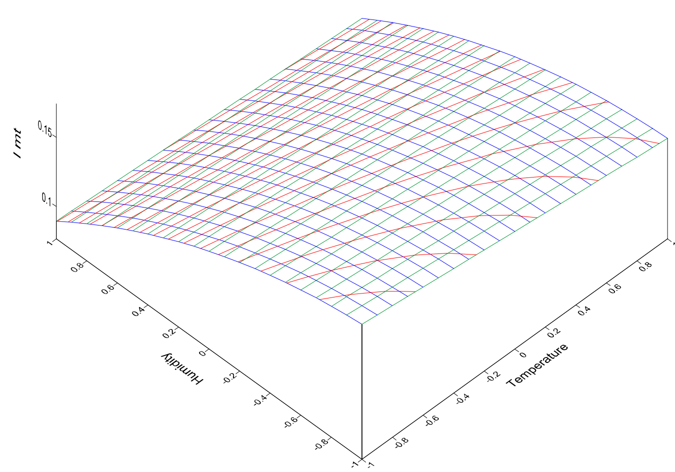


Figure 4.16 The effect of Temperature and Humidity on the I_{mt}

Water vapor permeability index has values between 0 and 1. A value of 0 implies that the tested fabric is water vapor impermeable, that is, it has infinite water vapor resistance, and a material that has a value of 1 has both the water vapor resistance and the thermal resistance of an air layer with the same thickness and it determines the total fabric breathability, which is an important factor with in such climatic condition.

4.2 94%Cotton 6%Lycra

The thermal comfort properties of the produced 94%Cotton 6%Lycra garments were investigated in the different climatic conditions that exist in hot countries. It is clear from Table 4.2 how the thermophysiological properties for the material under study acts in the different simulated hot weather conditions.

Table 4.2 94% Cotton 6% Lycra Thermophysiological properties in different weather conditions

Climaic Condition	Effusivity (Ws½/m²K)	k (W/mK)	Rct (m^2Kw^{-1})	Diffusivity (m^2/s)	Air permeability m/sec	Pores %	Ret m^2Pa/W	I_{mt}
15°C+40%φ	124.56	0.061	0.0156	2.44	0.0153	0.14	5.7	0.16
15°C+60%φ	127.74	0.062	0.0153	2.39	0.0149	0.13	7.5	0.12
15°C+80%φ	147.47	0.067	0.0143	2.05	0.0141	0.05	10.5	0.08
25°C+40%φ	138.93	0.063	0.0151	2.07	0.0147	0.13	5.9	0.15
25°C+60%φ	144.12	0.067	0.0144	2.14	0.0141	0.13	7.6	0.11
25°C+80%φ	162.02	0.073	0.0131	2.02	0.0132	0.04	11.1	0.07
35°C+40%φ	141.54	0.065	0.0148	2.08	0.0137	0.13	6.7	0.13
35°C+60%φ	142.34	0.067	0.0142	2.22	0.0116	0.09	7.8	0.11
35°C+80%φ	165.42	0.075	0.0127	2.07	0.0098	0.01	11.5	0.07

4.2.1 Effusivity (Ws½/m²K)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.2, for analysis of the results, the following equation was obtained:

$$\text{Effusivity} = 142.6 + 8.2\,X + 11.6\,Y - 6.8\,X^2 + 8.5\,Y^2 \qquad (52)$$

From the R-squared = 99.4585 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0001.

From the above equation the factors affecting Effusivity (Ws½/m²K) behavior in 94% Cotton 6%Lycra fabrics can be concluded. It is clear that humidity has the highest positive effect and the temperature has the second highest effect. (Figure 4.17) and (figure 4.18) show the Effusivity (Ws½/m²K) behavior in that fabric.

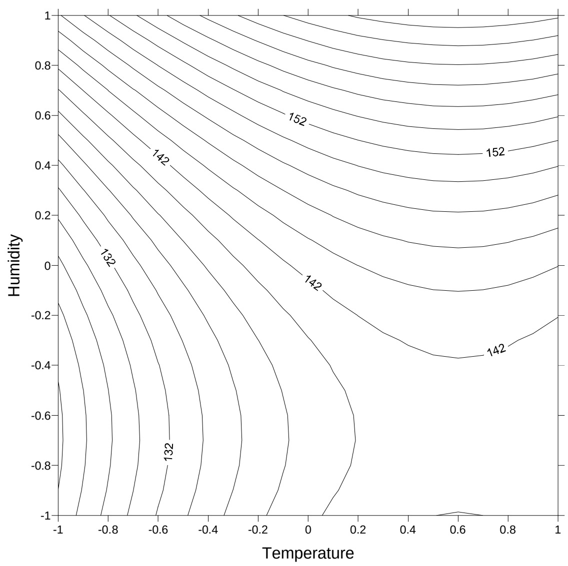


Figure 4.17 Contour lines showing the Effusivity (Ws½/m²K) behavior with in the different climatic conditions.

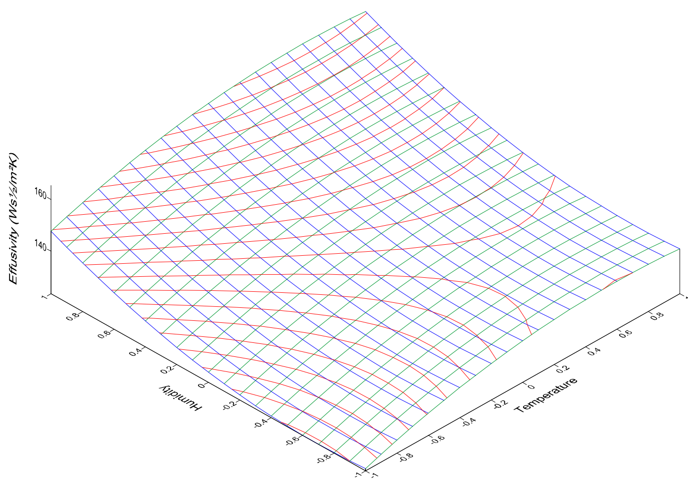


Figure 4.18 The effect of Temperature and Humidity on the Effusivity (Ws½/m²K).

Due to the high temperature and the high humidity, the Effusivity (Ws½/m²K); which assess the fabric's character in the aspect of it's surface feeling, is getting higher, and we can tell that the Fabrics with a low value of thermal Effusivity (Ws½/m²K) gives us a ''warm'' feeling and vise versa.

4.2.2 Thermal conductivity (K) (W/mK)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.2, for analysis of the results, the following equation was obtained:

$$k = 0.06 + 0.002\ X + 0.004\ Y - 0.001\ X^2 + 0.001\ Y^2 + 0.0013\ XY \qquad (53)$$

From the R-squared = 99.015percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0033

From the above equation the factors affecting K (W/mK) behavior in 94% Cotton 6%Lycra fabrics can be concluded. It is clear that humidity has a positive effect and the temperature has also a positive effect as well as the interaction between the humidity and the temperature. (Figure 4.19) and (Figure 4.20) show the K (W/mK) behavior in that fabric under study.

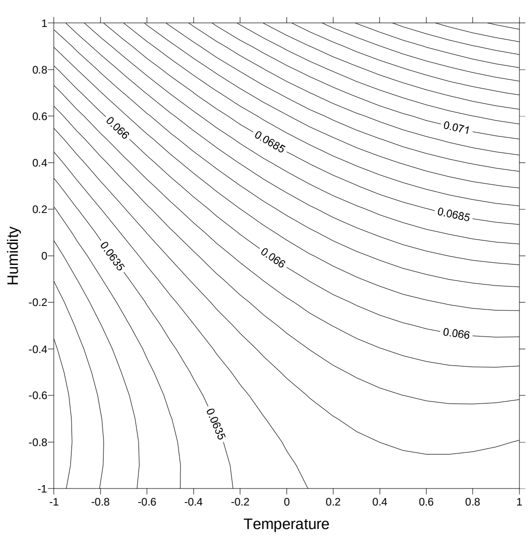


Figure 4.19 Contour lines showing the Thermal conductivity (W/mK) behavior with in the different climatic conditions.

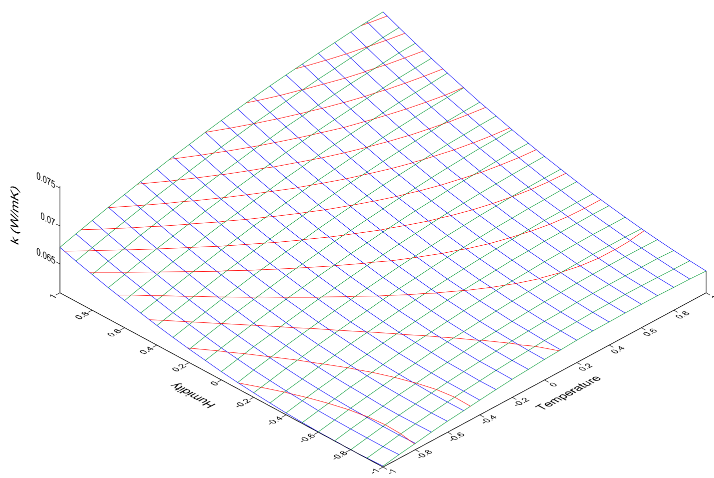


Figure 4.20 The effect of Temperature and Humidity on the Thermal conductivity (W/mK)

Fabrics having a large thermal conductivity value are good conductors of heat; one with a small thermal conductivity value is a poor heat conductor and it can be a good insulator. Hence, we are stimulating the hot condition we need fabrics that easily release the heat from the body, knowledge of the thermal conductivity value allows for quantitative comparisons to be made between the thermal insulation efficiencies of different fabrics and the effect of increasing the Lycra ratio does not have that obvious effect on the thermal conductivity of the materials.

4.2.3 Thermal resistance (Rct) (m^2Kw^{-1})

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.2, the following equation was obtained:

$$Rct = 0.014 - 0.0005\,X - 0.0008\,Y + 0.0002\,X^2 - 0.0003\,Y^2 - 0.00021\,XY \qquad (54)$$

From the R-squared = 99.126 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0028.

From the above equation the factors affecting Rct (m^2Kw^{-1}) behavior in 94% Cotton 6%Lycra fabrics can be concluded. It is clear that both humidity and the temperature have a negative effect with their increase, as well as the interaction between both of them. (Figure 4.21) and (Figure 4.22) show the Thermal resistance (m^2Kw^{-1}) behavior in the fabric under study.

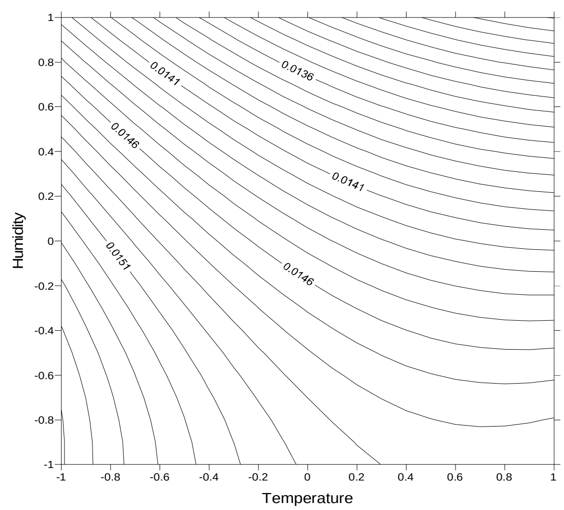


Figure 4.21 Contour lines showing the Rct (m^2Kw^{-1}) behavior with in the different climatic conditions.

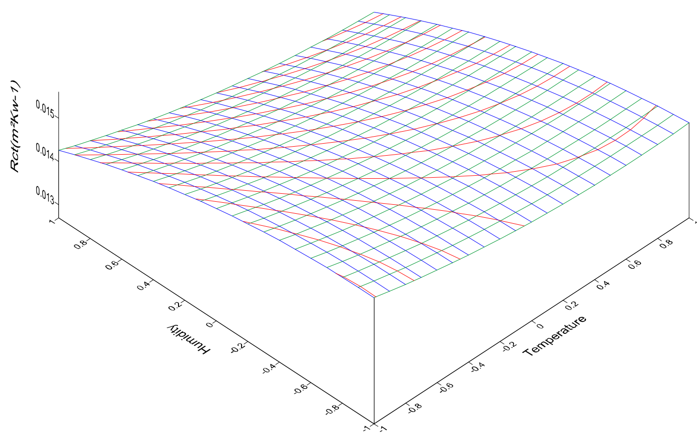


Figure 4.22 The effect of Temperature and Humidity on the Rct (m²Kw-1)

Due to the high temperature and the high humidity, Rct (m^2Kw^{-1}) which is a very important parameter from the point of view of thermal insulation is getting lower mainly because of the water content increasing, and in such hot condition with higher temperature and higher humidity, it is desirable for the human being to wear something that is easy to release body temperature, in a way to feel cooler and here we can figure out the effect of the Lycra ratio increase on the property, because of the variation of the construction between the cotton and the Lycra , where the latest is actually a rigid one without amorphous regions with in between spaces .

4.2.4 Diffusivity (m^2/s)

The multiple linear regression is being used to analyze the data for the Diffusivity obtained from Table 4.2, for analysis of the results, the following equation was obtained:

$$\text{Diffusivity} = 2.15 - 0.08\,X - 0.07Y + 0.13\,X^2 - 0.12\,Y^2 + 0.09\,XY \qquad (55)$$

It is concluded from R-squared that the equation represents 95.6168 percent of the results model and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0299.

From the above equation the factors affecting Diffusivity (m^2/s) behavior in 94% Cotton 6%Lycra fabrics can be concluded. It is clear that humidity and temperature have a negative effect on it on the other side the interaction of them has a positive effect. (Figure 4.23) and (Figure 4.24) show the Diffusivity (m^2/s) behavior in that fabric.

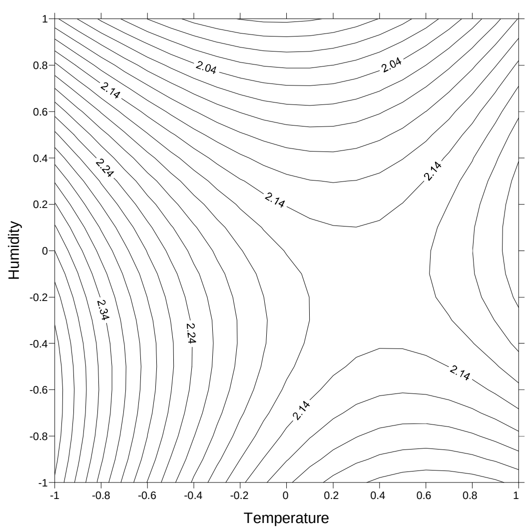


Figure 4.23 Contour lines showing the Diffusivity (m^2/s) behavior with in the different climatic conditions.

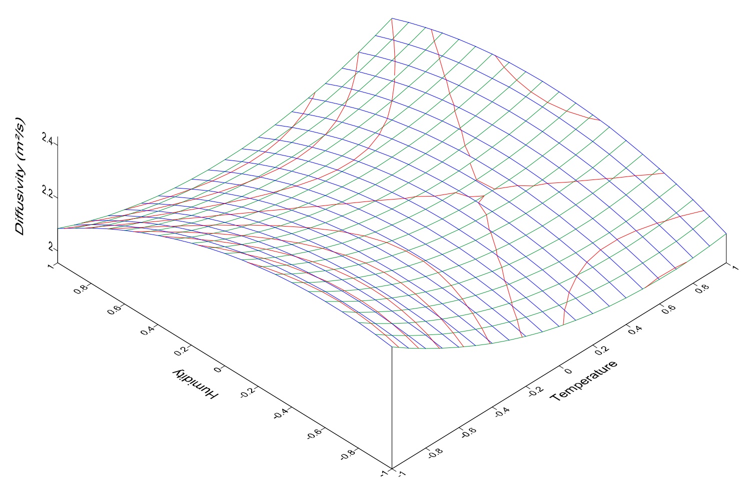


Figure 4.24 The effect of Temperature and Humidity on the Diffusivity (m^2/s)

Due to the high temperature and the high humidity, Diffusivity (m^2/s) which is the ability related to the heat flow through the fabric structure is getting lower, and it is noticed that with the increase in the moisture content that ability in the fabric is getting lower, but on the other side it is desired in such tropical condition to wear a material that can release heat from the body to make the wearer more cooler, so such information could lead in helping in the design of such fabrics that could adapt in the hot weather countries and here we can notice the effect of the Lycra ratio increase on the Thermal Diffusivity (m^2/s).

4.2.5 Air permeability (m/sec)

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.2, for analysis of the results, the following equation was obtained:

$$\text{Air permeability} = 0.014 - 0.0015\,X - 0.0011\,Y - 0.0007\,X^2 - 0.0006\,XY \qquad (56)$$

From the R-squared = 98.2677 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0009.

From the above equation the factors affecting Air permeability (m/sec) behavior in 94% Cotton 6%Lycra fabrics can be concluded. It is clear that humidity and temperature have negative effect as well as the interaction between the humidity and the temperature. (Figure 4.25) and (Figure 4.26) show the Air permeability (m/sec) behavior in that fabric.

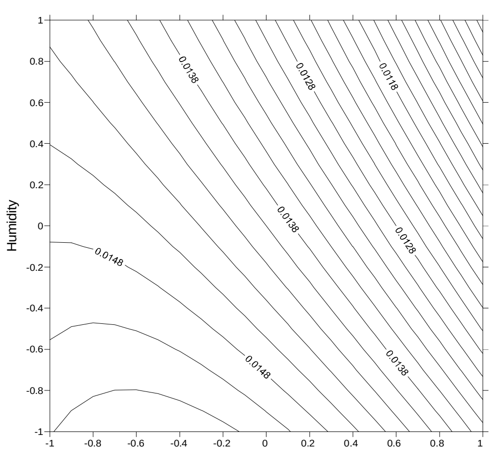


Figure 4.25 Contour lines showing the Air permeability (m/sec) behavior with in the different climatic conditions.

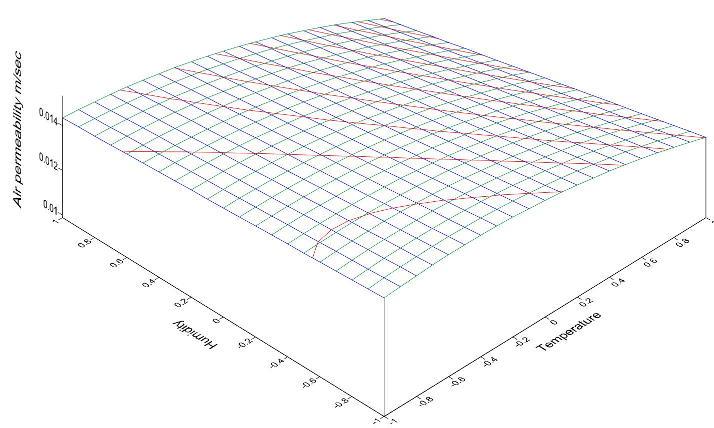


Figure 4.26 The effect of Temperature and Humidity on the Air permeability (m/sec)

Due to the high temperature and the high humidity, the Air permeability (m/sec); which is a dominant factor in water vapor transfer is dramatically decreasing with the increase of humidity, it could be referred to the cotton structure, which when absorbs water, causes the fibers to swell leading to minimizing the pores with in the fabric causing more air resistance and less air permeability, adding to this the increase of the Lycra ratio , which also increase the impermeable areas in the yarn , causing less air permeability.

4.2.6 Pores ratio

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.2, for analysis of the results, the following equation was obtained:

$$\text{Pores ratio} = 0.127 - 0.01\,X - 0.05\,Y - 0.04\,Y^2 - 0.01XY \qquad (57)$$

From the R-squared = 99.5649 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0001.

From the above equation the factors affecting Pores ratio behavior in 94% Cotton 6%Lycra fabrics can be concluded. It is clear that humidity has the highest negative effect and the temperature has the second highest negative effect as well as the interaction between the humidity and the temperature. (Figure 4.27) and (Figure 4.28) show the Pores ratio behavior in that fabric.

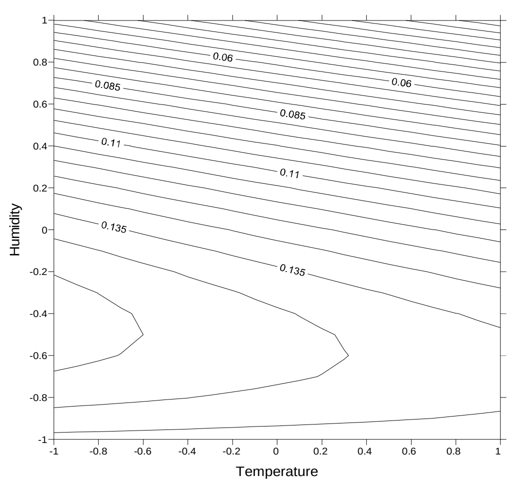


Figure 4.27 Contour lines showing the Pores ratio behavior with in the different climatic conditions

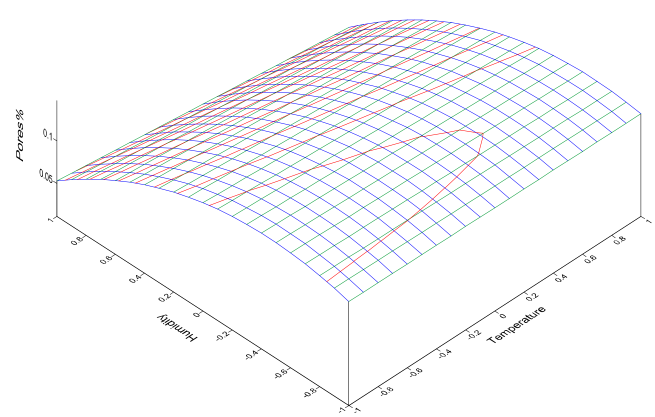


Figure 4.28 The effect of Temperature and Humidity on the Pores ratio

Due to the high temperature and the high humidity, the Pores ratio; which is a dominant factor in air permeability and water vapor transfer is dramatically decreasing with the increase of humidity, it is referred also to the cotton structure, which when absorbs water, causes the fibers to swell, and also for the Lycra existence by higher ratio, leading to minimizing the pores with in the fabric causing more air resistance and less air permeability.

4.2.7 Water vapor resistance (Ret) (m^2Pa/W)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.2, and the following equation was obtained:

$$Ret = 7.63 + 0.38\,X + 2.46\,Y + 0.93\,Y^2 \qquad (58)$$

From the R-squared = 99.4114 percent, it is obvious that the equation highly represents the experimental results, and there is a highly statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0000.

From the above equation the factors affecting Ret (m^2Pa/W) behavior in 94% Cotton 6%Lycra fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it causes more resistance to the water vapor transfer. (Figure 4.29) and (Figure 4.30) show the Water vapor resistance (m^2Pa/W) behavior in the fabric under study.

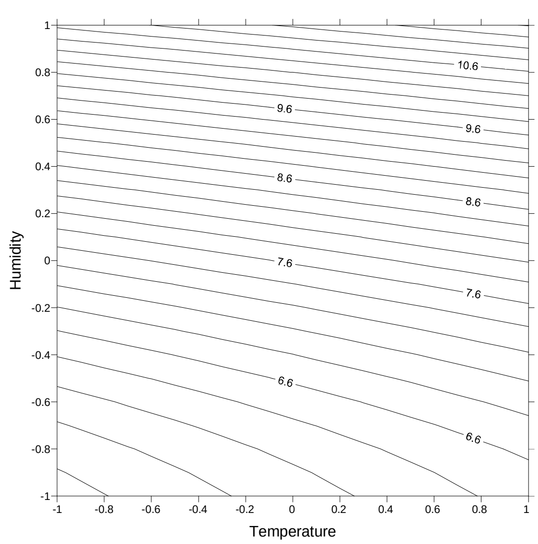


Figure 4.29 Contour lines showing the Ret (m^2Pa/W) behavior with in the different climatic conditions

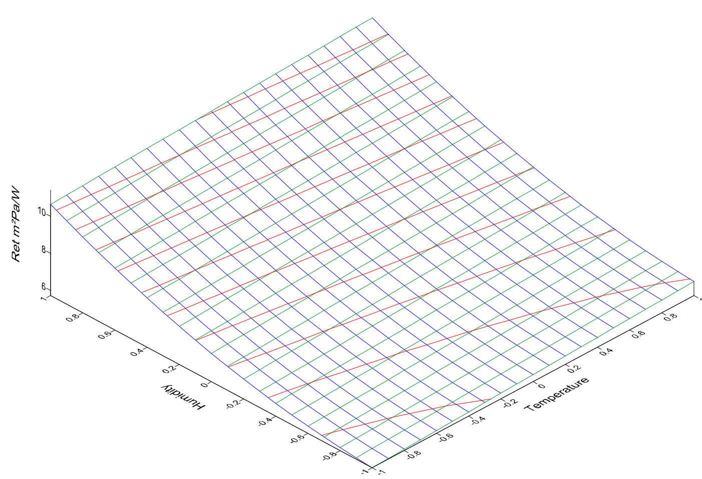


Figure 4.30 The effect of Temperature and Humidity on the Ret (m^2Pa/W)

With the increase of temperature and humidity, the cotton absorbs that humidity causing the fibers to swell affecting the Pores ratio with in the fabric and minimizing it; as the water vapor transfers from regions with high water vapor pressure to others with low water vapor pressure going through the pores in the fabric, so the transfer is difficult because of the reduced pores areas and at the same time because of the higher humidity existence adding to this the high ratio of Lycra, leading to higher water vapor resistance and less wear comfort in that tropical condition.

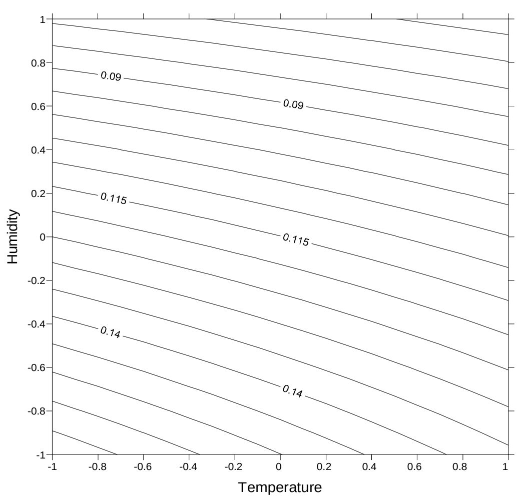
4.2.8 Water vapor permeability index (I_{mt})

From the data obtained from the previous results shown in Table 4.2, the following equation was obtained using multiple linear regression:

$$Imt= 0.115 - 0.009 X - 0.038 Y - 0.00007 X2 - 0.003 Y2 + 0.003 XY \qquad (59)$$

From the R-squared = 99.2661 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0021.

From the above equation the factors affecting Water vapor permeability index behavior can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it leads to significant negative change in the water vapor permeability index. (Figure 4.31) and (Figure 4.32) show the water vapor permeability index behavior.



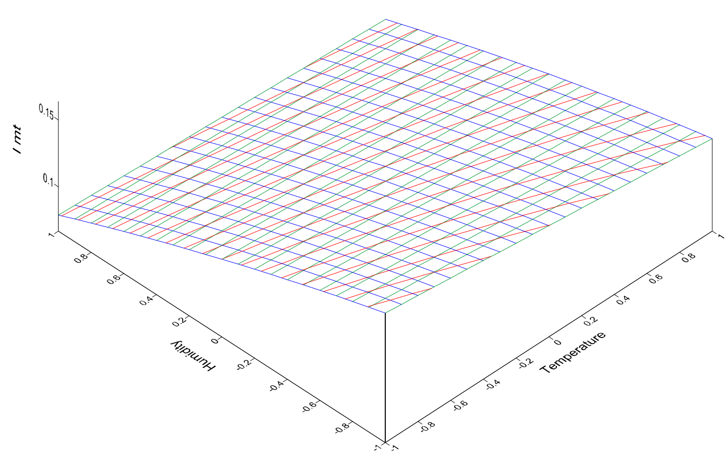


Figure 4.31 Contour lines showing the Imt behavior with in the different climatic conditions.

Figure 4.32 The effect of Temperature and Humidity on the water vapor permeability index.

4.3 92%Cotton 8%Lycra

The thermal comfort properties of the produced 92%Cotton 8%Lycra garments were investigated in the different climatic conditions that exist in hot countries. The effect of increasing the Lycra ration in the core is obvious at this stage, and it could be noticed especially comparing the results with the sample made from four percent Lycra ratio.

It is clear from Table 4.3 how the thermophysiological properties for the material under study acts in the different simulated hot weather conditions.

Table 4.3 92%Cotton 8%Lycra Thermophysiological properties in different weather conditions

Climaic Condition	Effusivity (Ws½/m²K)	k (W/mK)	Rct (m^2Kw^{-1})	Diffusivity (m²/s)	Air permeability m/sec	Pores %	Ret m²Pa/W	I_{mt}
15°C+40%ϕ	123.13	0.062	0.0156	2.51	0.0130	0.13	6.1	0.15
15°C+60%ϕ	125.47	0.064	0.0150	2.32	0.0128	0.12	8.3	0.11
15°C+80%ϕ	141.49	0.069	0.0140	2.06	0.0121	0.04	11.2	0.08
25°C+40%ϕ	130.97	0.063	0.0152	2.35	0.0122	0.13	6.3	0.14
25°C+60%ϕ	132.91	0.069	0.0140	2.69	0.0118	0.11	8.5	0.10
25°C+80%ϕ	156.55	0.073	0.0131	2.20	0.0106	0.04	11.5	0.07
35°C+40%ϕ	131.03	0.065	0.0148	2.46	0.0113	0.12	7.1	0.13
35°C+60%ϕ	139.88	0.071	0.0135	2.59	0.0106	0.10	8.7	0.09
35°C+80%ϕ	167.56	0.078	0.0123	2.19	0.0086	0.02	12.1	0.06

4.3.1 Effusivity (Ws½/m²K)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.3, for analysis of the results, the following equation was obtained:

$$\text{Effusivity} = 132.75 + 8.06\, X + 13.41\, Y + 9.03\, Y^2 + 4.54\, XY \qquad (60)$$

From the R-squared = 99.1292 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0002.From the above equation the factors affecting Thermal Effusivity (Ws½/m²K) behavior in the fabrics made from 92% Cotton 8%Lycra can be concluded. It is clear that humidity has the highest positive effect and the temperature has the second highest effect as well as all the dominant factors; and all the interaction between the factors listed in the obvious equation; as they increase, we can see that the property under study is increasing. The Effusivity (Ws½/m²K) behavior in that fabric can be noticed from (Figure 4.33) and (figure 4.34).

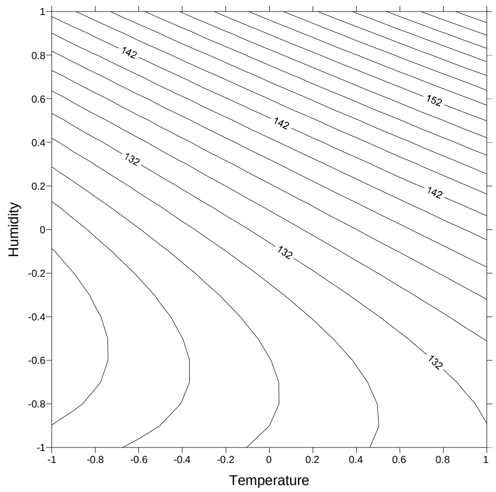


Figure 4.33 Contour lines showing the Effusivity (Ws½/m²K) behavior with in the different climatic conditions.

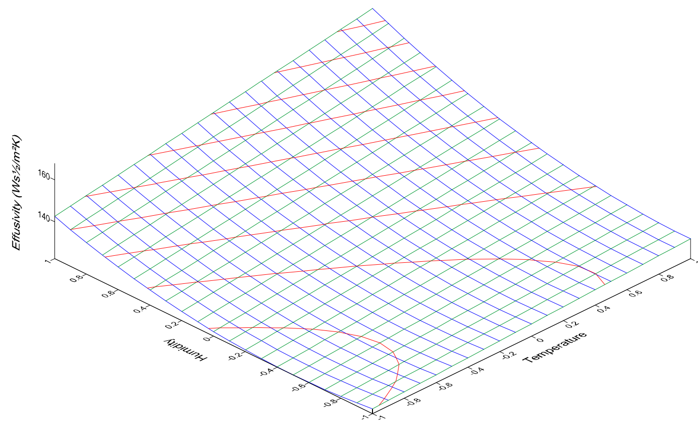


Figure 4.34 The effect of Temperature and Humidity on the Effusivity (Ws½/m²K)

Due to the high temperature and the high humidity, the Effusivity (Ws½/m²K); which assess the fabric's character in the aspect of it's 'coolwarm'' feeling, is getting higher, and we can tell that the Fabrics with a low value of thermal Effusivity (Ws½/m²K) gives us a ''warm'' feeling and vise versa and here we can see the effect of increasing Lycra ratio on the 'coolwarm'' feeling, it is clear that with less Lycra ratio , the more comfortable is the fabric.

4.3.2 Thermal conductivity (K) (W/mK)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.3, for analysis of the results, the following equation was obtained:

$$K = 0.06 + 0.003\,X + 0.005\,Y + 0.001\,XY \qquad (61)$$

From the R-squared = 99.4219 percent, it is obvious that the equation represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0000. From the above equation the factors affecting K (W/mK) behavior in 92% Cotton 8%Lycra fabrics can be concluded. It is clear that humidity has a positive effect and the temperature has also a positive effect as well as the interaction between the humidity and the temperature. (Figure 4.35) and (Figure 4.36) show the K (W/mK) behavior in that fabric under study.

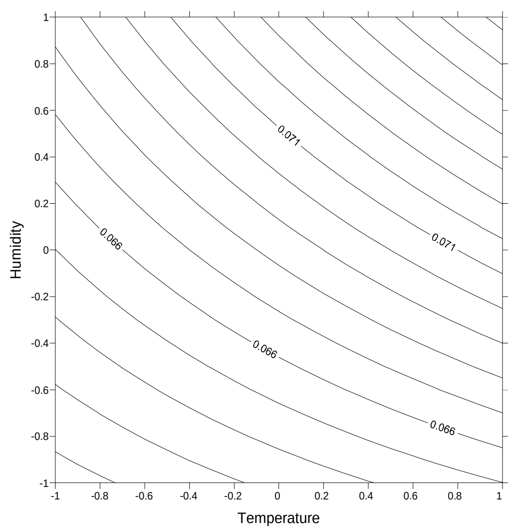


Figure 4.35 Contour lines showing the Thermal conductivity (W/mK) behavior with in the different climatic conditions

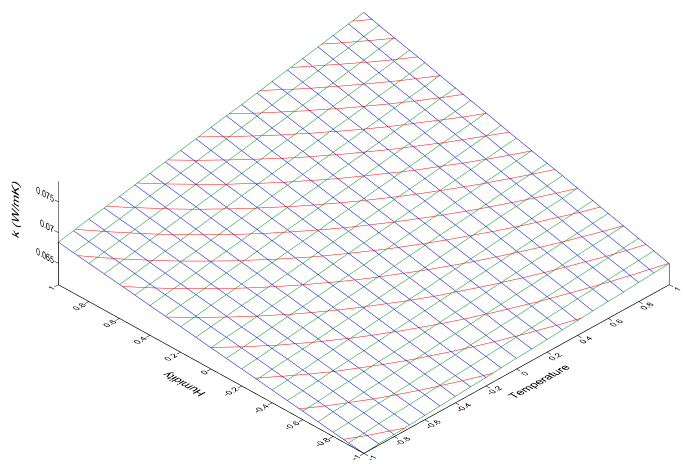


Figure 4.36 The effect of Temperature and Humidity on the Thermal conductivity (W/mK)

Hence, we are stimulating the hot condition we need fabrics that easily release the heat from the body, knowledge of the thermal conductivity value allows for quantitative comparisons to be made between the thermal insulation efficiencies of different fabrics, and the effect of increasing the Lycra ratio was different than fabrics with 4% Lycra.

4.3.3 Thermal resistance (Rct) (m^2Kw^{-1})

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.3, the following equation was obtained:

$$Rct = 0.014 - 0.0006\,X - 0.001\,Y + 0.0001\,X^2 + 0.000003\,Y^2 - 0.0002\,XY \qquad (62)$$

From the R-squared = 99.5212 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0011.

From the above equation the factors affecting Rct (m^2Kw^{-1}) behavior in 92% Cotton 8%Lycra fabrics can be concluded. It is clear that both humidity and the temperature have a negative effect with their increase, as well as the interaction between both of them. (Figure 4.37) and (Figure 4.38) show the Thermal resistance (m^2Kw^{-1}) behavior in the fabric under study.

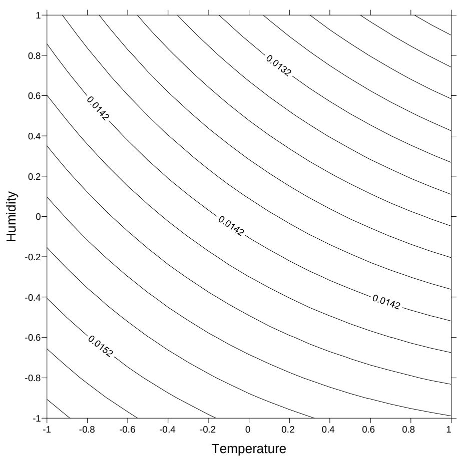


Figure 4.37 Contour lines showing the Rct (m^2Kw^{-1}) behavior with in the different climatic conditions

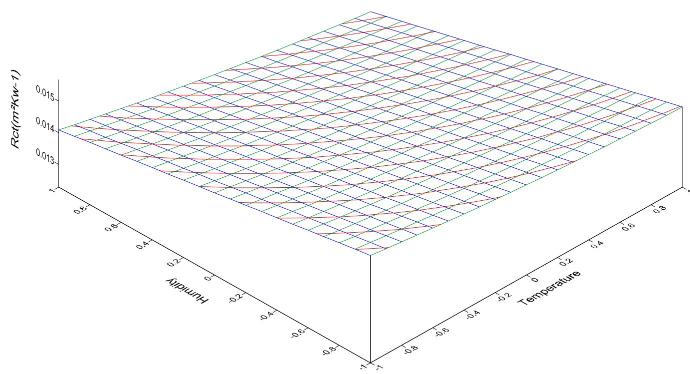


Figure 4.38 The effect of Temperature and Humidity on the Rct (m^2Kw^{-1})

In such hot condition with higher temperature and higher humidity, it is desirable for the human being to wear something that is easy to release body temperature, in a way to feel cooler and here we can figure out the effect of the Lycra ratio increase on the property, because of the variation of the construction between the cotton and the Lycra, where the latest is actually a rigid one with less amorphous regions in between spaces. Due to the high temperature and the high humidity, Rct (m^2Kw^{-1}) which is a very important parameter from the point of view of thermal insulation is getting lower mainly because of the water content increasing, and we can observe the effect of higher Lycra ratio.

4.3.4 Diffusivity (m²/s)

The multiple linear regression is being used to analyze the data for the Diffusivity obtained from Table 4.3, for analysis of the results, the following equation was obtained:

$$\text{Diffusivity} = 2.5 + 0.05\ X - 0.14\ Y - 0.05\ X^2 - 0.23\ Y^2 + 0.04\ XY \qquad (63)$$

It is concluded from R-squared that the equation represents 70.8033 percent of the results model and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0249. (Figure 4.39) and (Figure 4.40) show the Diffusivity (m²/s) behavior in that fabric

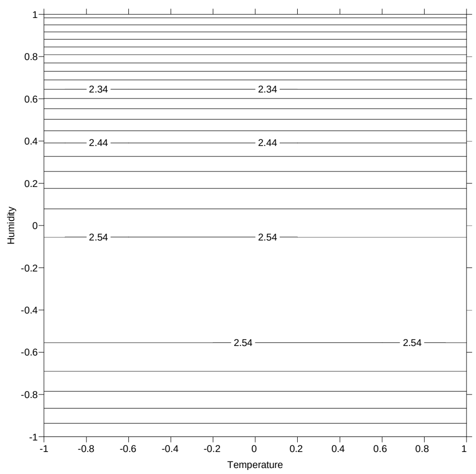


Figure 4.39 Contour lines showing the Diffusivity (m²/s) behavior with in the different climatic conditions

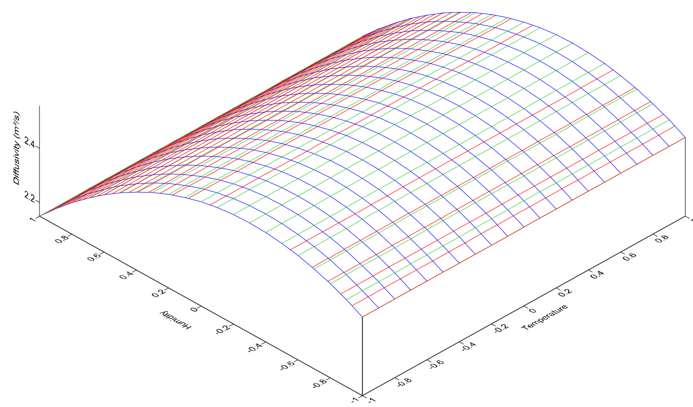


Figure 4.40 The effect of Temperature and Humidity on the Diffusivity (m²/s)

4.3.5 Air permeability (m/sec)

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.3, for analysis of the results, the following equation was obtained:

$$\text{Air permeability} = 0.011 - 0.001\ X - 0.0008\ Y - 0.0004\ Y^2 - 0.0004\ XY \qquad (64)$$

From the R-squared = 99.3075 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0001.

From the above equation the factors affecting Air permeability (m/sec) behavior in 92% Cotton 8%Lycra fabrics can be concluded. It is clear that humidity and temperature have negative effect as well as the interaction between the humidity and the temperature. (Figure 4.41) and (Figure 4.42) show the Air permeability (m/sec) behavior in that fabric.

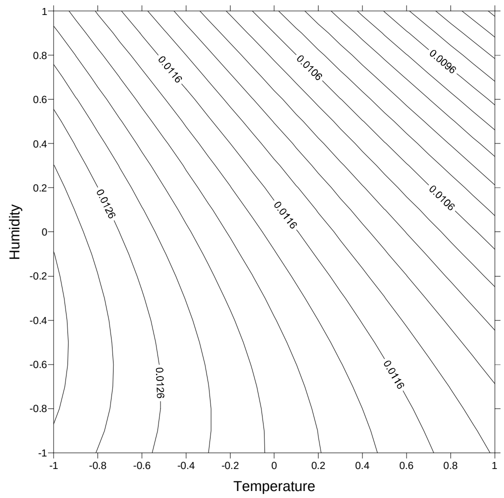


Figure 4.41 Contour lines showing the Air permeability (m/sec) behavior with in the different climatic conditions.

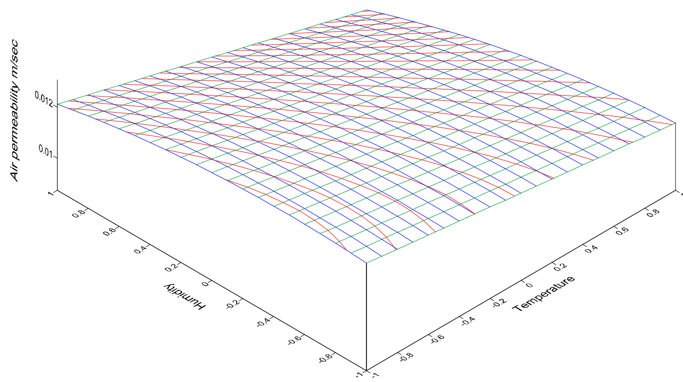


Figure 4.42 The effect of Temperature and Humidity on the Air permeability (m/sec)

With the increasing of temperature and due to the high humidity, the Air permeability (m/sec); which is a dominant factor in water vapor transfer is dramatically decreasing with the increase of humidity, it could be referred to the cotton structure, which when absorbs water, causes the yarn diameter to increase leading to minimizing the pores spaces with in the fabric causing more air resistance and less air permeability, adding to this the more increase of the Lycra ratio , which also increase the impermeable areas in the yarn , minimizing the air permeability of the fabric under investigation.

4.3.6 Pores ratio

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.3, for analysis of the results, the following equation was obtained:

$$\text{Pores ratio} = 0.11 - 0.011\,X - 0.05\,Y - 0.03\,Y^2 - 0.007\,XY \qquad (65)$$

From the R-squared = 99.6524 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0000.

From the above equation the factors affecting Pores ratio behavior in 92% Cotton 8%Lycra fabrics can be concluded. It is clear that humidity has the highest negative effect and the temperature has also a high negative effect as well as the interaction between the humidity and the temperature. (Figure 4.43) and (Figure 4.44) show the Pores ratio behavior in that fabric.

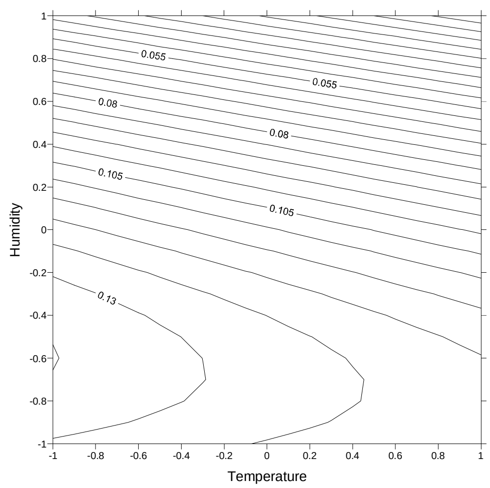


Figure 4.43 Contour lines showing the Pores ratio behavior with in the different climatic conditions

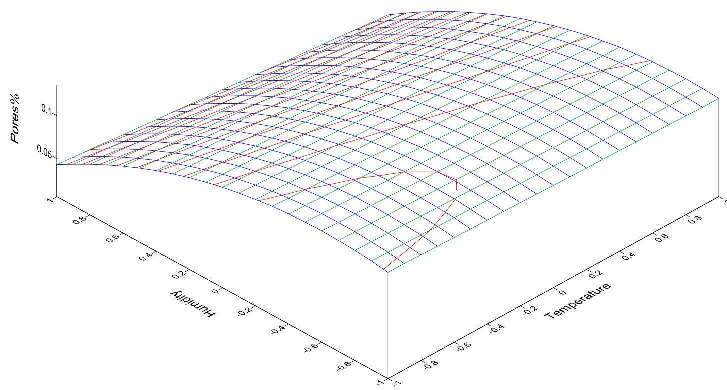


Figure 4.44 The effect of Temperature and Humidity on the Pores ratio

Due to the high temperature and the high humidity, the Pores ratio; which is a dominant factor in air permeability and water vapor permeability, is dramatically decreasing with the increase of humidity, it is referred to the cotton structure, which when absorbs that humidity, it swells, and also for the Lycra existence by 8% ratio which increases also the impermeable regions, leading to minimizing the pores and the spaces with in the fabric causing more air resistance and less air permeability.

4.3.7 Water vapor resistance (Ret) (m^2Pa/W)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.3, and the following equation was obtained:

$$Ret = 8.5 + 0.38\, X + 2.55\, Y + 0.55\, Y^2 \qquad (66)$$

From the R-squared = 99.5616 percent, it is obvious that the equation highly represents the experimental results, and there is a highly statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0000.

From the above equation the factors affecting Ret (m^2Pa/W) behavior in 92% Cotton 8%Lycra fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it causes more resistance to the water vapor transfer. (Figure 4.45) and (Figure 4.46) show the Water vapor resistance (m^2Pa/W) behavior in the fabric under study.

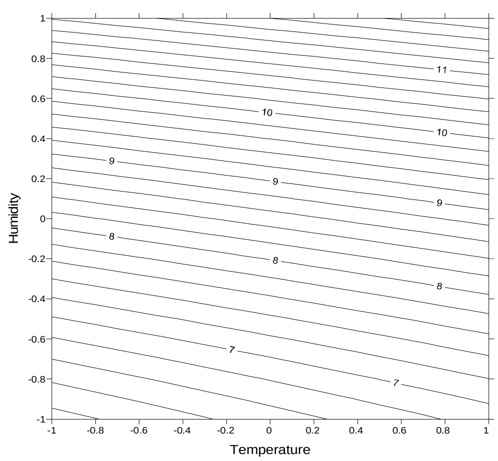


Figure 4.45 Contour lines showing the Ret (m^2Pa/W) behavior with in the different climatic conditions.

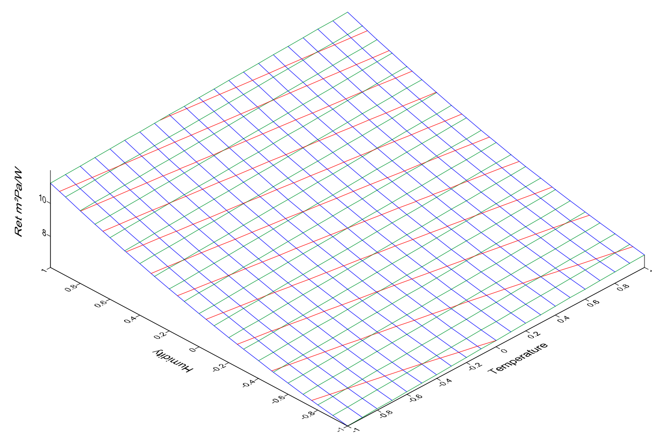


Figure 4.46 The effect of Temperature and Humidity on the Ret (m^2Pa/W)

With the increase of temperature and humidity, and from what observed above , the pores ratio decreases, and the air permeability as well, the cotton absorbs that humidity causing the fibers to swell affecting the Pores ratio with in the fabric and minimizing it; as the water vapor transfers from regions with high pressure to others with low water vapor pressure going through the pores in the fabric, so the transfer is difficult because of the reduced pores areas and at the same time because of the higher humidity existence adding to this the high ratio of Lycra, leading to higher water vapor resistance and less wear comfort in that tropical condition.

4.3.8 Water vapor permeability index (I_{mt})

From the data obtained from the previous results shown in Table 4.3, the following equation was obtained using multiple linear regression:

$$Imt = 0.1001 - 0.009\ X - 0.03\ Y + 0.004\ Y^2 + 0.003\ XY \qquad (67)$$

From the R-squared = 99.627 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0000.From the above equation the factors affecting Water vapor permeability index behavior in 92% Cotton 8% Lycra fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it leads to significant negative change in the water vapor permeability index. (Figure 4.47) and (Figure 4.48) show the water vapor permeability index behavior.

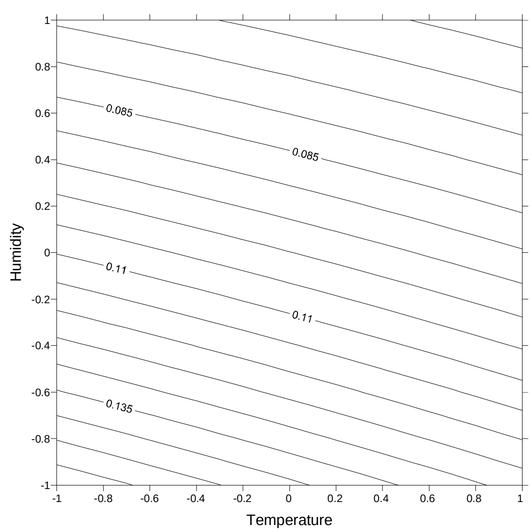


Figure 4.47 Contour lines showing the I_{mt} behavior with in the different climatic conditions.

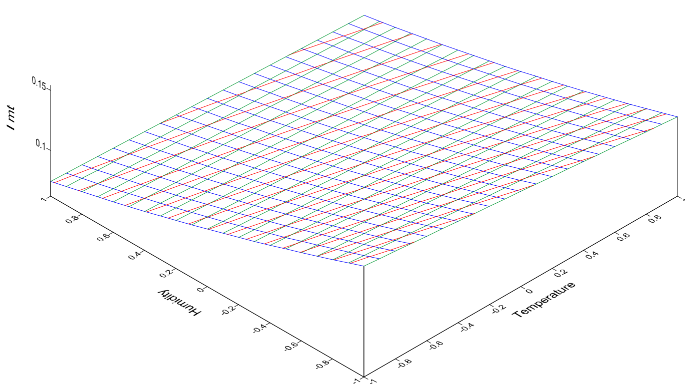


Figure 4.48 The effect of Temperature and Humidity on the water vapor permeability index

The higher the Water vapor permeability index the more comfort is the fabric in such a tropical weather, where the fabrics are demanded to be water vapor permeable, to help the body get rid of the water vapor, and we can figure out here the effect of the temperature and the humidity on the property.

4.4 Polypropylene

The thermal comfort properties of the produced Polypropylene garments were investigated in the different climatic conditions that exist in hot countries. It is clear from Table 4.4 how the thermophysiological properties for the material under study acts in the different simulated hot weather conditions.

Table 4.4 Polypropylene Thermophysiological properties in different weather conditions

Climaic Condition	Effusivity (Ws½/m²K)	K (W/mK)	Rct (m^2Kw^{-1})	Diffusivity (m^2/s)	Air permeability m/sec	Pores %	Ret m^2Pa/W	I_{mt}
15°C+40%ϕ	105.14	0.055	0.0158	2.77	0.1767	1.82	4.6	0.21
15°C+60%ϕ	110.31	0.057	0.0153	2.67	0.1767	1.81	4.8	0.19
15°C+80%ϕ	111.83	0.058	0.0150	2.71	0.1765	1.81	5.8	0.16
25°C+40%ϕ	110.98	0.057	0.0153	2.66	0.1766	1.82	5.1	0.18
25°C+60%ϕ	112.52	0.059	0.0148	2.77	0.1761	1.81	5.3	0.17
25°C+80%ϕ	114.08	0.063	0.0138	3.07	0.1759	1.79	6.1	0.14
35°C+40%ϕ	111.25	0.057	0.0152	2.65	0.1765	1.82	5.7	0.16
35°C+60%ϕ	114.25	0.059	0.0147	2.70	0.1761	1.81	5.9	0.15
35°C+80%ϕ	125.10	0.066	0.0131	2.82	0.1758	1.81	7.2	0.11

4.4.1 Effusivity (Ws½/m²K)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.4, for analysis of the results, the following equation was obtained:

$$\text{Effusivity} = 112.82 + 3.88\,X + 3.94\,Y \quad (68)$$

From the R-squared = 81.0778 percent, it is obvious that the equation represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0068. The factors affecting Effusivity (Ws½/m²K) behavior in Polypropylene fabrics can be concluded. It is clear that humidity has the highest positive effect and the temperature has the second highest effect, (Figure 4.49) and (figure 4.50) show the Effusivity (Ws½/m²K) behavior in that fabric.

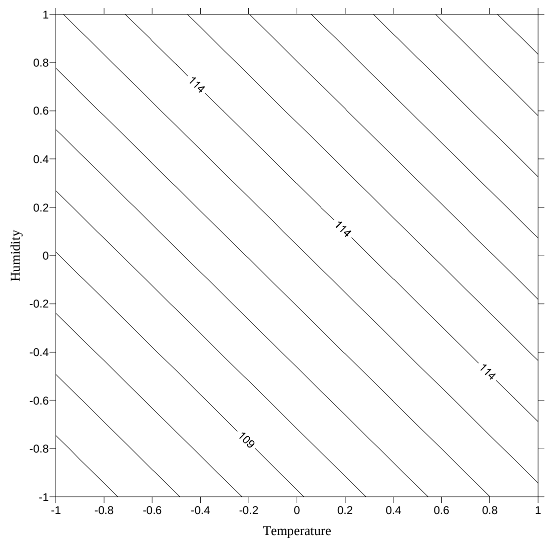


Figure 4.49 Contour lines showing the Effusivity (Ws½/m²K) behavior with in the different climatic conditions

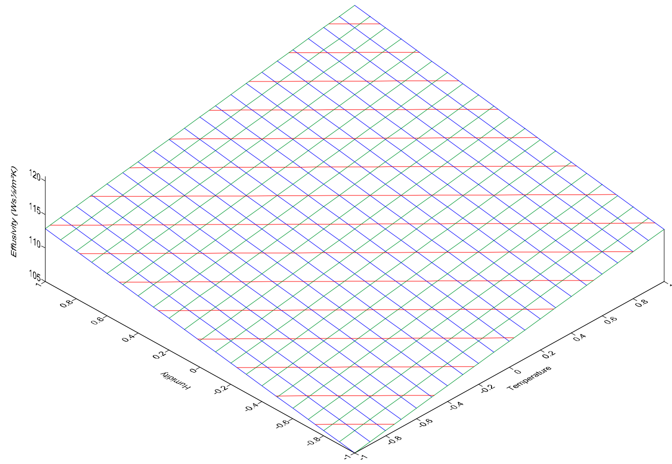


Figure 4.50 The effect of Temperature and Humidity on the Effusivity (Ws½/m²K)

Due to the high temperature and the high humidity, the Effusivity (Ws½/m²K); which assess the fabric's character in the aspect of it's 'coolwarm'' feeling, is getting higher, and we can tell that the Fabrics with a low value of thermal Effusivity (Ws½/m²K) gives us a ''warm'' feeling and vise versa, it is obvious how different is the behavior of Polypropylene fabrics than the cotton ones.

4.4.2 Thermal conductivity (K) (W/mK)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.4, for analysis of the results, the following equation was obtained:

$$K = 0.059 + 0.0021\ X + 0.0029\ Y + 0.0015\ XY \qquad (69)$$

From the R-squared = 93.3023 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0023.

From the above equation the factors affecting K (W/mK) behavior in Polypropylene fabrics can be concluded. It is clear that humidity has a positive effect and the temperature has also a positive effect as well as the interaction between the humidity and the temperature. (Figure 4.51) and (Figure 4.52) show the K (W/mK) behavior in that fabric under study.

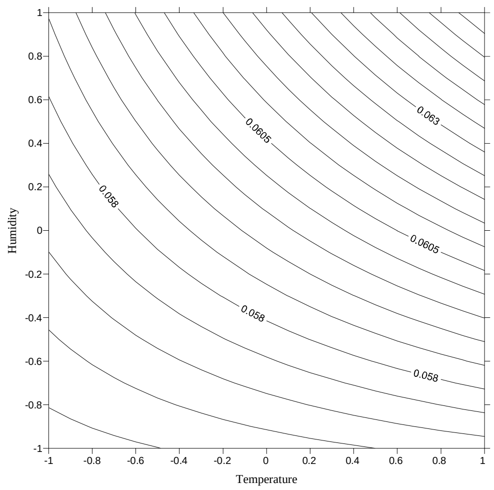


Figure 4.51 Contour lines showing the Thermal conductivity (W/mK) behavior with in the different climatic conditions.

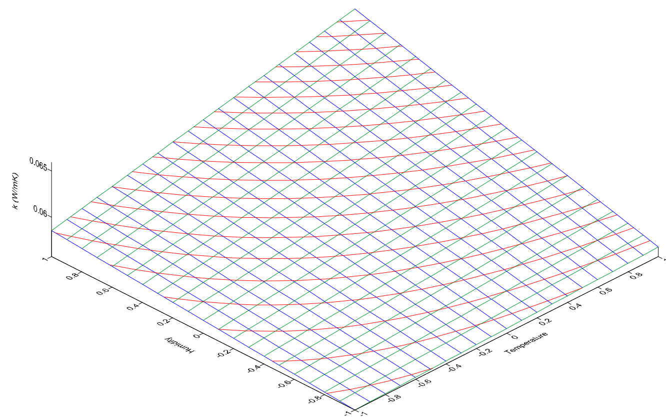


Figure 4.52 The effect of Temperature and Humidity on the Thermal conductivity (W/mK)

As mentioned before Fabrics having a large thermal conductivity value are good conductors of heat; one with a small thermal conductivity value is a poor heat conductor and it can be a good insulator. Hence, we are stimulating the hot condition we need fabrics that easily release the heat from the body, and as noticed that the humidity which is the dominant factor, and sine Polypropylene doesn’t absorb water, we can see here how the behavior changes does from cotton garments.

4.4.3 Thermal resistance (Rct) (m^2Kw^{-1})

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.4, the following equation was obtained:

$$Rct = 0.014 - 0.0005\ X - 0.0007\ Y - 0.0003\ XY \qquad (70)$$

From the R-squared = 93.8078 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0019.From the above equation the factors affecting Rct (m^2Kw^{-1}) behavior in Polypropylene fabrics can be concluded.

It is clear that both humidity and the temperature have a negative effect with their increase, as well as the interaction between both of them. (Figure 4.53) and (Figure 4.54) show the Thermal resistance (m^2Kw^{-1}) behavior in the fabric under study.

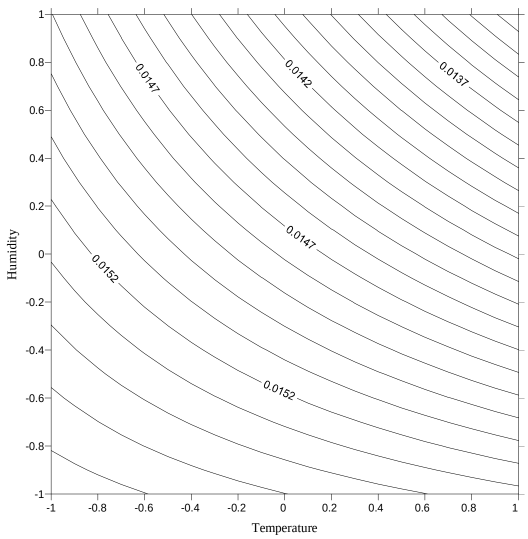


Figure 4.53 Contour lines showing the Rct (m^2Kw^{-1}) behavior with in the different climatic conditions.

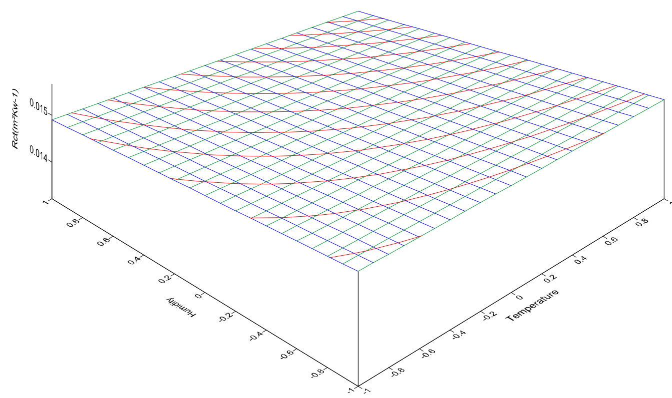


Figure 4.54 The effect of Temperature and Humidity on the Rct (m^2Kw^{-1})

Due to the high temperature and the high humidity, Rct (m^2Kw^{-1}) which is a very important parameter from the point of view of thermal insulation and which is proportional to the fabric structure is getting lower mainly because of the water content increasing, but as we see the difference as the Polypropylene doesn't absorb water, and in such hot condition with higher temperature and higher humidity, it is desirable for the human being to wear something that is easy to release body temperature, in a way to feel cooler.

4.4.4 Diffusivity (m^2/s)

The multiple linear regression is being used to analyze the data for the Diffusivity obtained from Table 4.4, for analysis of the results, the following equation was obtained:

$$\text{Diffusivity} = 2.784 + 0.0048\,X + 0.085\,Y - 0.109\,X^2 + 0.06\,Y^2 + 0.059\,XY \qquad (71)$$

It is concluded from R-squared that the equation represents 67.5545 percent of the results model and there isn't a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.4554, the Polypropylene different construction which made it doesn't absorb water caused the change in the thermal behavior of the fabric, (Figure 4.55) and (Figure 4.56) show the Diffusivity (m²/s) behavior in Polypropylene fabric.

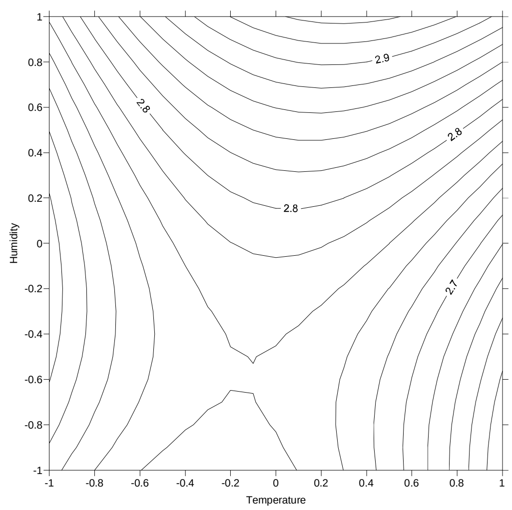


Figure 4.55 Contour lines showing the Diffusivity (m²/s) behavior with in the different climatic conditions.

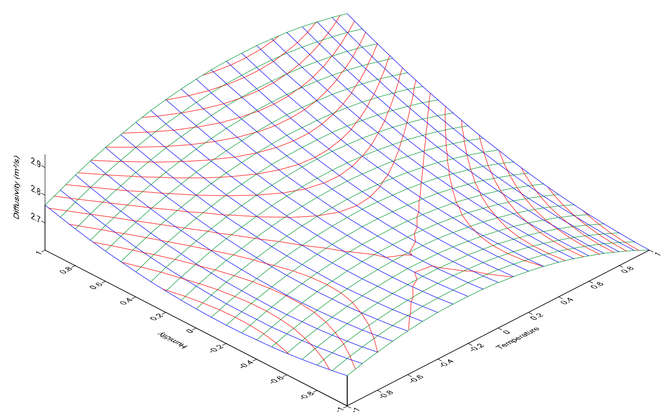


Figure 4.56 The effect of Temperature and Humidity on the Diffusivity (m²/s)

4.4.5 Air permeability (m/sec)

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.4, for analysis of the results, the following equation was obtained:

$$\text{Air permeability} = 0.17 - 0.00023\,X - 0.00026\,Y + 0.00018\,X^2 - 0.00013\,X\,Y \quad (72)$$

From the R-squared = 95.7882 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0052.

From the above equation the factors affecting Air permeability (m/sec) behavior in Polypropylene fabrics can be concluded. It is clear that humidity and temperature have negative effect as well as the interaction between the humidity and the temperature. (Figure 4.57) and (Figure 4.58) show the Air permeability (m/sec) behavior in that fabric.

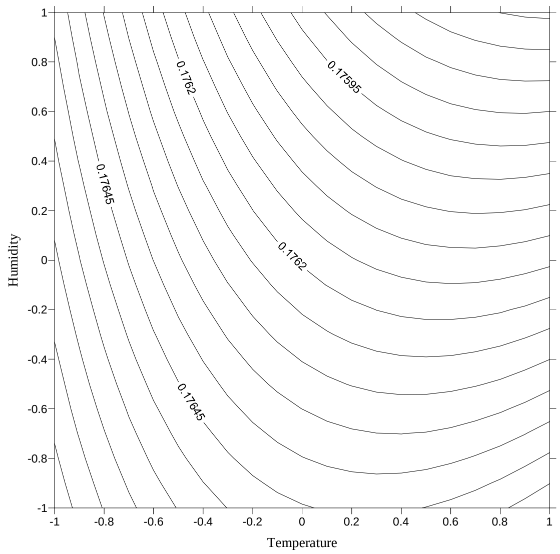


Figure 4.57 Contour lines showing the Air permeability (m/sec) behavior with in the different climatic conditions

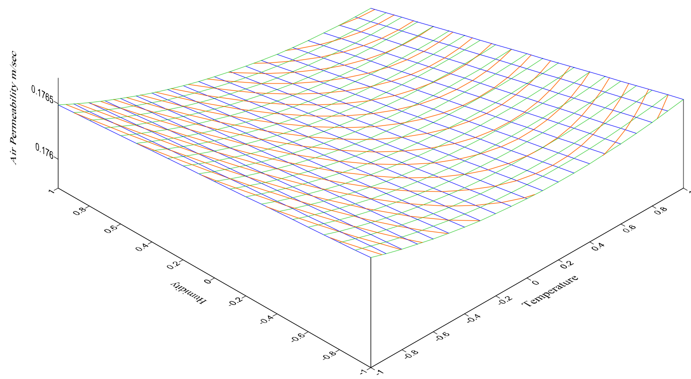


Figure 4.58 The effect of Temperature and Humidity on the Air permeability (m/sec)

Due to the high temperature and the high humidity, the Air permeability (m/sec); which is a dominant factor in water vapor transfer is not that much decreasing with the increase of humidity as in cotton, it could be referred to the difference between cotton structure and the Polypropylene one, as in Polypropylene it doesn't absorb water, but in cotton which when absorbs water, causes the fibers to swell leading to minimizing the pores with in the fabric causing more air resistance and less air permeability.

4.4.6 Pores ratio

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.4, for analysis of the results, the following equation was obtained:

$$\text{Pores ratio} = 1.8 - 0.005\,X - 0.012\,Y - 0.007\,XY \qquad (73)$$

From the R-squared = 91.1595 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0046.From the above equation the factors affecting Pores ratio behavior in Polypropylene fabrics can be concluded. It is clear that humidity and the temperature have a negative effect as well as the interaction between the humidity and the temperature but not as the cotton material and as mentioned before it refers to the structure of the material itself. (Figure 4.59) and (Figure 4.60) show the Pores ratio behavior in that fabric.

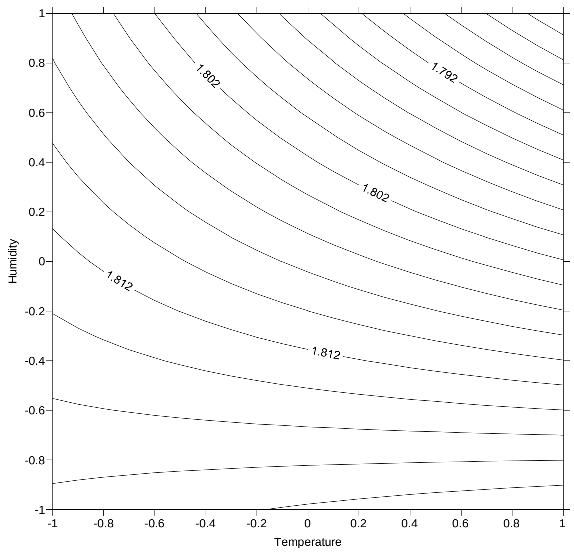


Figure 4.59 Contour lines showing the Pores ratio behavior with in the different climatic conditions

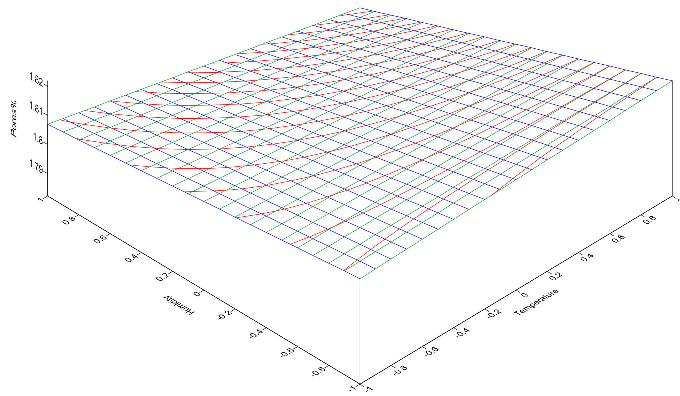


Figure 4.60 The effect of Temperature and Humidity on the Pores ratio

4.4.7 Water vapor resistance (Ret) (m^2Pa/W)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.4, and the following equation was obtained:

$$Ret = 5.33 + 0.6\,X + 0.61\,Y + 0.41Y^2 \qquad (74)$$

From the R-squared = 97.1596 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0003.

From the above equation the factors affecting Ret (m^2Pa/W) behavior in Polypropylene fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it causes more resistance to the water vapor and here the effect of the humidity is very obvious, but the resistance here is referring to the higher partial pressure that makes the transfer of the water vapor not easy. (Figure 4.61) and (Figure 4.62) show the Water vapor resistance (m^2Pa/W) behavior in that fabric.

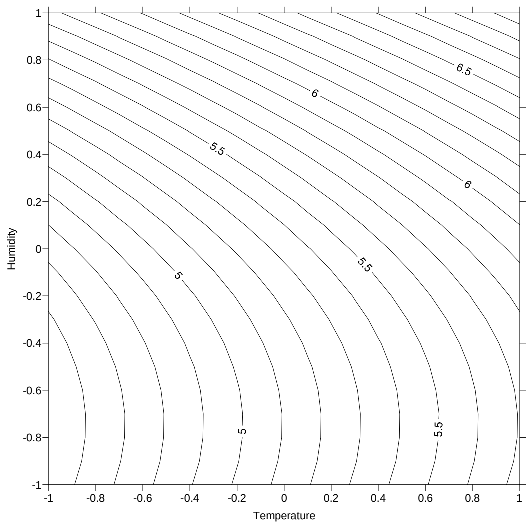


Figure 4.61 Contour lines showing the Ret (m^2Pa/W) behavior with in the different climatic conditions.

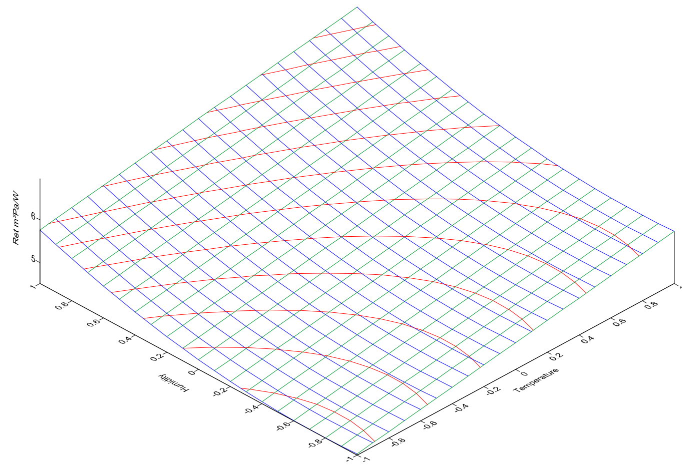


Figure 4.62 The effect of Temperature and Humidity on the Ret (m^2Pa/W).

4.4.8 Water vapor permeability index (I_{mt})

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.4, and the following equation was obtained:

$$I_{mt} = 0.16 - 0.022\ X - 0.024\ Y - 0.011\ Y^2 \qquad (75)$$

From the R-squared = 99.5697 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0000.

From the above equation the factors affecting Water vapor permeability index behavior in Polypropylene fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it leads to significant negative change in the water vapor permeability index. (Figure 4.63) and (Figure 4.64) show the water vapor permeability index behavior. The higher the Water vapor permeability index the more comfort is the fabric in such a tropical weather, where the fabrics are preferable to be water vapor permeable, to help the body get rid of the water vapor, and we can figure out here the effect of the temperature and the humidity on the property.

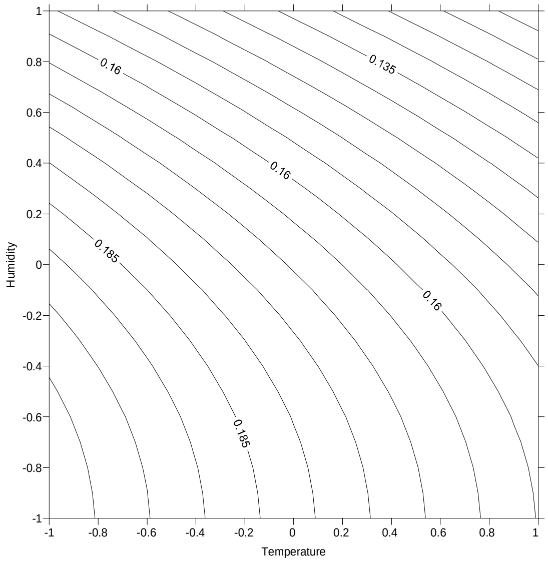


Figure 4.63 Contour lines showing the I_{mt} behavior with in the different climatic conditions

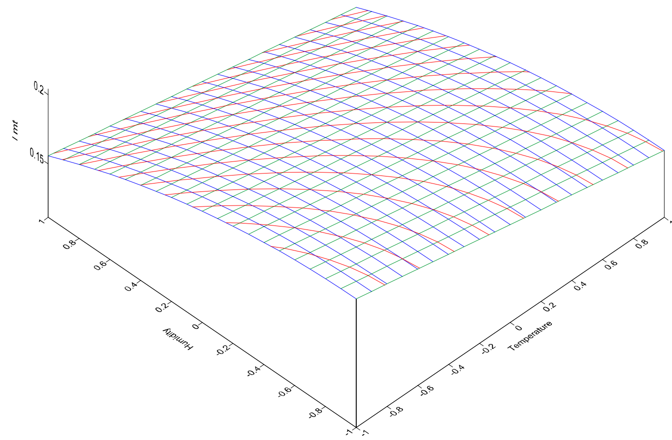


Figure 4.64 The effect of Temperature and Humidity on the water vapor permeability index

4.5 Merino wool

The thermal comfort properties of the produced Merino wool garments were investigated in the different climatic conditions that exist in tropical countries. It is clear from Table 4.5 how the thermophysiological properties for the material under study acts in the different conditions. The dominant factor in the thermal behavior of the Merino wool is the special construction of the fiber and how fine they are, as well as the air gaps in there. Merino is excellent at regulating body temperature, especially when worn against the skin. The wool provides some warmth, without overheating the wearer.

Table 4.5 Merino wool Thermophysiological properties in different conditions.

Climaic Condition	Effusivity (Ws½/m²K)	k (W/mK)	Rct (m^2Kw^{-1})	Diffusivity (m^2/s)	Air permeability m/sec	Pores %	Ret m^2Pa/W	I_{mt}
15°C+40%ϕ	104.45	0.055	0.0177	2.79	0.1800	1.87	3.7	0.29
15°C+60%ϕ	111.83	0.057	0.0169	2.64	0.1792	1.81	4.1	0.25
15°C+80%ϕ	114.01	0.058	0.0167	2.60	0.1781	1.76	5.7	0.18
25°C+40%ϕ	122.67	0.061	0.0159	2.48	0.1710	1.82	4.6	0.21

25°C+60%ϕ	126.73	0.063	0.0156	2.44	0.1692	1.80	5.0	0.19
25°C+80%ϕ	134.71	0.065	0.0150	2.31	0.1681	1.73	5.9	0.15
35°C+40%ϕ	123.64	0.062	0.0156	2.54	0.1652	1.80	5.3	0.18
35°C+60%ϕ	129.44	0.063	0.0154	2.37	0.1553	1.78	5.4	0.17
35°C+80%ϕ	160.59	0.073	0.0134	2.06	0.1329	1.69	6.1	0.13

4.5.1 Effusivity (Ws½/m²K)

The following equation was obtained:

$$\text{Effusivity} = 125.34 + 13.89\,X + 9.75\,Y + 6.84\,XY \qquad (76)$$

From the R-squared = 91.0331 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0047.Factors affecting Thermal Effusivity (Ws½/m²K) can be concluded. It is clear that Temperature has the highest positive effect and the humidity has the second one as well as the interaction between the factors. The Effusivity (Ws½/m²K) behavior in that fabric can be noticed from (Figure 4.65) and (figure 4.66).

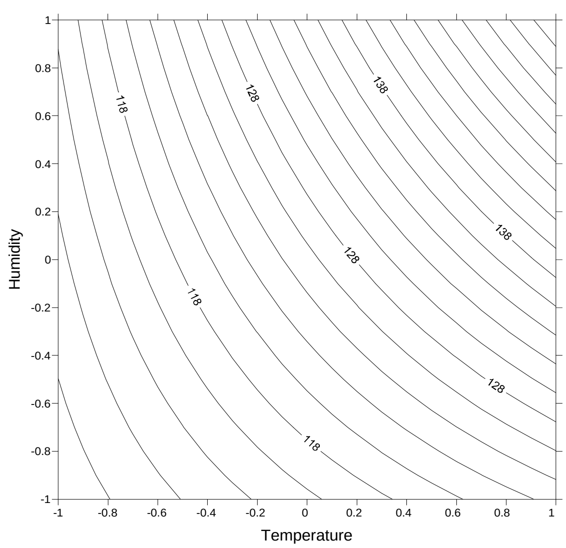


Figure 4.65 Contour lines showing the Effusivity (Ws½/m²K) behavior with in the different climatic conditions.

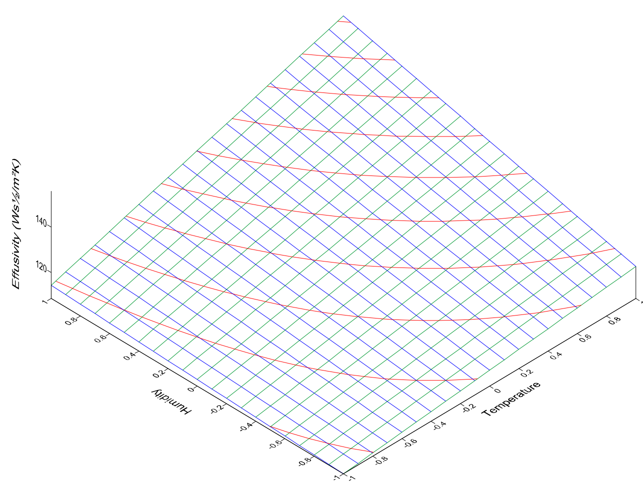


Figure 4.66 The effect of Temperature and Humidity on the Effusivity (Ws½/m²K).

Due to the high temperature and the high humidity, the Effusivity (Ws½/m²K) is getting higher, and we can tell that the Fabrics with a low value of thermal Effusivity (Ws½/m²K) gives us a ‘‘warm’’ feeling and vice versa as previously mentioned.

4.5.2 Thermal conductivity (K) (W/mK)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.5, for analysis of the results, the following equation was obtained:

$$k = 0.06 + 0.004\ X + 0.002\ Y \qquad (77)$$

From the R-squared = 83.0369 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0049.

From the above equation the factors affecting K (W/mK) behavior in Merino wool fabrics can be concluded. It is clear here that Temperature has a positive effect and the humidity has also a positive. (Figure 4.67) and (Figure 4.68) show the K (W/mK) behavior in that fabric under study.

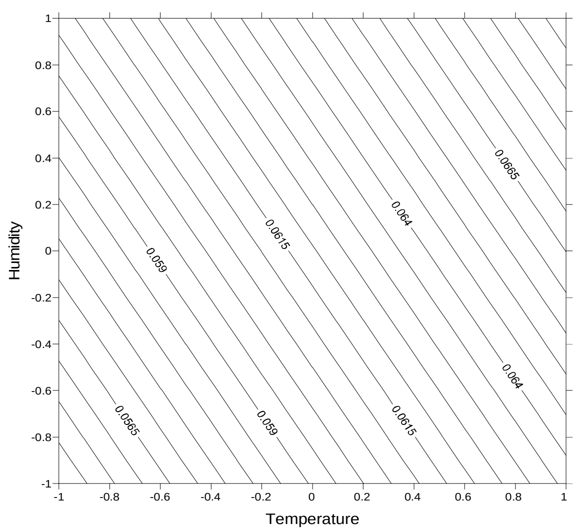


Figure 4.67 Contour lines showing the Thermal conductivity (W/mK) behavior with in the different climatic conditions.

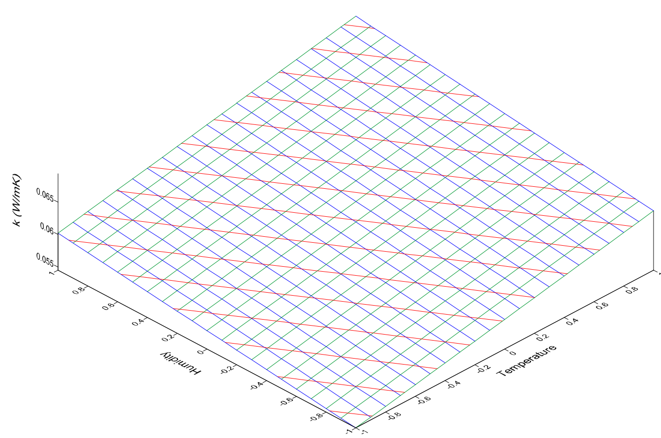


Figure 4.68 The effect of Temperature and Humidity on the Thermal conductivity (W/mK).

Hence, we are stimulating the hot condition we need fabrics that easily release the heat from the body, and in the same time allowing good breathability, and here the effect of the special structure of the Merino wool fibers is obvious.

4.5.3 Thermal resistance (Rct) (m^2Kw^{-1})

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.5, the following equation was obtained:

$$Rct = 0.015 - 0.001\ X - 0.0006\ Y \qquad (78)$$

From the R-squared = 86.3551 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0025.

From the above equation the factors affecting Rct (m^2Kw^{-1}) behavior in Merino wool fabrics can be concluded. It is clear that both humidity and the temperature have a negative effect with their increase. (Figure 4.69) and (Figure 4.70) show the Thermal resistance (m^2Kw^{-1}) behavior in the fabric under study.

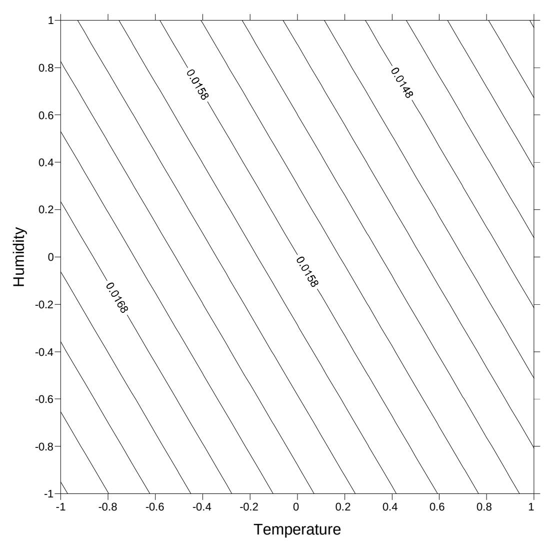


Figure 4.69 Contour lines showing the Rct (m^2Kw^{-1}) behavior with in the different climatic conditions.

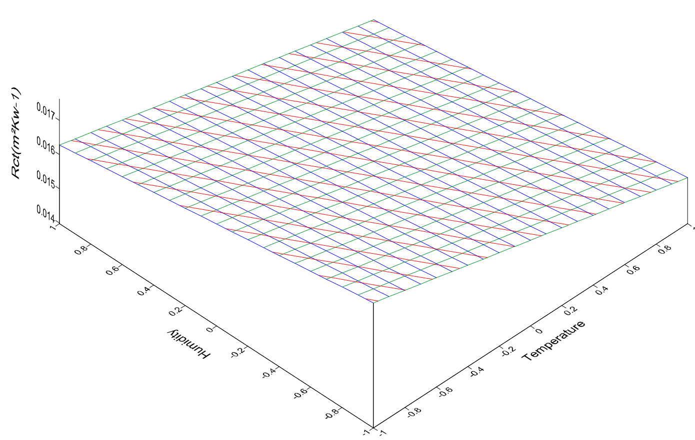


Figure 4.70 The effect of Temperature and Humidity on the Rct (m^2Kw^{-1}).

In such tropical weather with higher temperature and higher humidity, it is desirable for the human being to wear something that is easy to release body temperature, in a way to feel cooler and here we can figure out the effect of the unique structure of Merino wool due to the high temperature and the high humidity, Rct (m^2Kw^{-1}) which is a very important parameter from the point of view of thermal insulation is getting lower mainly because of the water content increasing.

4.5.4 Diffusivity (m²/s)

The multiple linear regression is being used to analyze the data for the Diffusivity obtained from Table 4.5, for analysis of the results, the following equation was obtained:

$$\text{Diffusivity} = 2.4 - 0.17\,X - 0.14\,Y + 0.09\,X2 - 0.07\,XY \qquad (79)$$

It is concluded from R-squared that the equation represents 95.9133 percent of the results model and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0049. (Figure 4.71) and (Figure 4.72) show the Diffusivity (m²/s) behavior in that fabric , the effect of the unique structure of the Merino wool fibers can be observed comparable to the cotton fibers or the Polypropylene one.

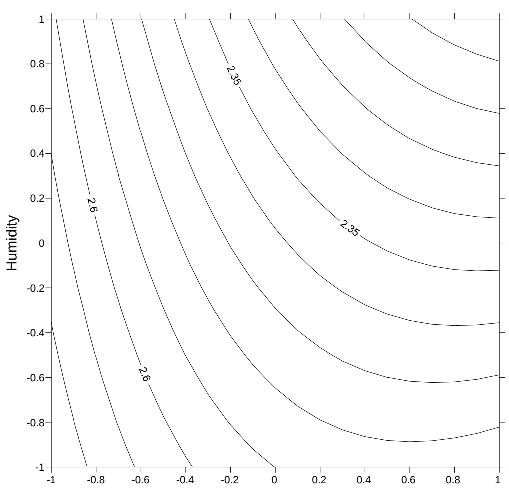


Figure 4.71 Contour lines showing the Diffusivity (m²/s) behavior with in the different climatic conditions.

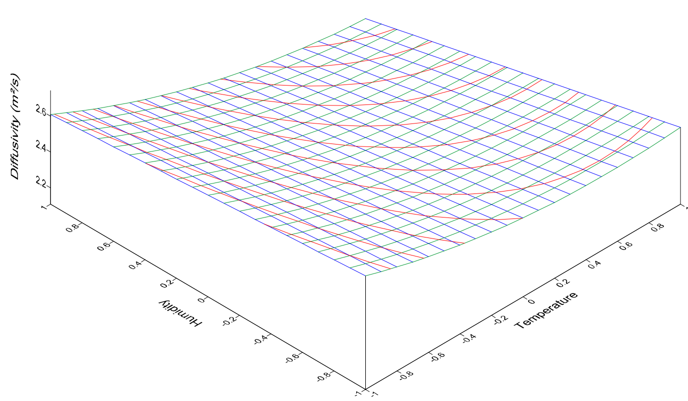


Figure 4.72 The effect of Temperature and Humidity on the Diffusivity (m²/s).

4.5.5 Air permeability (m/sec)

The following equation was obtained using the multiple linear regression:

$$\text{Air permeability} = 0.166 - 0.013\,X - 0.006\,Y - 0.007\,XY \qquad (80)$$

From the R-squared = 92.5964 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0030.

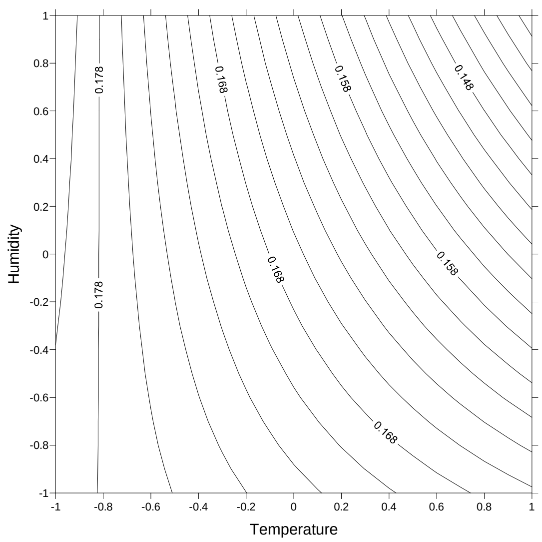


Figure 4.73 Contour lines showing the Air permeability (m/sec) behavior with in the different climatic conditions.

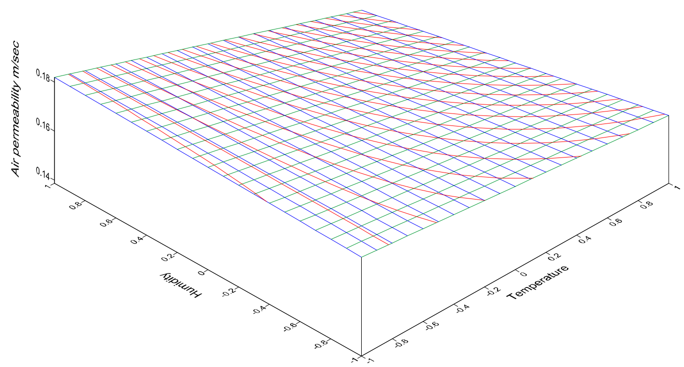


Figure 4.74 The effect of Temperature and Humidity on the Air permeability (m/sec).

From the above equation the factors affecting Air permeability (m/sec) behavior in Merino wool fabrics can be concluded. It is clear that humidity and temperature have negative effect as well as the interaction between the humidity and the temperature. (Figure 4.73) and (Figure 4.74) show the Air permeability (m/sec) behavior in that fabric. Where we can see the effect of the complex structure with a hydrophobic exterior (water repelling) and a hydrophilic interior (water holding) so it could be due to trapping of the water vapor molecules inside the gaps, causing some resistance to air passage through the fibers.

4.5.6 Pores ratio

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.5, for analysis of the results, the following equation was obtained:

$$\text{Pores ratio} = 1.79 - 0.028\,X - 0.051\,Y - 0.018\,Y^2 \qquad (81)$$

From the R-squared = 96.775 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0004.

From the above equation the factors affecting Pores ratio behavior in Merino wool fabrics can be concluded. It is clear that humidity has the highest negative effect and the temperature has also a high negative effect. (Figure 4.75) and (Figure 4.76) show the Pores ratio behavior in that fabric.

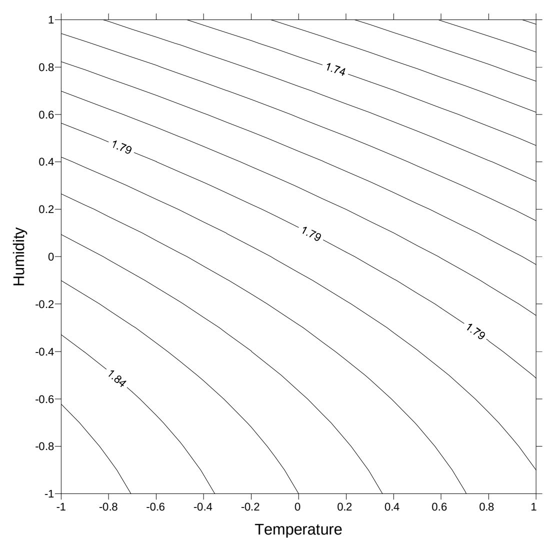


Figure 4.75 Contour lines showing the Pores ratio behavior with in the different climatic conditions.

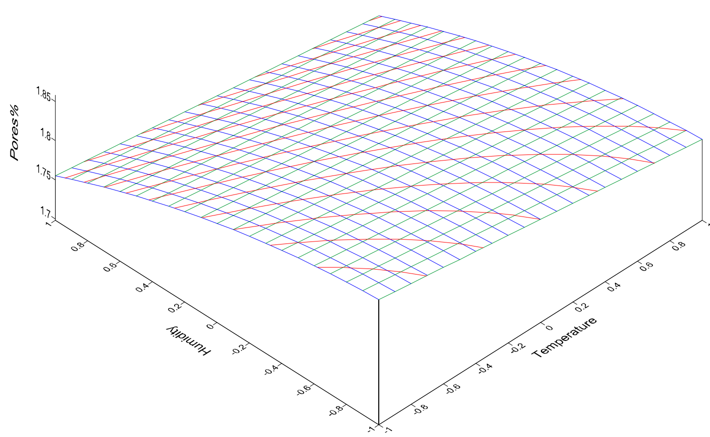


Figure 4.76 The effect of Temperature and Humidity on the Pores ratio.

4.5.7 Water vapor resistance (Ret) (m^2Pa/W)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.5, and the following equation was obtained:

$$Ret = 4.82 + 0.55\ X + 0.68\ Y + 0.39\ Y^2 - 0.3\ XY \qquad (82)$$

From the R-squared = 98.7668 percent, it is obvious that the equation highly represents the experimental results, and there is a highly statistically significant relationship between the variables at the 95.0% confidence level since P value was: 0.0005.

From the above equation the factors affecting Ret (m^2Pa/W) behavior in Merino wool a fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it causes more resistance to the water vapor transfer. (Figure 4.77) and (Figure 4.78) show the Water vapor resistance (m^2Pa/W) behavior in the fabric under study.

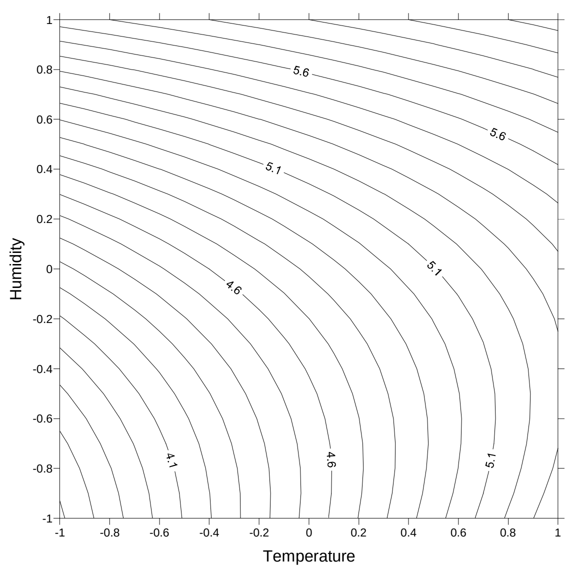


Figure 4.77 Contour lines showing the Ret (m^2Pa/W) behavior with in the different climatic conditions.

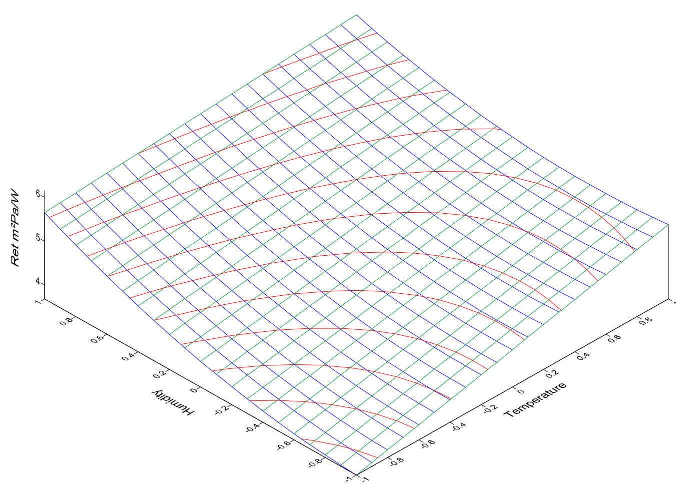


Figure 4.78 The effect of Temperature and Humidity on the Ret (m^2Pa/W).

This increase in water vapor resistance could be due to the trapping of the water vapor molecules inside the air gaps within the structure, causing some resistance to air passage through the fibers. That complex structure with a hydrophobic exterior and a hydrophilic interior which is water holding, causes this and the other reason due to the high presence of humidity which make it difficult for the water vapor to transfer away from the skin to the environment.

4.5.8 Water vapor permeability index (I_{mt})

From the data obtained from the previous results shown in Table 4.5, the following equation was obtained using multiple linear regression:

$$Imt = 0.192 - 0.038\,X - 0.035\,Y + 0.015\,X^2 - 0.013\,Y^2 + 0.016\,XY \qquad (83)$$

From the R-squared = 98.8204 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0043.

From the above equation the factors affecting Water vapor permeability index behavior in Merino wool fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it leads to significant negative change in the water vapor permeability index. (Figure 4.79) and (Figure 4.80) show the water vapor permeability index behavior.

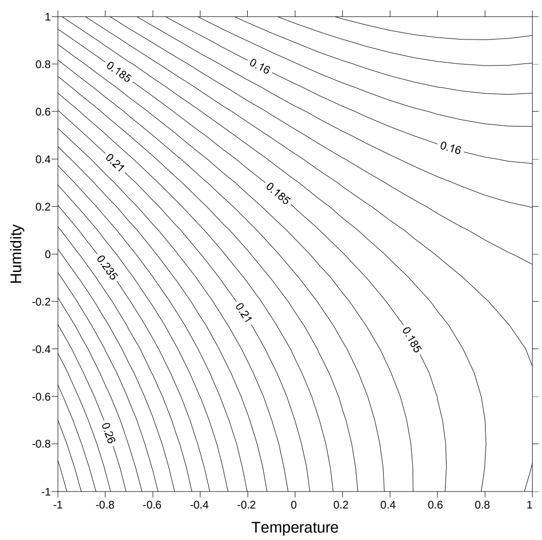


Figure 4.79 Contour lines showing the I_{mt} behavior with in the different climatic conditions.

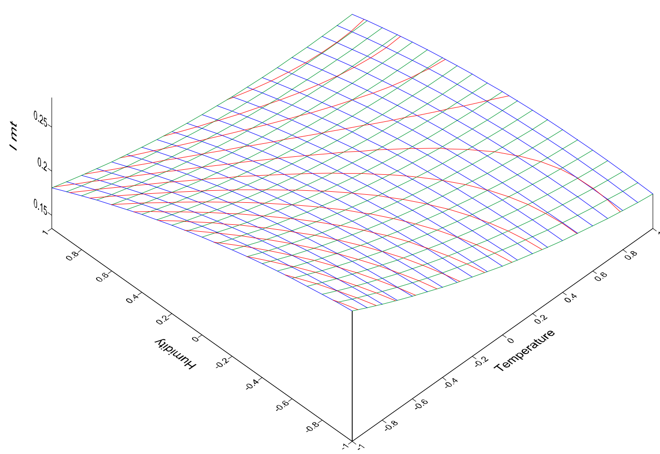


Figure 4.80 The effect of Temperature and Humidity on the water vapor permeability index.

The higher the Water vapor permeability index the more comfort is the fabric in such a tropical weather, where the fabrics are demanded to be water vapor permeable, to help the body get rid of the water vapor, and we can figure out here the effect of the temperature and the humidity on the property , comparable to other materials used in the research , we can tell that the difference of the thermal behavior of Merino wool fibers is mainly because of the unique structure as discussed previously.

4.6 95%Viscose fiber made from bamboo plants, 5%Lycra

As the world now is approaching towards green products, a special concern was given to Viscose fiber made from bamboo plants [160-162].The bamboo fiber belongs to cellulose crystalline structure as flax, cotton and ramie [163]. The thermal comfort properties of the produced 95%Viscose fiber made from bamboo plants, 5%Lycra garments were investigated in the different climatic conditions that exist in hot countries. It is clear from Table 4.6 how the thermophysiological properties for the material under study acts in the different simulated hot weather conditions.

Table 4.6 95%Viscose fiber made from bamboo plants, 5%Lycra Thermophysiological properties in different weather conditions

Climaic Condition	Effusivity (Ws½/m²K)	K (W/mK)	Rct (m^2Kw^{-1})	Diffusivity (m²/s)	Air permeability m/sec	Pores %	Ret m²Pa/W	I_{mt}
15°C+40%ϕ	185.04	0.081	0.0119	1.90	0.0870	0.82	5.5	0.13
15°C+60%ϕ	190.17	0.082	0.0117	1.87	0.0866	0.79	5.8	0.12
15°C+80%ϕ	199.28	0.085	0.0113	1.83	0.0861	0.75	7.4	0.09
25°C+40%ϕ	185.87	0.081	0.0119	1.90	0.0851	0.81	6.7	0.11
25°C+60%ϕ	209.15	0.088	0.0109	1.79	0.0846	0.78	7.1	0.09
25°C+80%ϕ	219.62	0.092	0.0105	1.75	0.0828	0.73	7.8	0.08
35°C+40%ϕ	201.98	0.086	0.0112	1.82	0.0753	0.81	7.6	0.09
35°C+60%ϕ	215.59	0.090	0.0106	1.76	0.0631	0.77	7.8	0.08
35°C+80%ϕ	225.10	0.096	0.0100	1.84	0.0546	0.72	8.2	0.07

4.6.1 Effusivity (Ws½/m²K)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.6, for analysis of the results, the following equation was obtained:

$$\text{Effusivity} = 203.53 + 11.36\,X + 11.85\,Y \qquad (84)$$

From the R-squared = 92.2175 percent, it is obvious that the equation represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0005. The factors affecting Effusivity (Ws½/m²K) behavior in 95%Viscose fiber made from bamboo plants, 5%Lycra fabrics can be concluded. It is clear that humidity has the highest positive effect and the temperature has the second highest effect, (Figure 4.81) and (figure 4.82) show the Effusivity (Ws½/m²K) behavior in that fabric.

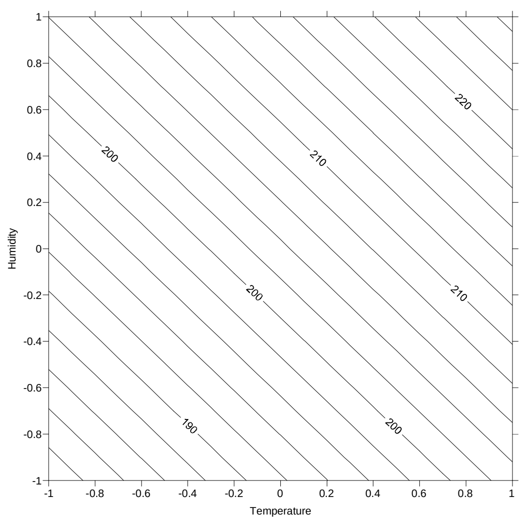


Figure 4.81 Contour lines showing the Effusivity (Ws½/m²K) behavior with in the different climatic conditions.

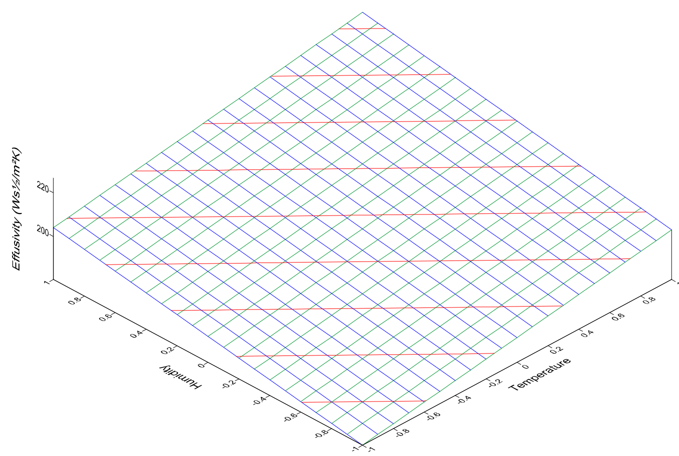


Figure 4.82 The effect of Temperature and Humidity on the Effusivity (Ws½/m²K).

Due to the high temperature and the high humidity, the Effusivity (Ws½/m²K), is getting higher, and we can tell that the Fabrics with a low value of thermal Effusivity (Ws½/m²K) gives us a ''warm'' feeling and vise versa as mentioned before, it is obvious how different is the behavior of 95%Viscose fiber made from bamboo plants, 5%Lycra which was affected by the unique structure.

4.6.2 Thermal conductivity (K) (W/mK)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.6, for analysis of the results, the following equation was obtained:

$$K = 0.08 + 0.0041\,X + 0.0042\,Y + 0.0014\,XY \qquad (85)$$

From the R-squared = 96.7806 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0004.

From the above equation the factors affecting K (W/mK) behavior in 95%Viscose fiber made from bamboo plants, 5%Lycra fabrics can be concluded. It is clear that humidity has a positive effect and the temperature has also a positive effect as well as the interaction between the humidity and the temperature. (Figure 4.83) and (Figure 4.84) show the K (W/mK) behavior in that fabric under study.

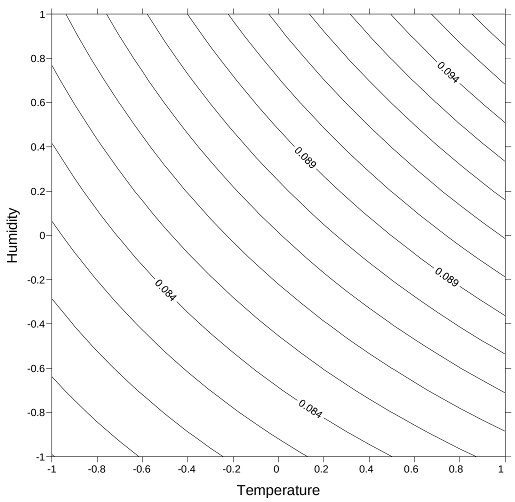


Figure 4.83 Contour lines showing the Thermal conductivity (W/mK) behavior with in the different climatic conditions.

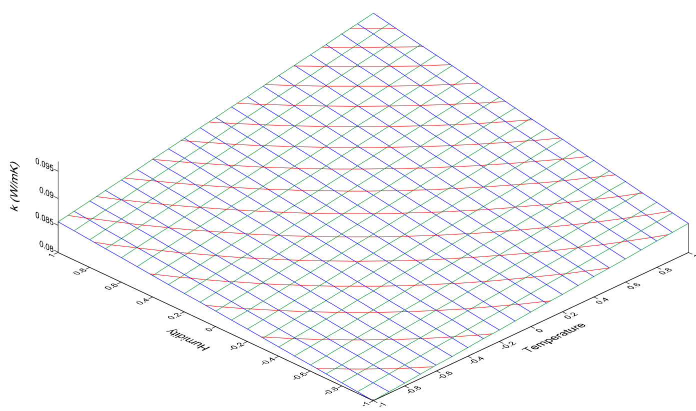


Figure 4.84 The effect of Temperature and Humidity on the Thermal conductivity (W/mK).

By the increase of heat the thermal conductivity increases leading to high heat conductivity but the dominant factor here is the humidity, which when absorbed by the fibers it leads to high conductivity mainly because of the water content. As mentioned before Fabrics having a large thermal conductivity value are good conductors of heat; one with a small thermal conductivity value is a poor heat conductor and it can be a good insulator. Hence, we are stimulating the hot condition we need fabrics that easily release the heat from the body causing the body to feel more comfortable.

4.6.3 Thermal resistance (Rct) (m^2Kw^{-1})

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.6, the following equation was obtained:

$$Rct = 0.01 - 0.0005\ X - 0.0005\ Y \quad (86)$$

From the R-squared = 93.7018 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0002.

From the above equation the factors affecting Rct (m^2Kw^{-1}) behavior in 95%Viscose fiber made from bamboo plants, 5%Lycra fabrics can be concluded. It is clear that both humidity and the temperature have a negative effect with their increase. (Figure 4.85) and (Figure 4.86) show the Thermal resistance (m^2Kw^{-1}) behavior in the fabric under study. And it is noticed that the thermal resistance is affected negatively by the presence of humidity, when the fabric absorbs water, molecules of the water vapor released from the body in addition to the moisture content in the environment as well as from the body, leads to lower thermal resistance (m^2Kw^{-1}).

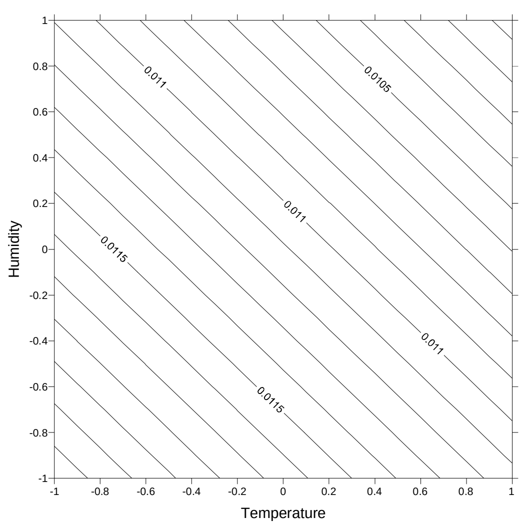


Figure 4.85 Contour lines showing the Rct (m^2Kw^{-1}) behavior with in the different climatic conditions.

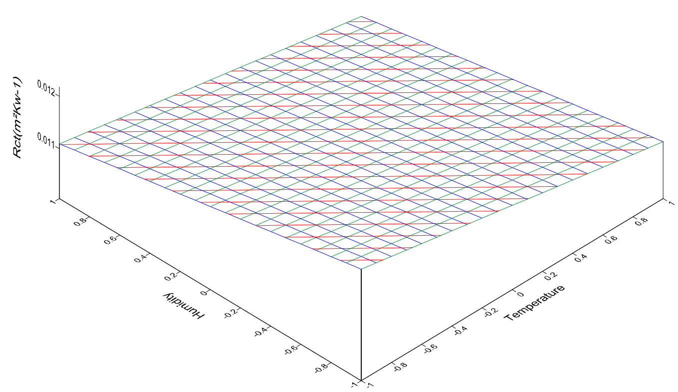


Figure 4.86 The effect of Temperature and Humidity on the Rct (m^2Kw^{-1}).

4.6.4 Diffusivity (m^2/s)

The multiple linear regression is being used to analyze the data for the Diffusivity obtained from Table 4.6, for analysis of the results, the following equation was obtained:

$$\text{Diffusivity} = 1.79 - 0.031\,X - 0.033\,Y + 0.026\,X^2 + 0.03\,Y^2 + 0.022\,XY \qquad (87)$$

It is concluded from R-squared that the equation represents 72.3581 percent of the results model and there isn't a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.3770, the 95%Viscose fiber made from bamboo plants, 5%Lycra different structure, the water content and the high temperature caused the change in the thermal Diffusivity (m^2/s) behavior of the fabric, (Figure 4.87) and (Figure 4.88) show the Diffusivity (m^2/s) behavior in 95%Viscose fiber made from bamboo plants, 5%Lycra fabric.

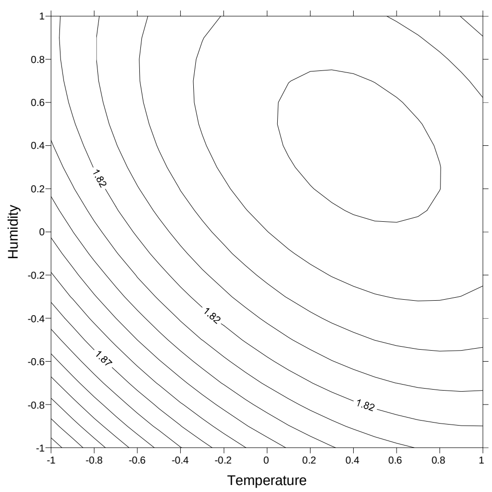


Figure 4.87 Contour lines showing the Diffusivity (m^2/s) behavior with in the different climatic conditions.

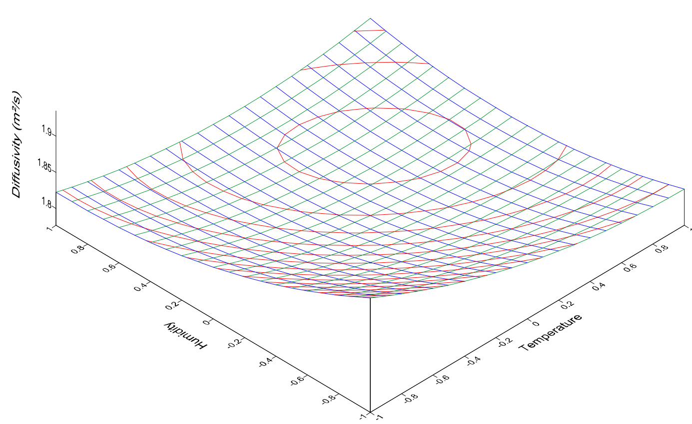


Figure 4.88 The effect of Temperature and Humidity on the Diffusivity (m^2/s).

4.6.5 Air permeability (m/sec)

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.6, for analysis of the results, the following equation was obtained:

$$\text{Air permeability} = 0.084 - 0.011X - 0.0039\,Y - 0.0087\,X^2 - 0.0049\,XY \qquad (88)$$

From the R-squared = 97.6064 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0017

From the above equation the factors affecting Air permeability (m/sec) behavior in 95%Viscose fiber made from bamboo plants, 5%Lycra fabrics can be concluded. It is clear that humidity and temperature have negative effect as well as the interaction between the humidity and the temperature. (Figure 4.89) and (Figure 4.90) show the Air permeability (m/sec) behavior in that fabric

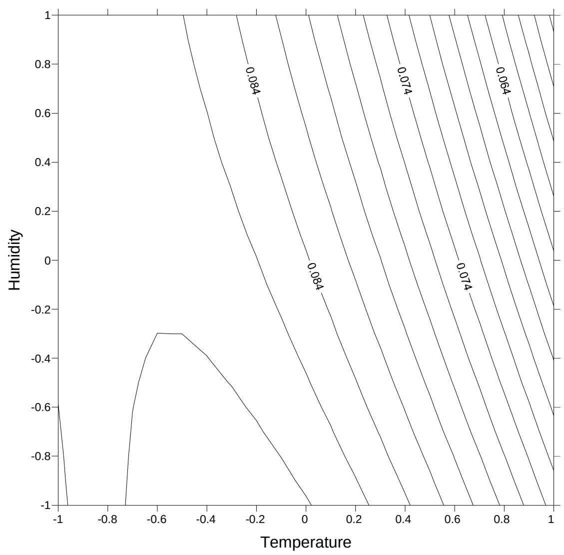


Figure 4.89 Contour lines showing the Air permeability (m/sec) behavior with in the different climatic conditions.

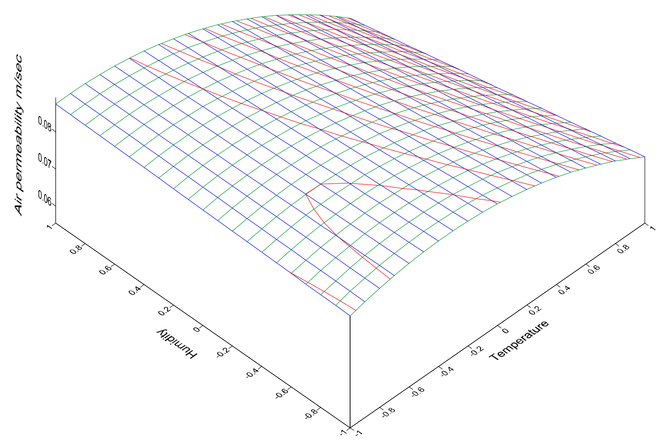


Figure 4.90 The effect of Temperature and Humidity on the Air permeability (m/sec).

Due to the high temperature and the high humidity, the Air permeability (m/sec); which is a dominant factor in water vapor transfer is affected with the increase of humidity, it could be referred to the special structure of Viscose fiber made from bamboo plants which when absorbs water, causes more air resistance and less air permeability, but in general it is noticed that the behavior of the 95%Viscose fiber made from bamboo plants, 5%Lycra is different that most of the other materials.

4.6.6 Pores ratio

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.6, for analysis of the results, the following equation was obtained:

$$\text{Pores ratio} = 0.78 - 0.01 X - 0.03 Y - 0.005 Y^2 - 0.0047 XY \quad (89)$$

From the R-squared = 99.9515 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0000.From the above equation the factors affecting Pores ratio behavior in 95%Viscose fiber made from bamboo plants, 5%Lycra fabrics can be concluded. It is clear that humidity and the temperature have a negative effect as well as the interaction between the humidity and the temperature but not as the other materials under investigation and as mentioned before it refers to the structure of the material itself. (Figure 4.91) and (Figure 4.92) show the Pores ratio behavior in that fabric.

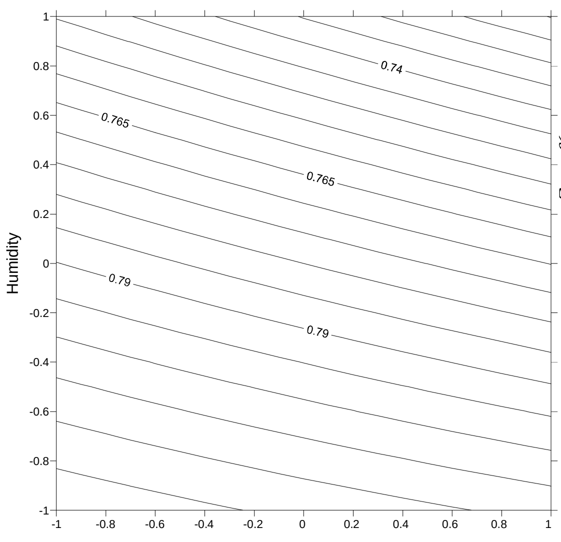


Figure 4.91 Contour lines showing the Pores ratio behavior with in the different climatic conditions.

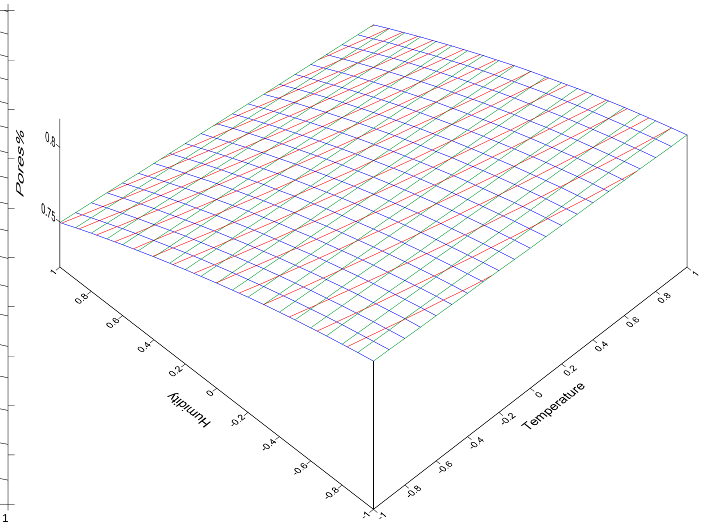


Figure 4.92 The effect of Temperature and Humidity on the Pores ratio.

4.6.7 Water vapor resistance (Ret) (m^2Pa/W)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.6, and the following equation was obtained:

$$Ret = 6.9 + 0.8\ X + 0.6\ Y + 0.3\ Y^2 - 0.32\ XY \qquad (90)$$

From the R-squared = 97.4664 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0019.

From the above equation the factors affecting Ret (m^2Pa/W) behavior in 95%Viscose fiber made from bamboo plants, 5%Lycra fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it causes more resistance to the water vapor and here the effect of the humidity is very obvious, but the resistance here is referring to the higher partial pressure that makes the transfer of the water vapor not easy, as well as the trapped molecules of water and water vapor in the pore structure of the material. (Figure 4.93) and (Figure 4.94) show the Water vapor resistance (m^2Pa/W) behavior in that fabric.

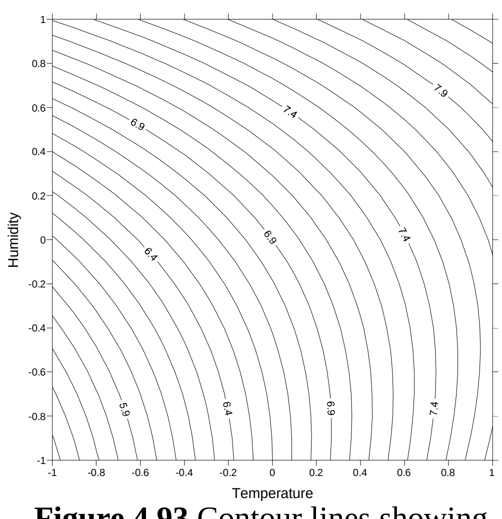


Figure 4.93 Contour lines showing the Ret (m^2Pa/W) behavior with in the different climatic conditions.

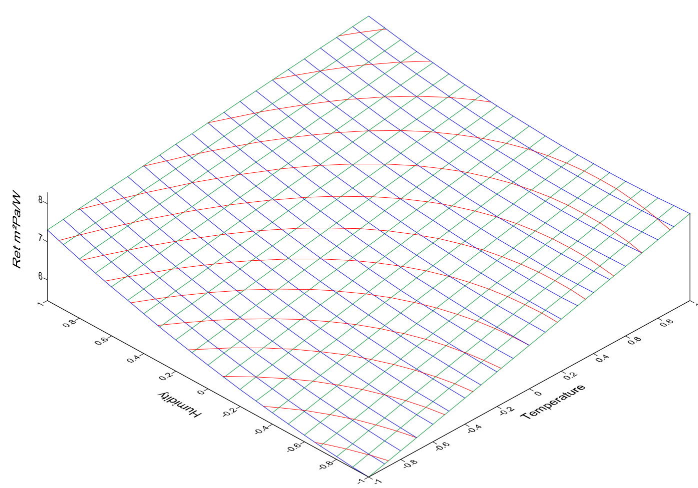


Figure 4.94 The effect of Temperature and Humidity on the Ret (m^2Pa/W).

4.6.8 Water vapor permeability index (I_{mt})

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.6, and the following equation was obtained:

$$I_{mt} = 0.096 - 0.016\ X - 0.013\ Y + 0.005\ XY \qquad (91)$$

From the R-squared = 96.1859 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0006.

From the above equation the factors affecting Water vapor permeability index behavior in 95%Viscose fiber made from bamboo plants, 5%Lycra fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it leads to significant negative change in the water vapor permeability index. (Figure 4.95) and (Figure 4.96) show the water vapor permeability index behavior. The higher the Water vapor permeability index the more comfort is the fabric in such a tropical weather, where the fabrics are preferable to be water vapor permeable, to help the body get rid of the water vapor and the moisture as well, and we can figure out here the effect of the temperature and the humidity on the property.

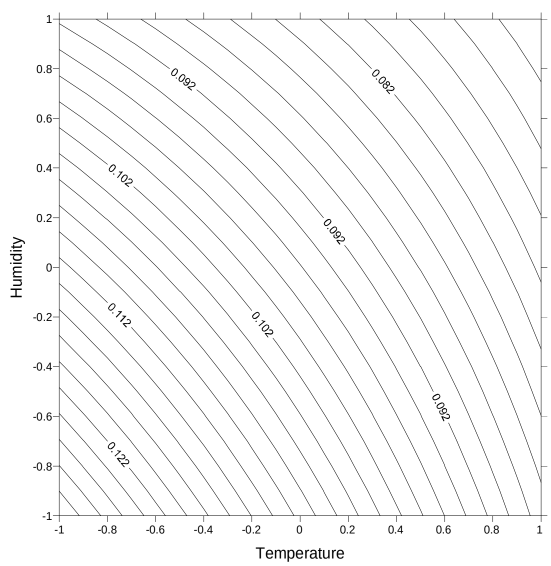


Figure 4.95 Contour lines showing the I_{mt} behavior with in the different climatic conditions.

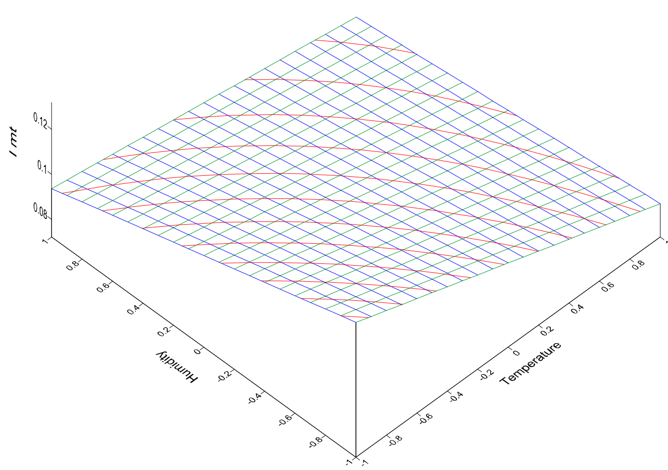


Figure 4.96 The effect of Temperature and Humidity on the water vapor permeability index.

4.7 62%PE Coolmax 32%PE micro 6%Lycra

This fabric under research at this stage is a compound between Polyester micro fibers and Coolmax ones. Coolmax is a trademark for a series of moisture-wicking technical fabrics developed in 1986. The fabrics employ specially-engineered polyester fibers to improve "breathability" compared to natural fibers like cotton. Clothing made from Coolmax is primarily intended to be worn during exertion; sweat can evaporate quickly so the wearer is kept dry [164, 165].The thermal comfort properties of the produced 62%PE Coolmax 32%PE micro 6%Lycra garments were investigated in the different climatic conditions that exist in tropical countries. It is clear from Table 4.7 how the thermophysiological properties for the material under study acts in the different simulated hot weather conditions.

Table 4.7 62%PE Coolmax 32%PE micro 6%Lycra Thermophysiological properties in different weather conditions

Climaic Condition	Effusivity (Ws½/m²K)	K (W/mK)	Rct (m^2Kw^{-1})	Diffusivity (m²/s)	Air permeability m/sec	Pores %	Ret m²Pa/W	I_{mt}
15°C+40%ϕ	110.04	0.054	0.0177	2.40	0.1667	1.30	4.9	0.22
15°C+60%ϕ	114.86	0.056	0.0169	2.41	0.1664	1.25	5.2	0.20
15°C+80%ϕ	116.15	0.058	0.0164	2.52	0.1659	1.20	6.4	0.15
25°C+40%ϕ	118.58	0.056	0.0172	2.20	0.1662	1.29	5.6	0.18
25°C+60%ϕ	119.19	0.059	0.0162	2.44	0.1657	1.24	5.8	0.17
25°C+80%ϕ	122.40	0.060	0.0160	2.37	0.1554	1.18	6.6	0.15
35°C+40%ϕ	120.59	0.059	0.0163	2.36	0.1561	1.28	6.5	0.15
35°C+60%ϕ	123.74	0.059	0.0162	2.27	0.1462	1.24	6.7	0.14
35°C+80%ϕ	125.90	0.062	0.0154	2.42	0.1271	1.15	7.5	0.12

4.7.1 Effusivity (Ws½/m²K)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.7, for analysis of the results, the following equation was obtained:

$$\text{Effusivity} = 120.057 + 4.864\ X + 2.539\ Y - 1.512\ X^2 \qquad (92)$$

From the R-squared = 97.516 percent, it is obvious that the equation represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0002. The factors affecting Effusivity (Ws½/m²K) behavior in the fabrics can be concluded. It is clear that Temperature has the highest positive effect and the humidity has the second highest effect, (Figure 4.97) and (figure 4.98) show the Effusivity (Ws½/m²K) behavior in that fabric. Due to the high temperature and the high humidity, the Effusivity (Ws½/m²K), is getting higher, and we can tell that here is the temperature which has the highest effect, it is obvious how different is the behavior of 62%PE Coolmax 32%PE micro 6%Lycra which was affected by the special yarns structure.

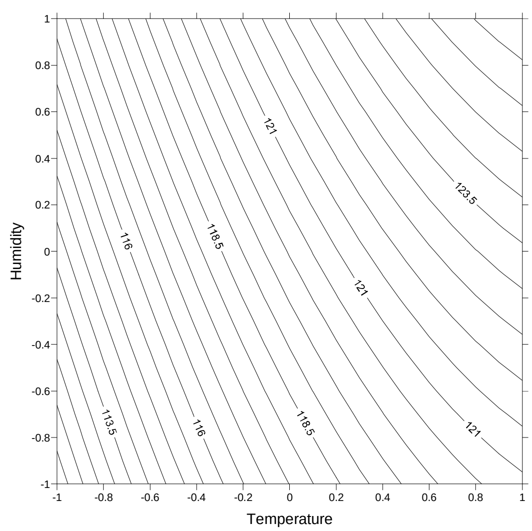


Figure 4.97 Contour lines showing the Effusivity (Ws½/m²K) behavior with in the different climatic conditions.

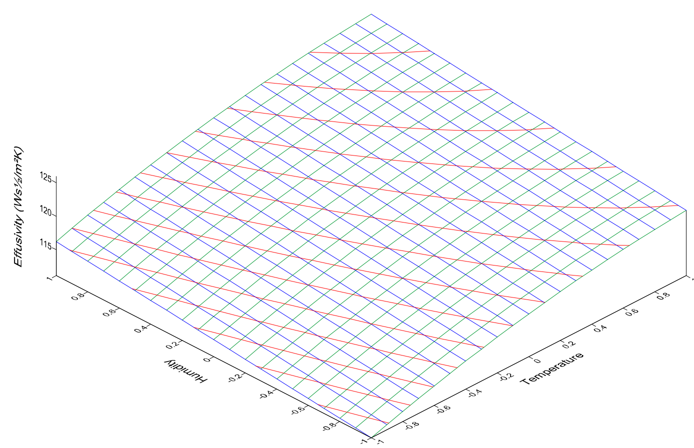


Figure 4.98 The effect of Temperature and Humidity on the Effusivity (Ws½/m²K).

4.7.2 Thermal conductivity (K) (W/mK)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.7, for analysis of the results, the following equation was obtained:

$$K = 0.058 + 0.0018\,X + 0.0019\,Y \qquad (93)$$

From the R-squared = 94.5991 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0002.

From the above equation the factors affecting K (W/mK) behavior in 62%PE Coolmax 32%PE micro 6%Lycra fabrics can be concluded. It is clear that humidity has a positive effect and the temperature has also a positive effect. (Figure 4.99) and (Figure 4.100) show the K (W/mK) behavior in that fabric under study.

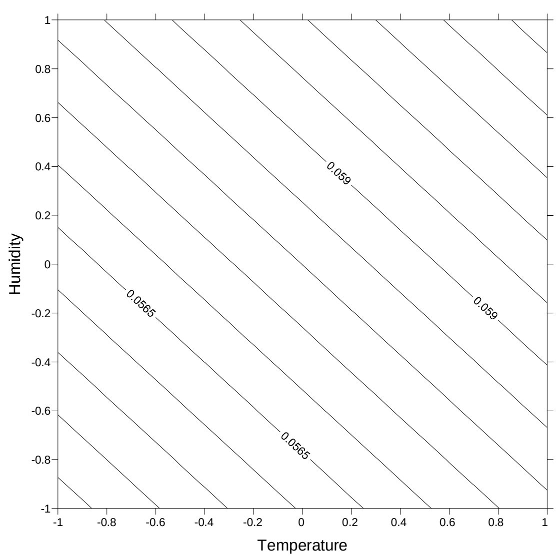


Figure 4.99 Contour lines showing the Thermal conductivity (W/mK) behavior with in the different climatic conditions.

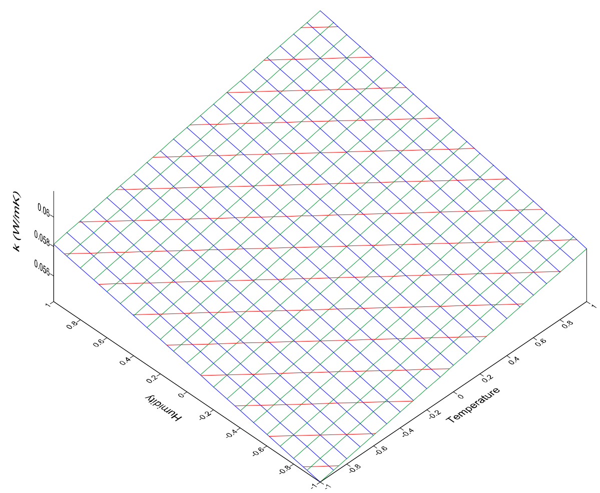


Figure 4.100 The effect of Temperature and Humidity on the Thermal conductivity (W/mK)

By the increase of heat the thermal conductivity increases leading to high heat conductivity but the dominant factor here is the humidity, which when trapped by the fibers it leads to high conductivity mainly because of the water content. As we are stimulating the hot condition we need fabrics that easily release the heat from the body causing the body to feel cooler and the effect of the micro structure and the Coolmax special fibers are clear as we can tell that when the sweat is wicked away from the body through fibers, in addition to the humidity content in the environment it leads to that change in the thermal conductivity.

4.7.3 Thermal resistance (Rct) (m^2Kw^{-1})

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.7, the following equation was obtained:

$$Rct = 0.016 - 0.0005\ X - 0.00056\ Y \quad (94)$$

From the R-squared = 93.9499 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0002.

From the above equation the factors affecting Rct (m^2Kw^{-1}) behavior in 62%PE Coolmax 32%PE micro 6%Lycra fabrics can be concluded. It is clear that both humidity and the temperature have a negative effect with their increase. (Figure 4.101) and (Figure 4.102) show the Thermal resistance (m^2Kw^{-1}) behavior in the fabric under study. And it is noticed that the thermal resistance is affected negatively by the presence of humidity, when the fabric absorbs water, molecules of the water vapor released from the body in addition to the moisture content in the environment as well as from the body, leads to lower thermal resistance (m^2Kw^{-1}).

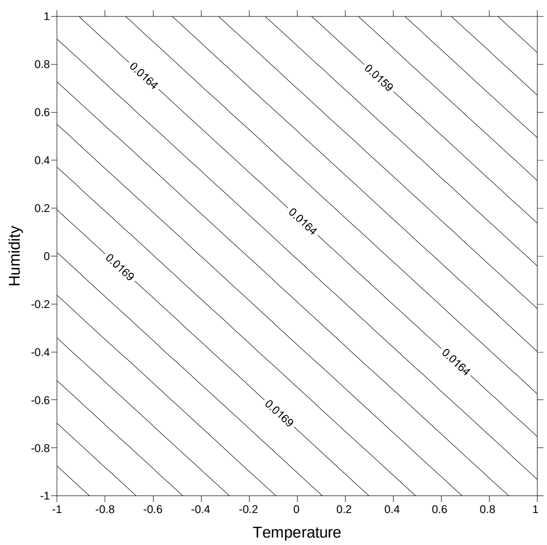


Figure 4.101 Contour lines showing the Rct (m^2Kw^{-1}) behavior with in the different climatic conditions.

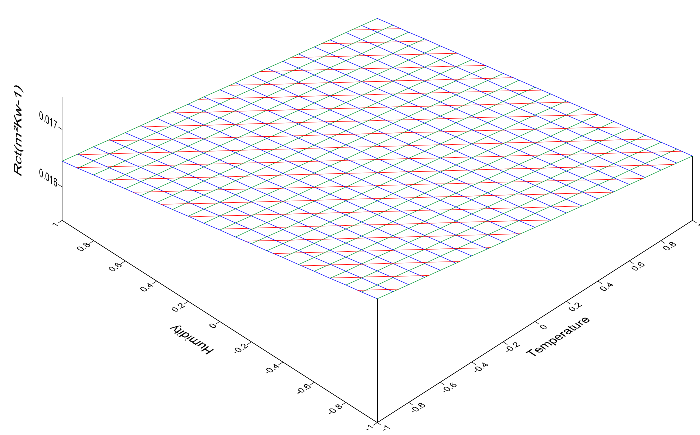


Figure 4.102 The effect of Temperature and Humidity on the Rct (m^2Kw^{-1}).

4.7.4 Diffusivity (m²/s)

The multiple linear regression is being used to analyze the data for the Diffusivity obtained from Table 4.7, for analysis of the results, the following equation was obtained:

$$\text{Diffusivity} = 2.332 - 0.047\,X + 0.058\,Y + 0.063\,X^2 + 0.0019\,Y^2 - 0.0156\,XY \qquad (95)$$

It is concluded from R-squared that the equation represents 60.695 percent of the results model and there isn't a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.5627, the 62%PE Coolmax 32%PE micro 6%Lycra different structure, the water content absorbed and the high temperature caused the change in the thermal Diffusivity (m²/s) behavior of the fabric, (Figure 4.103) and (Figure 4.104) show the Diffusivity (m²/s) behavior in the fabric under study.

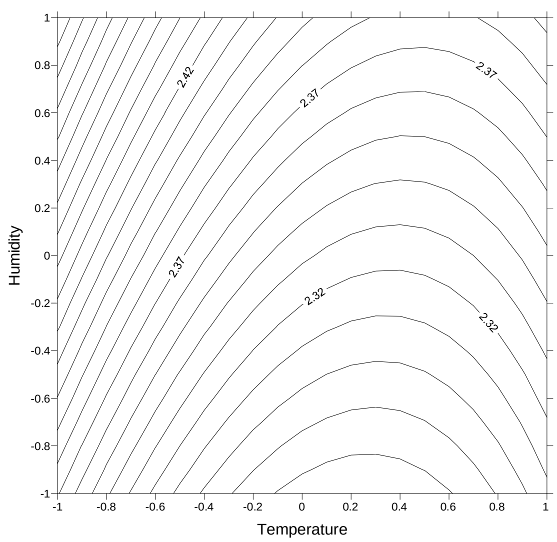


Figure 4.103 Contour lines showing the Diffusivity (m²/s) behavior with in the different climatic conditions.

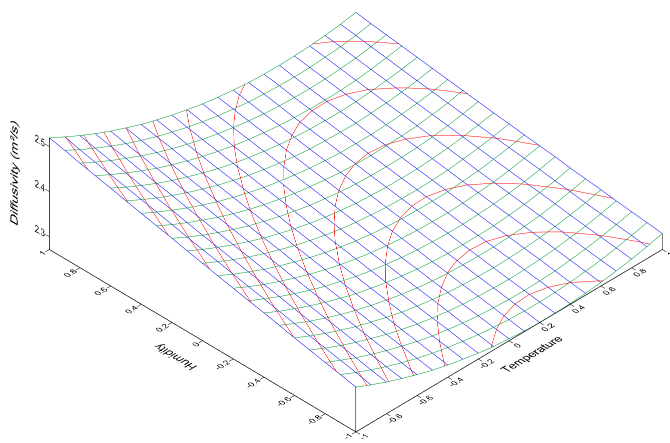


Figure 4.104 The effect of Temperature and Humidity on the Diffusivity (m²/s).

4.7.5 Air permeability (m/sec)

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.7, for analysis of the results, the following equation was obtained:

$$\text{Air permeability} = 0.164 - 0.011\,X - 0.0067\,Y - 0.0077\,X^2 - 0.003\,Y^2 - 0.007\,XY \qquad (96)$$

From the R-squared = = 98.9458 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0036

From the above equation the factors affecting Air permeability (m/sec) behavior in 62%PE Coolmax 32%PE micro 6%Lycra fabrics can be concluded. It is clear that humidity and temperature have negative effect as well as the interaction between the humidity and the temperature. (Figure 4.105) and (Figure 4.106) show the Air permeability (m/sec) behavior in that fabric

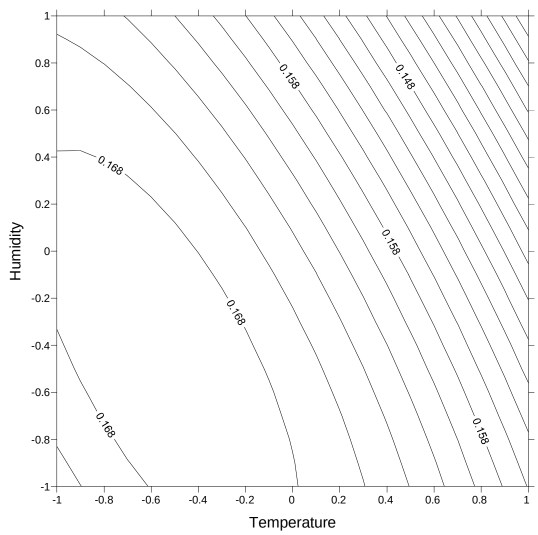


Figure 4.105 Contour lines showing the Air permeability (m/sec) behavior with in the different climatic conditions.

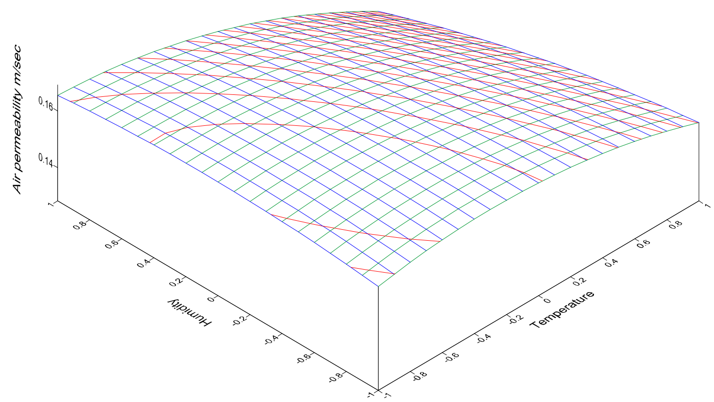


Figure 4.106 The effect of Temperature and Humidity on the Air permeability (m/sec)

Due to the high temperature and the high humidity, the Air permeability (m/sec); which is a dominant factor in water vapor transfer is affected with the increase of humidity, it could be referred to the special structure of Coolmax which when the water and water vapor molecules are trapped within the hollow structure between the yarns, causes more air resistance and less air permeability, but in general it is noticed that the behavior of the 62%PE Coolmax 32%PE micro 6%Lycra is different that cotton fibers which is widely used in that tropical conditions.

4.7.6 Pores ratio

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.7, for analysis of the results, the following equation was obtained:

$$\text{Pores ratio} = 1.243 - 0.0135\,X - 0.056\,Y - 0.011\,Y^2 - 0.0077\,XY \qquad (97)$$

From the R-squared = 98.9987 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0003.

From the above equation the factors affecting Pores ratio behavior in 62%PE Coolmax 32%PE micro 6%Lycra fabrics can be concluded. It is clear that humidity and the temperature have a negative effect as well as the interaction between the humidity and the temperature but not as the other materials under investigation like the cotton ones and as mentioned before it could be referred to the structure of the material itself. (Figure 4.107) and (Figure 4.108) Show the Pores ratio behavior in that fabric.

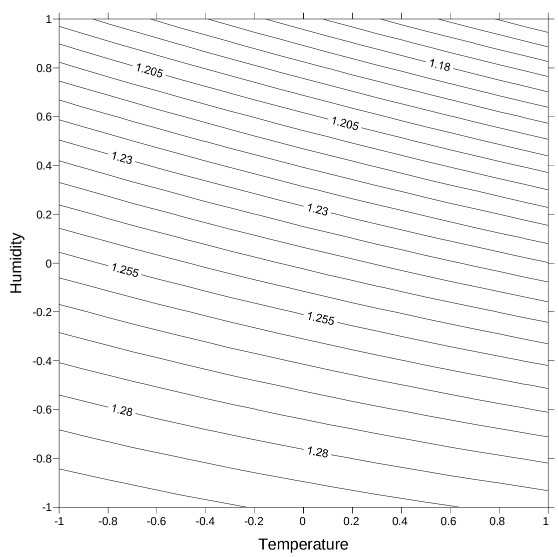


Figure 4.107 Contour lines showing the Pores ratio behavior with in the different climatic conditions.

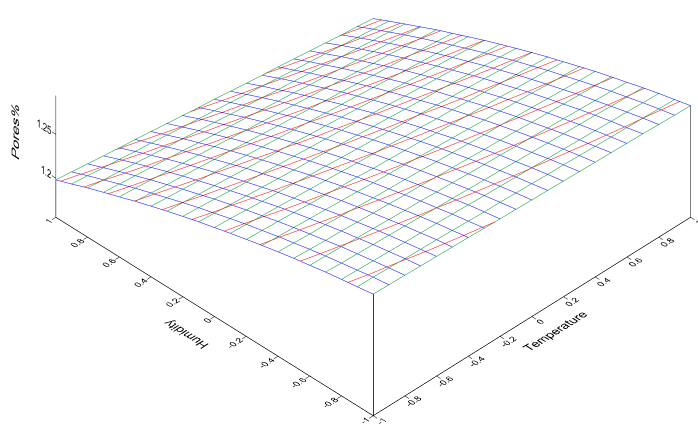


Figure 4.108 The effect of Temperature and Humidity on the Pores ratio.

4.7.7 Water vapor resistance (Ret) (m^2Pa/W)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.7, and the following equation was obtained:

$$Ret = 5.76 + 0.7\,X + 0.58\,Y + 0.2\,X^2 + 0.35\,Y^2 - 0.125\,XY \qquad (98)$$

From the R-squared = 99.429 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0015.

It is clear from the above equation factors that affect Ret (m^2Pa/W) behavior in 62%PE Coolmax 32%PE micro 6%Lycra fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it causes more resistance to the water vapor and here the effect of the temperature is very obvious, but the resistance here is referred to the higher partial water vapor pressure and the high percentage of humidity that makes the transfer of the water vapor not easy, as well as the trapped molecules of water and water vapor in the hollow structure between the fibers in the microstructure of the yarn. (Figure 4.109) and (Figure 4.110) show the Water vapor resistance (m^2Pa/W) behavior in that fabric.

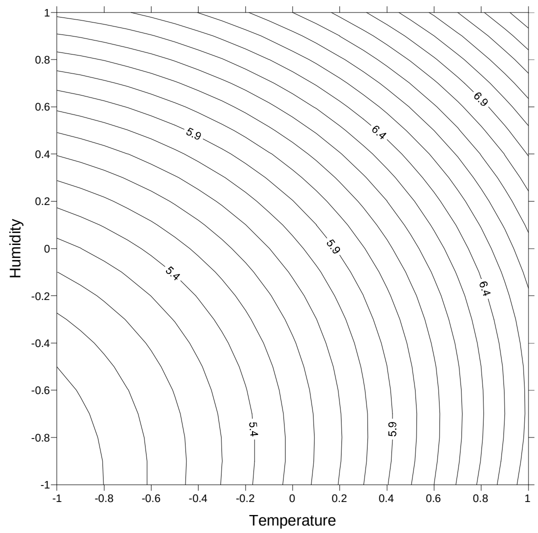


Figure 4.109 Contour lines showing the Ret (m^2Pa/W) behavior with in the different climatic conditions.

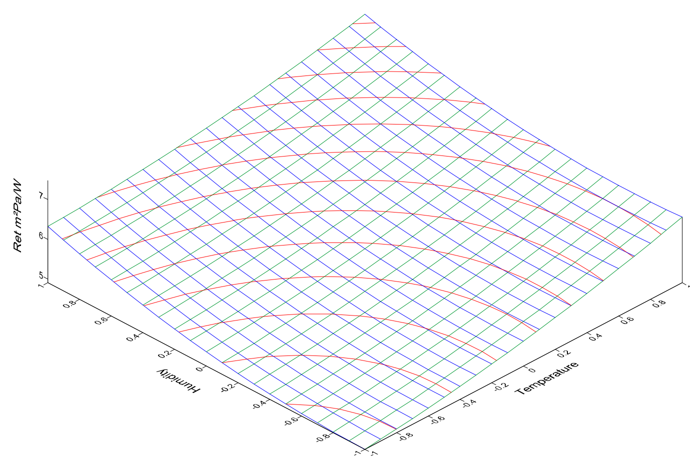


Figure 4.110 The effect of Temperature and Humidity on the Ret (m^2Pa/W).

4.7.8 Water vapor permeability index (I_{mt})

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.7, and the following equation was obtained:

$$I_{mt} = 0.169 - 0.024 X - 0.021 Y - 0.006 Y^2 + 0.009 XY \qquad (99)$$

From the R-squared = 99.398 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0001.

From the above equation the factors affecting Water vapor permeability index behavior in 62%PE Coolmax 32%PE micro 6%Lycra fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it leads to significant negative change in the water vapor permeability index. (Figure 4.111) and (Figure 4.112) show the water vapor permeability index behavior. The higher the Water vapor permeability index the more comfort is the fabric in such a hot weather, where the fabrics are preferable to be water vapor permeable, to help the body get rid of the water vapor and the moisture as well, and we can figure out here the effect of the temperature and the humidity on the Water vapor permeability index (I_{mt}).

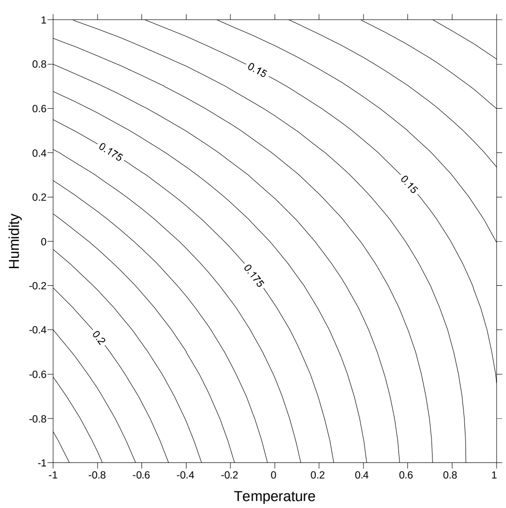


Figure 4.111 Contour lines showing the I_{mt} behavior with in the different climatic conditions.

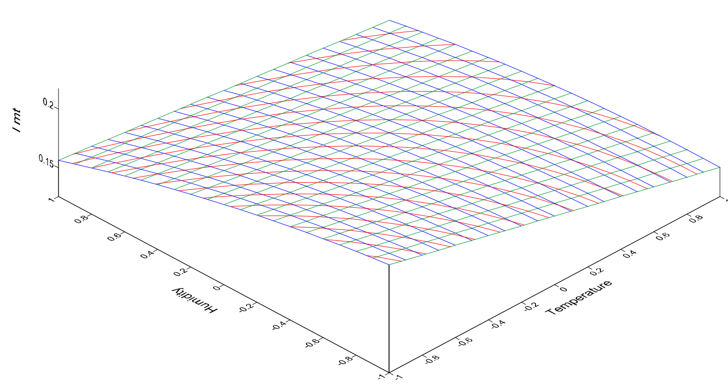


Figure 4.112 The effect of Temperature and Humidity on the water vapor permeability index.

4.8 94%PE 6%Lycra

The thermal comfort properties of the produced 94%PE 6%Lycra garments were investigated in the different climatic conditions that exist in tropical countries. It is clear from Table 4.8 how the thermophysiological properties for the material under study acts in the different simulated hot weather conditions.

Table 4.8 94%PE 6%Lycra Thermophysiological properties in different weather conditions

Climaic Condition	Effusivity (Ws½/m²K)	K (W/mK)	Rct (m^2Kw^{-1})	Diffusivity (m^2/s)	Air permeability m/sec	Pores %	Ret m^2Pa/W	I_{mt}
$15^oC+40\%\phi$	94.87	0.051	0.0201	2.93	0.1533	1.11	5.3	0.23
$15^oC+60\%\phi$	97.41	0.052	0.0198	2.87	0.1533	1.01	5.6	0.21
$15^oC+80\%\phi$	98.71	0.053	0.0194	2.91	0.1526	0.98	6.9	0.17
$25^oC+40\%\phi$	98.65	0.053	0.0194	2.92	0.1522	1.09	6.1	0.19
$25^oC+60\%\phi$	101.07	0.054	0.0191	2.86	0.1511	0.98	6.8	0.17
$25^oC+80\%\phi$	104.09	0.055	0.0188	2.79	0.1413	0.95	7.1	0.16
$35^oC+40\%\phi$	105.55	0.055	0.0186	2.76	0.1424	1.09	6.9	0.16
$35^oC+60\%\phi$	109.00	0.057	0.0181	2.75	0.1226	0.87	7.1	0.15
$35^oC+80\%\phi$	114.61	0.057	0.0180	2.51	0.1112	0.86	7.8	0.14

4.8.1 Effusivity (Ws½/m²K)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.8, and the following equation was obtained using multiple linear regression:

$$\text{Effusivity} = 101.268 + 6.36\ X + 3.055\ Y + 2.09\ X^2 + 1.305\ XY \qquad (100)$$

From the R-squared = 99.545 percent, the equation represents the results, and there is a significant relationship 95.0% confidence level as P value was 0.0001. It is clear from (Figure 4.113) and (figure 4.114) that Temperature and humidity have positive effect.

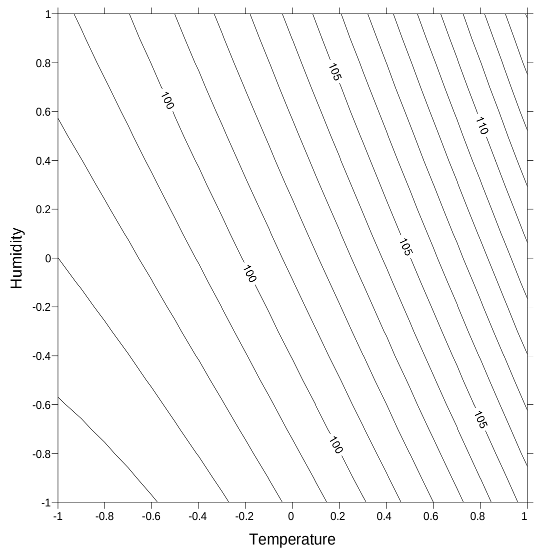


Figure 4.113 Contour lines showing the Effusivity (Ws½/m²K) behavior.

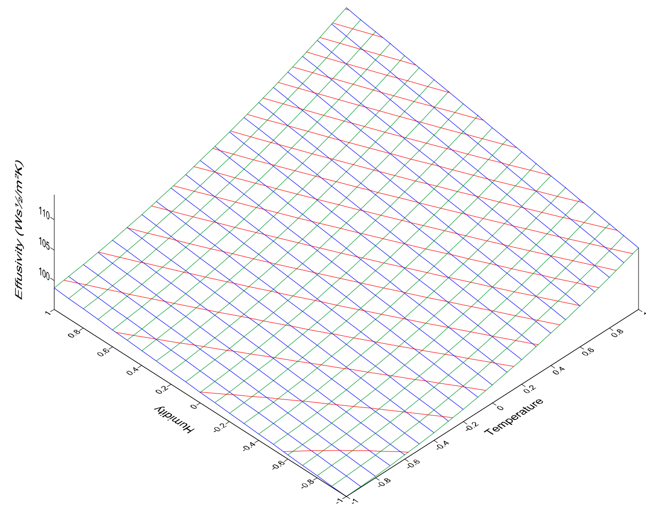


Figure 4.114 The effect of Temperature and Humidity on the Effusivity (Ws½/m²K).

Due to the high temperature and the high humidity, it leads to increasing the Effusivity (Ws½/m²K), and we can tell that here is the temperature which has the highest effect, it is obvious how different is the behavior of 94%PE 6%Lycra ,the difference between this material and the Coolmax is clear when comparing them together.

4.8.2 Thermal conductivity (K) (W/mK)

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.8, for analysis of the results, the following equation was obtained:

$$K = 0.054 + 0.002\,X + 0.0009\,Y \qquad (101)$$

From the R-squared = 98.2913 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0000.

From the above equation the factors affecting K (W/mK) behavior in 94%PE 6%Lycra fabrics can be concluded. It is clear that humidity has a positive effect and the temperature has also a positive one. (Figure 4.115) and (Figure 4.116) show the K (W/mK) behavior in that fabric under study.

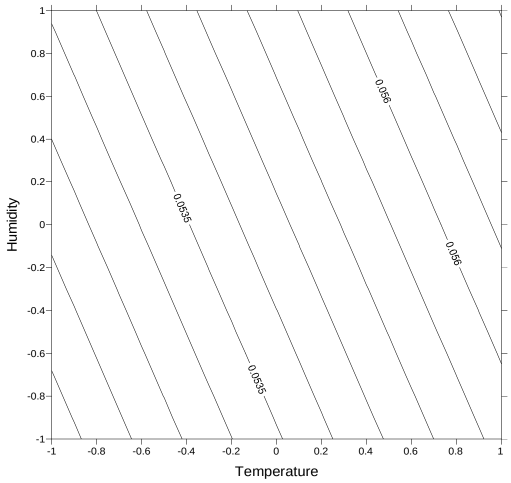


Figure 4.115 Contour lines showing the Thermal conductivity (W/mK) behavior with in the different climatic conditions.

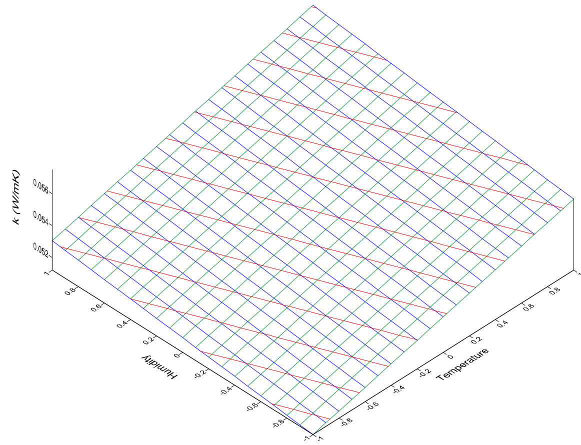


Figure 4.116 The effect of Temperature and Humidity on the Thermal conductivity (W/mK).

By the increase of heat the thermal conductivity increases leading to high heat conductivity but the dominant factor here is the temperature as the normal polyester fibers doesn't absorb humidity that much. As we are stimulating the hot condition we need fabrics that easily release the heat from the body causing the body to feel cooler and more comfortable and at this point we can compare it with the Coolmax and micro fibers and see how the last have more enhanced thermal properties.

4.8.3 Thermal resistance (Rct) (m^2Kw^{-1})

The multiple linear regression is being used to analyze the data obtained from results shown in Table 4.8, the following equation was obtained:

$$Rct = 0.019 - 0.0007\ X - 0.0003\ Y \qquad (102)$$

From the R-squared = 98.691 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0000.

From the above equation the factors affecting Rct (m^2Kw^{-1}) behavior in 94%PE 6%Lycra fabrics can be concluded. It is clear that both humidity and the temperature have a negative effect with their increase. (Figure 4.117) and (Figure 4.118) show the Thermal resistance (m^2Kw^{-1}) behavior in the fabric under study. The difference between the normal polyester and the micro fibers and the Coolmax are clear here, as we can see that the temperature is the dominant factor here since the material doesn't absorb the humidity, which leads to the Rct (m^2Kw^{-1}) change.

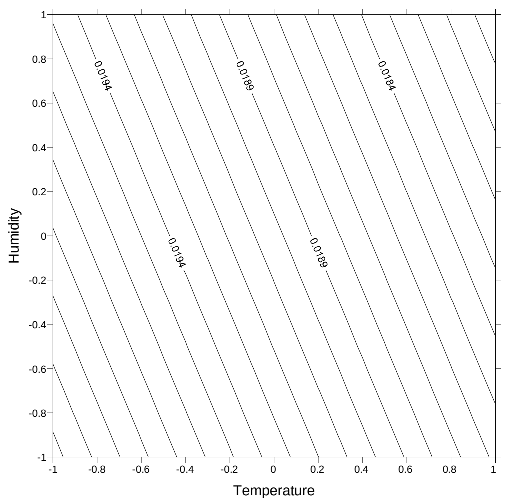


Figure 4.117 Contour lines showing the Rct (m^2Kw^{-1}) behavior.

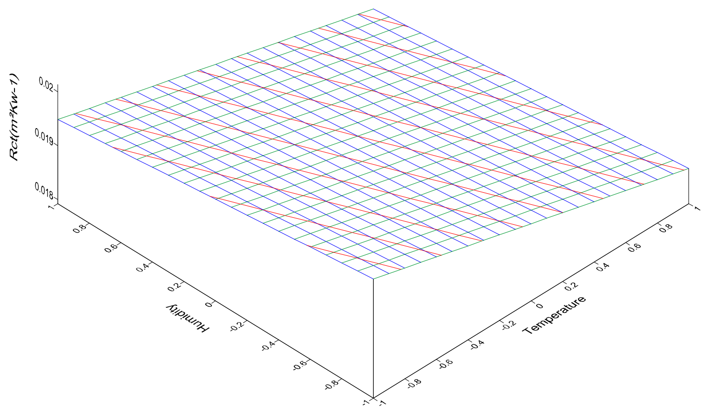


Figure 4.118 The effect of Temperature and Humidity on the Rct (m^2Kw^{-1}).

4.8.4 Diffusivity (m^2/s)

The following equation was obtained:

$$\text{Diffusivity} = 2.812 - 0.112\,X - 0.066\,Y \qquad (103)$$

It is concluded from R-squared that the equation represents 75.0473 percent of the results model and there is a statistically significance as P value was 0.0155, the 94%PE 6%Lycra structure which doesn't absorb water that much and the high temperature caused that change in the thermal Diffusivity (m^2/s) behavior of the fabric than the one made from the micro fibers and the Coolmax which is more moisture management effective. (Figure 4.119) and (Figure 4.120) show the Diffusivity (m^2/s) behavior in the fabric under study.

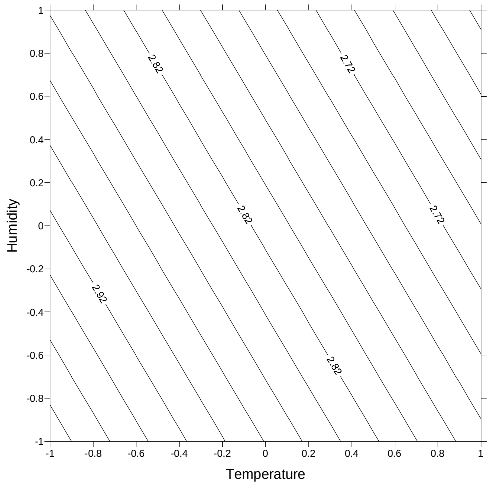


Figure 4.119 Contour lines showing the Diffusivity (m²/s) behavior.

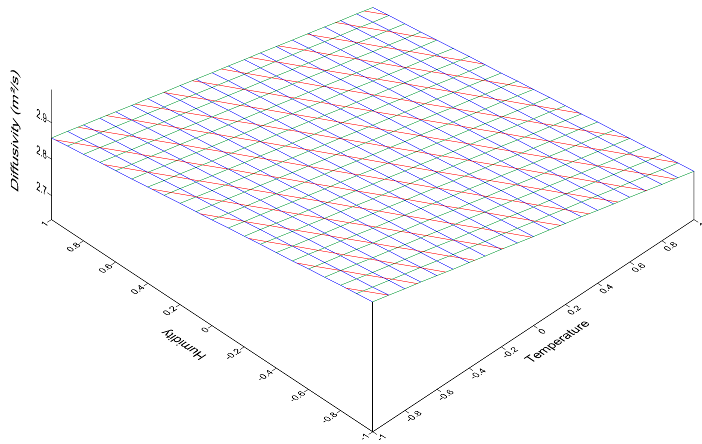


Figure 4.120 The effect of Temperature and Humidity on the Diffusivity (m²/s).

4.8.5 Air permeability (m/sec)

The following equation was obtained using data in Table 4.8 and using the multiple regression:

$$\text{Air permeability} = 0.148 - 0.013\,X - 0.007\,Y - 0.008\,X^2 - 0.007\,XY \qquad (104)$$

From the R-squared 98.2451 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0009. It is clear that humidity, temperature and the interaction between them have negative effect. (Figure 4.121) and (Figure 4.122) show the Air permeability (m/sec) behavior in that fabric. Due to the high temperature and the high humidity, the Air permeability (m/sec); which is a dominant factor in water vapor transfer is affected with the increase of humidity and temperature, and the difference here is clear between normal polyester and the other materials, where in the case of Coolmax the property is enhanced, and in general it is noticed that the behavior of the polyester fibers is different than cotton fibers which are widely used in hot conditions.

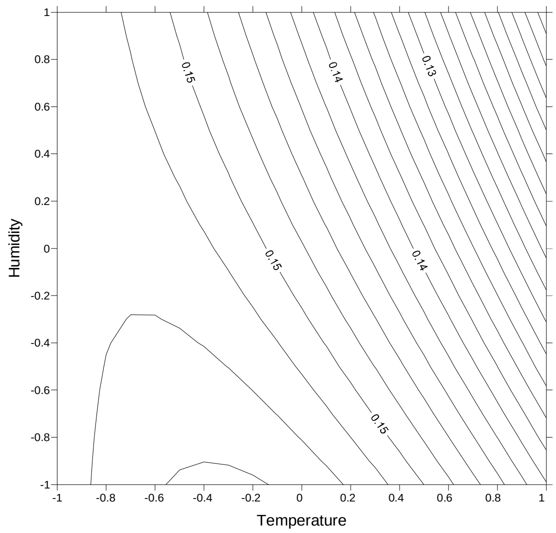


Figure 4.121 Contour lines showing the Air permeability (m/sec) behavior with in the different climatic conditions.

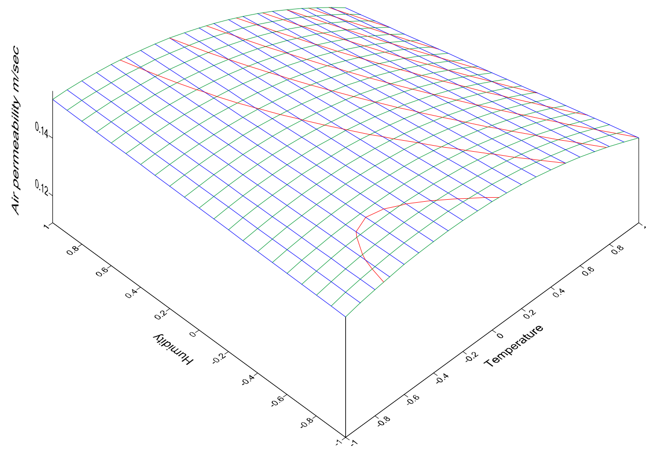


Figure 4.122 The effect of Temperature and Humidity on the Air permeability (m/sec).

4.8.6 Pores ratio

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.8, for analysis of the results, the following equation was obtained:

$$\text{Pores ratio} = 0.953 - 0.047\ X - 0.082\ Y + 0.059\ Y^2 \qquad (105)$$

From the R-squared = 91.6238 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0040.

From the above equation the factors affecting Pores ratio behavior in 94%PE 6%Lycra fabrics can be concluded. It is clear that humidity and the temperature have a negative but not as the other materials under investigation like the cotton ones and as mentioned before it could be referred to the structure of the material itself because it doesn’t absorb that much water even after 48 hours in the climatic condition. (Figure 4.123) and (Figure 4.124) show the Pores ratio behavior in that fabric.

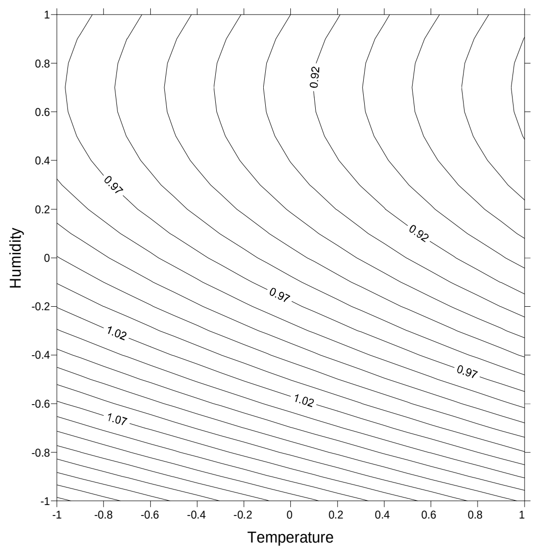


Figure 4.123 Contour lines showing the Pores ratio behavior.

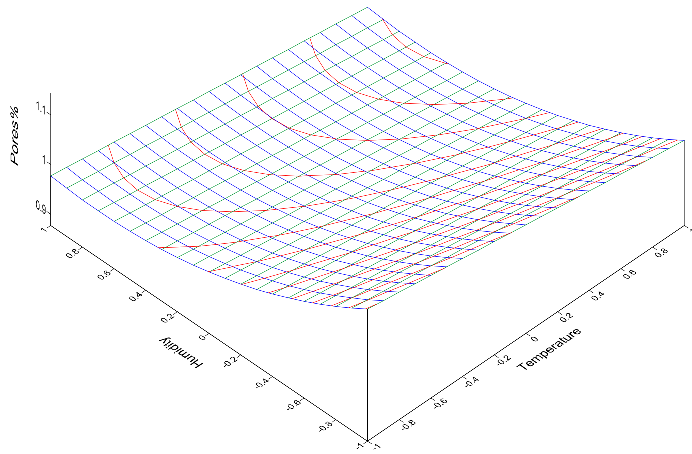


Figure 4.124 The effect of Temperature and Humidity on the Pores ratio.

4.8.7 Water vapor resistance (Ret) (m^2Pa/W)

The following equation was obtained:

$$Ret = 6.622 + 0.666\ X + 0.583\ Y \qquad (106)$$

From the R-squared = 92.4008 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0004. From the above equation the factors affecting Ret (m^2Pa/W) behavior in 94%PE 6%Lycra fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it causes more resistance to the water vapor and here the effect of the temperature is very obvious, but the resistance here is referred to the higher partial water vapor pressure and the high percentage of humidity that makes the transfer of the water vapor not easy. (Figure 4.125) and (Figure 4.126) show the Ret (m^2Pa/W) behavior.

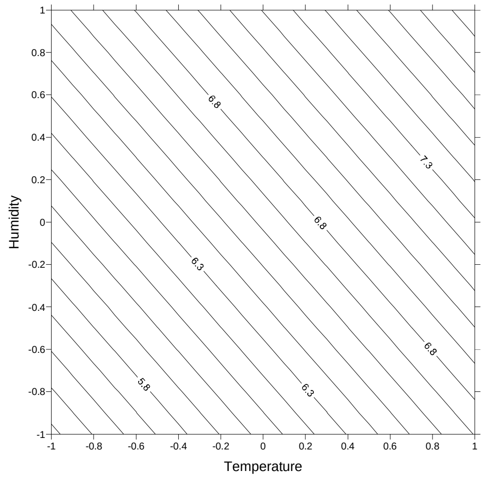


Figure 4.125 Contour lines showing the Ret (m²Pa/W) behavior.

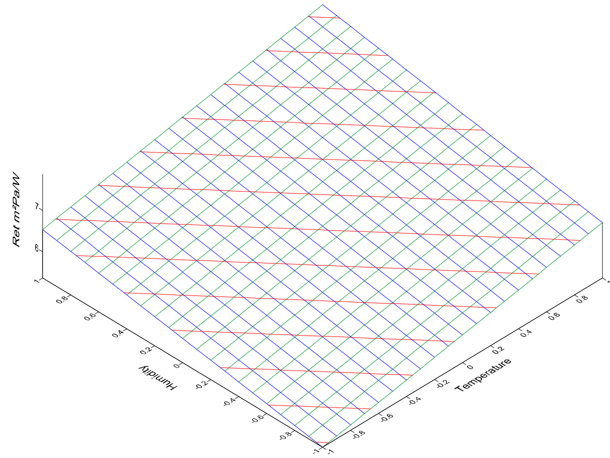


Figure 4.126 The effect of Temperature and Humidity on the Ret (m²Pa/W).

4.8.8 Water vapor permeability index (I_{mt})

The multiple linear regression is being used to analyze the data obtained from the previous results shown in Table 4.8, and the following equation was obtained:

$$Imt = 0.175 - 0.025\,X - 0.019\,Y + 0.0088\,XY \qquad (107)$$

From the R-squared = 96.6519 percent, it is obvious that the equation highly represents the experimental results, and there is a statistically significant relationship between the variables at the 95.0% confidence level since P value was 0.0004.

From the above equation the factors affecting Water vapor permeability index behavior in 94%PE 6%Lycra fabrics can be concluded. It is clear that as the humidity ratio and the temperature degree rise up it leads to significant negative change in the water vapor permeability index. (Figure 4.127) and (Figure 4.128) show the water vapor permeability index behavior. The higher the Water vapor permeability index the more comfort is the fabric in such a hot weather, where the fabrics are preferable to be water vapor permeable and we can figure out here the effect of the temperature and the humidity on the Water vapor permeability index (I_{mt}).

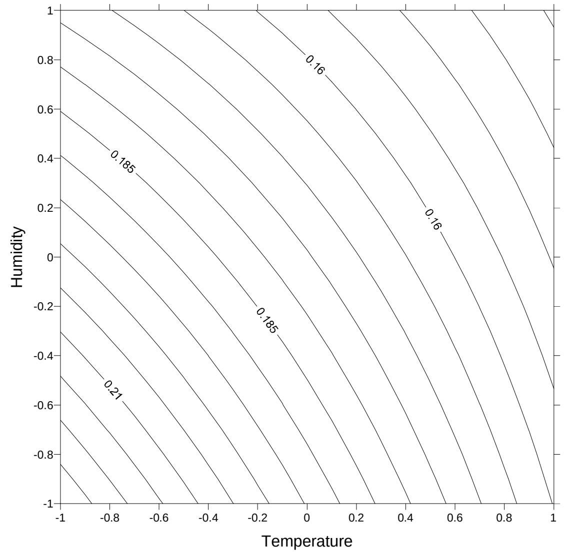


Figure 4.127 Contour lines showing the I_{mt} behavior with in the different climatic conditions.

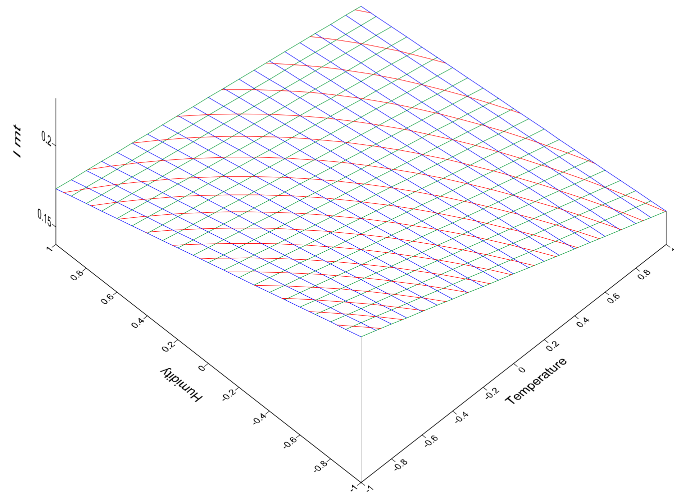


Figure 4.128 The effect of Temperature and Humidity on the water vapor permeability index.

4.9 A comparative study in a selected condition

A comparative study of the tested fabrics was held in 25 ^{o}C with 40% humidity as a neutral condition related to the other conditions and wearer trial have been accomplished, a trial was done by a healthy human being and photos with thermal camera were taken after forty minutes of continuous normal cycling, each of the trials was done in a single day to avoid over heating of the body ,also to make sure that there is no body over temperature involved in the thermal photographing, and to maintain the same body effort level as constant as possible, this was to see which of the fabrics will maintain the best thermoregulation properties compared with the other samples (Figures 4.129- 4.135) show the difference of the thermophysiological properties of the tested garments in the selected condition .

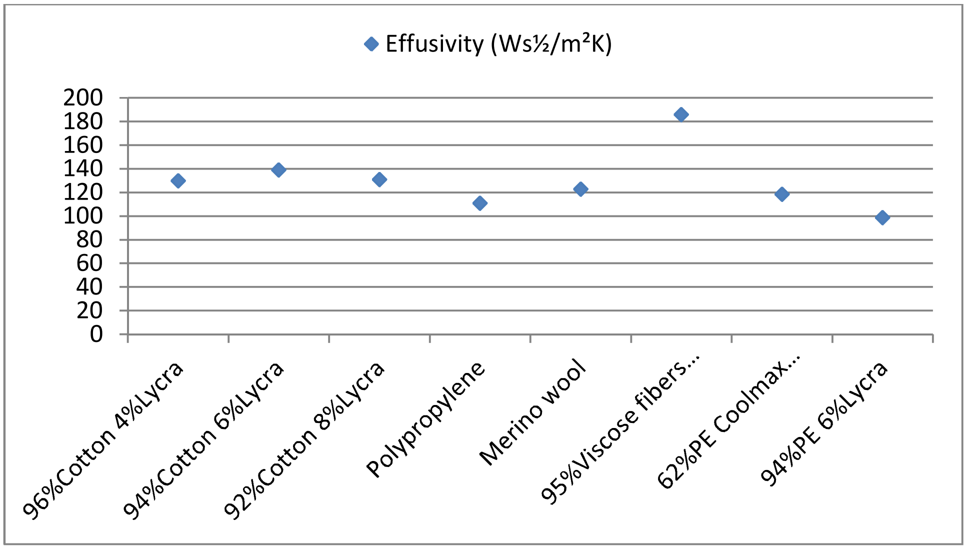


Figure 4.129 The Effusivity (Ws½/m²K) of the tested materials in the selected condition

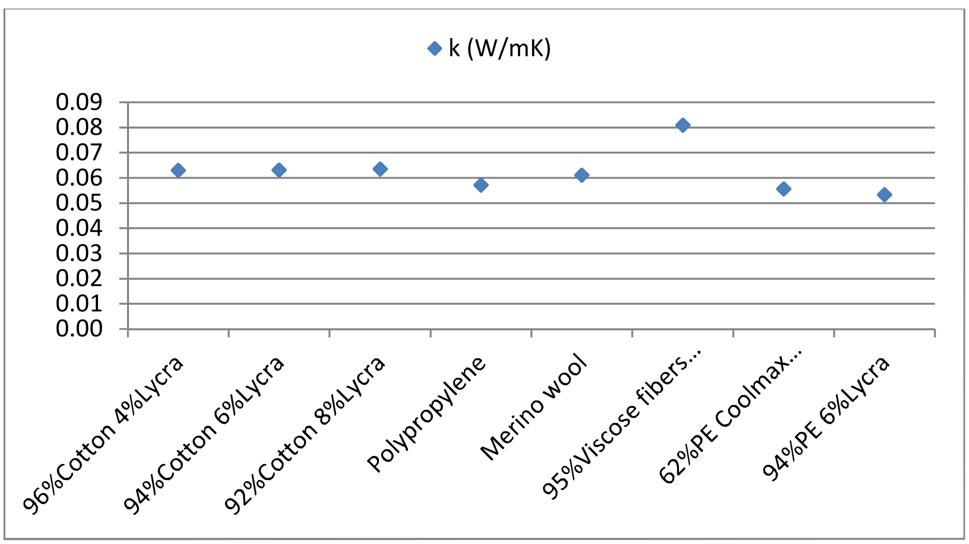


Figure 4.130 The Conductivity (W/mK) of the tested materials in the selected condition

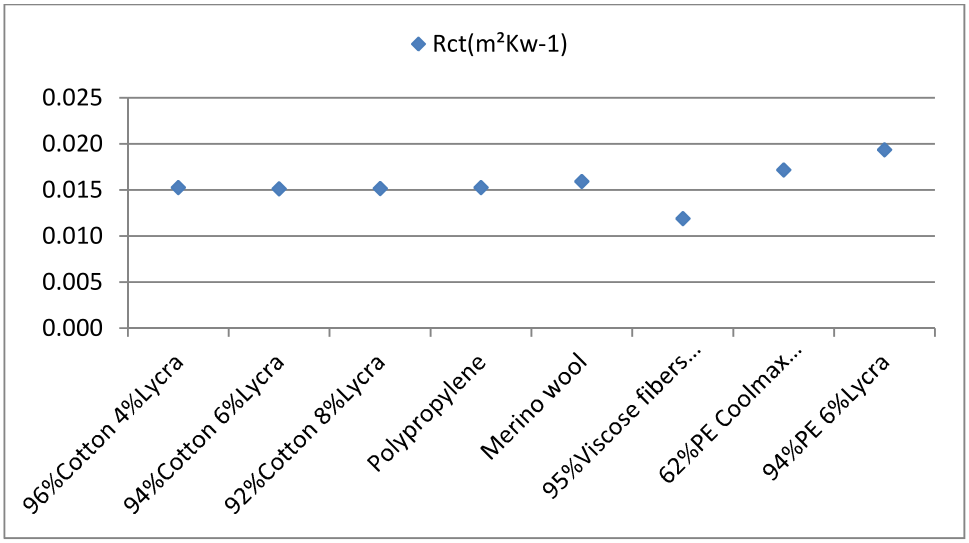


Figure 4.131 Thermal resistance (m^2Kw^{-1}) of the tested materials in the selected condition

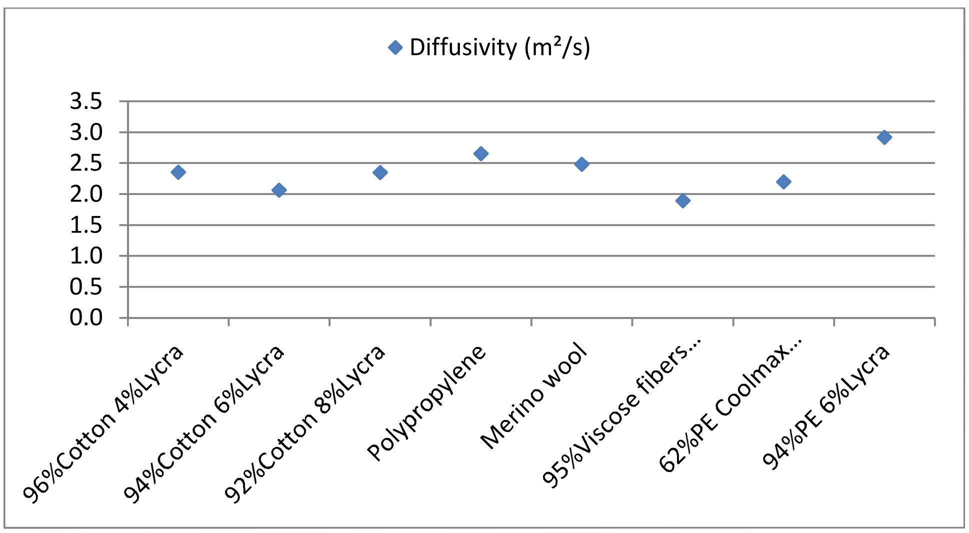


Figure 4.132 Thermal diffusivity (m^2/s) of the tested materials in the selected condition

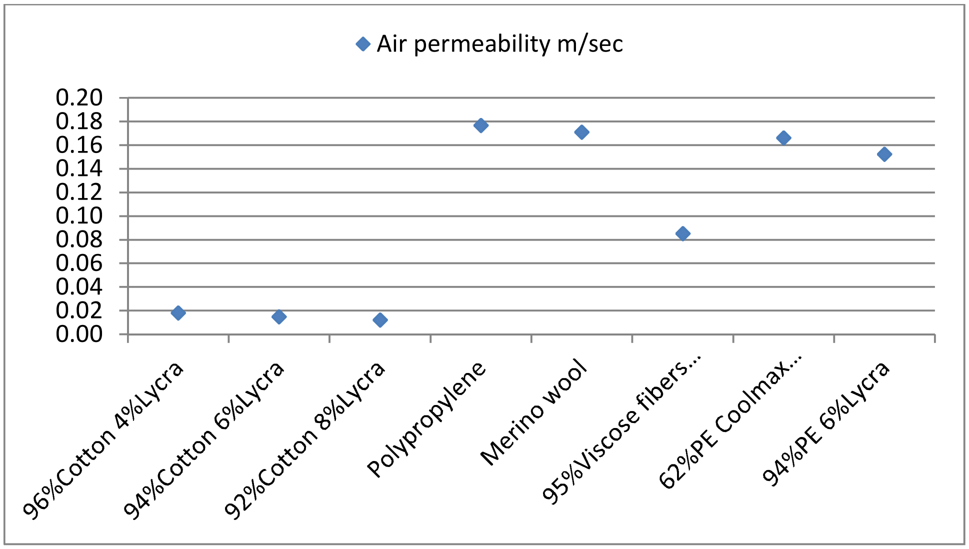


Figure 4.133 Air permeability (m/s) of the tested materials in the selected condition

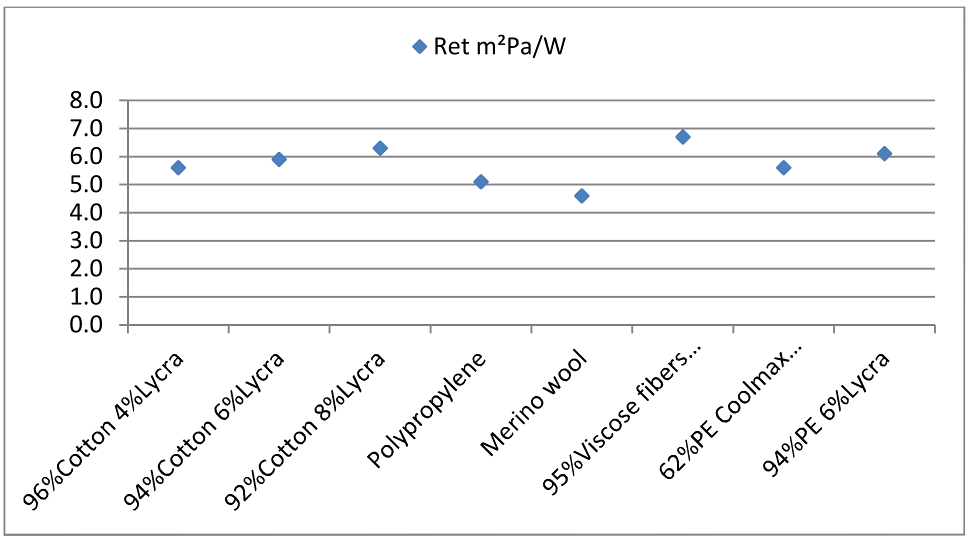


Figure 4.134 Water vapor resistance (m^2Pa/W) of the tested materials in the selected condition

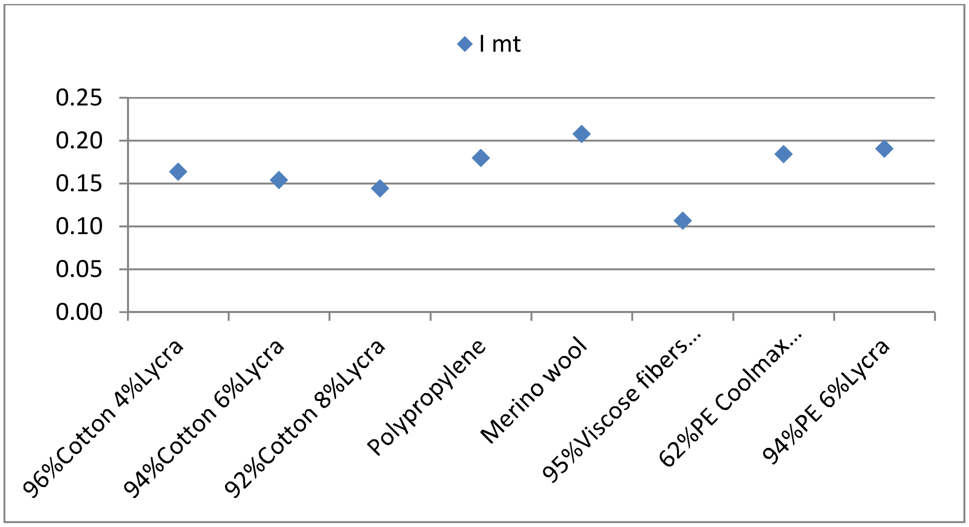


Figure 4.135 Water vapor permeability index for the tested materials in the selected condition

The previous figures show the thermophysiological properties of the tested fabrics, and as we are studying here the hot condition, special properties are recommended, concerning the Effusivity, as mentioned before the lower the Effusivity the warmer the feeling, but here we need the cooler feeling, we can find this feeling is achieved with the 95%Viscose fiber made from bamboo plants, 5%Lycra.

About the conductivity, it is clear that; here as most of the times in that hot condition, the temperature of the environment is much higher that the human being and as the heat normally transfers from regions with higher temperature to others with lower one, it is desired here to have a material with lower heat conductivity so that the heat will not transfer rapidly from the environment through the clothing material to the wearer, and we can see that it is achieved with using 94%PE 6%Lycra, but it is the only property that is achieved with in that material , so it is not desired to use it in the hot condition.

Concerning the thermal resistance, in such a hot condition, insulation is not desired as we need the body to release heat easily if overheated, and we can see that this condition is achieved by using 95%Viscose fiber made from bamboo plants, 5%Lycra, and here we can tell that is the second desired thermophysiologiacl property achieved by using 95%Viscose fiber made from bamboo plants, 5%Lycra.

Material that rapidly adjust its temperature with its surrounding has high thermal Diffusivity, and here it is desired to have a material that doesn't, as it is not desired to wear a material that quickly adjust its temperature with that higher temperature environment , it will cause the body to feel the surrounding heat even without doing any effort yet, and it is clear here also that 95%Viscose fiber made from bamboo plants, 5%Lycra achieves this requirement, which is here the third desired thermophysiological property existing in this material.

Polypropylene achieves only the highest air permeability , but it doesn't achieve any of the other desired thermophysiological properties comparing to the other materials , so it is not desired for use with in that hot condition . Thermal photos (Figure 4.136) show the thermal behavior of the garments after wearer trial in the selected condition.

while Merino wool achieves two of the most significant thermophysiological properties desired for materials used in such a hot condition, which are; the lowest water vapor resistance , and in that case it allows the ease of water vapor transfer in the form of sweat to the outer environment , and the other property is the highest water vapor permeability index, as mentioned before that its value is normally between 0 and 1 , where 0 indicates that the material is water vapor impermeable and 1 indicates that the material have both a thermal resistance and water vapor resistance as an air layer, so here the higher is the better in such hot conditions. While merino wool achieves these two properties, we can find also that these two properties are accepted by using 95%Viscose fiber made from bamboo plants, 5%Lycra.

Cotton is widely used in such hot conditions, although cotton garments provide a good combination of softness and comfort. However, cotton absorbs too much sweat when used in base layer clothing because of its tendency to absorb and retain moisture. When wet, cotton garments cling to the skin, causing discomfort; it also becomes heavy when wet. The slow-to-dry and cold-when-wet characteristics of cotton make this material unsuitable in conditions in which there are high levels of moisture-either perspiration or precipitation.

Moisture handling properties of textiles during intense physical activities have been regarded as major factor in the comfort performance. Actually the comfort perceptions of clothing are influenced by the wetness or dryness of the fabric and thermal feelings resulting from the interactions of fabric moisture and heat transfer related properties. For the garment that is worn next to skin should have, good sweat absorption, sweat releasing property to the atmosphere, and fast drying property for getting more tactile comfort. It has been found that frictional force required for fabric to move against sweating skin (resulting from physical activities, high temperature and humidity of surroundings) is much higher than that for movement against dry skin. Which means, the wet fabric, due to its clinging tendency, will give an additional stress to the wearer.

On the other side, we can see that 95%Viscose fiber made from bamboo plants, 5%Lycra and merino wool which are not commonly used within that conditions, are more comfort concerning the thermal behavior, and they are highly recommended to be used in that tropical condition, especially Bamboo because it is available in such regions and it is also naturally anti-bacterial which is good to wear in that conditions where the human being releases a lot of sweat, which is a good media for bacteria to grow. It is naturally antibacterial, antifungal and anti-static because it has a unique anti-bacteria and bacteriostasis bio-agent named "bamboo kun" which bonds tightly with bamboo cellulose molecules during the normal process of bamboo fiber growth. This feature gets retained in viscose fibers made from bamboo plants fabrics too. Many tests have been conducted whose results show over 70% death rate after bacteria was incubated on bamboo fiber. Tests held by the Japanese Textile Inspection Association shows that, even after fifty washes, bamboo fabric still possessed these properties. It makes bamboo fabrics healthier, germ free and odor free. It is also UV protective and we can tell how important is this when it comes to that hot condition with long time of exposure to sun during long summer days, it is also green and biodegradable which means that it is safe to get rid of it without having any effect on the environment[160-162,166] . It is also breathable , cool, strong, flexible, soft and has a luxurious shiny appearance as mentioned before when discussing the bamboo fiber properties, we can tell it is good to use viscose fiber made from bamboo plants instead of cotton, not only because of its advantages but also may be because the cotton is good in absorbing sweat and humidity, but it is not that good when it comes to loosing that humidity , and in the same time that humidity when absorbed by the fibers causes the fibers to swell , leading to less air permeability , which is also a dominant factor in releasing the water vapor from the skin to the environment, also this humidity causes unpleasant feeling when wearing as it sticks to the body , leading to less comfort to the wearer.

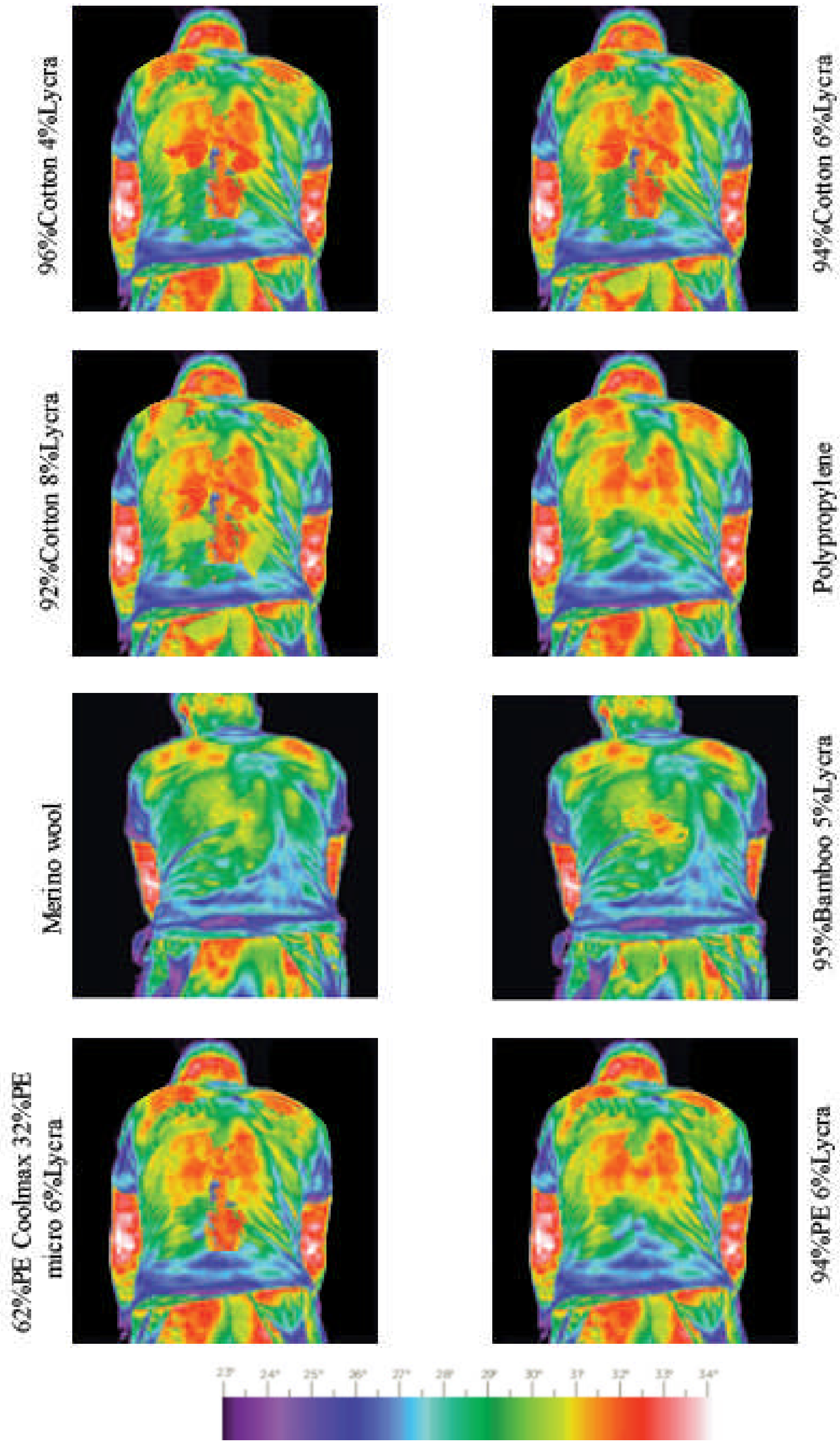


Figure 4.136 Thermal photos showing the thermal behavior of the garments after wearer trial in the selected condition

Evaluation of physiological Index of Comfort IC is a complex combination of individual fabrics properties connected with physiological comfort [167]. Thermal comfort is generally connected with sensations of hot, cold or dampness in clothes and is usually associated with environmental factors, such as moisture transport, thermal conductivity and air permeability. Here all the dominant factors that affect the thermophysiological properties are combined together to create a unique comfort code.

The procedure for evaluation physiological Index of Comfort IC starts with specification of K properties R_1 ,...,R_K characterizing comfort (e.g. thermal resistivity, air permeability, areal weight).

Based on the direct or indirect measurements it is possible to obtain some comfort characteristics x_1,...,x_k. These characteristics represent comfort properties. Functional transformation of these characteristics leads to partial comfort functions.

$$U_i = f(x_i ,L ,H) \qquad (108)$$

Where L is value of characteristic for just non acceptable value (smallest U_i usually = 0) and H is value of characteristic for just fully acceptable product (U_i equal to highest value = 1). Physiological Index of Comfort IC is weighted average of U_i with weights bi

$$IC = ave (ui ,bi) \qquad (109)$$

Weight bi corresponds to the importance of given comfort property [167]. The weighted geometric mean used as average has following advantages:

• For zero value of U_i is also IC = 0. This means that non acceptable comfort property cannot be replaced by combinations of other comfort properties.

• Geometric mean is for not constant U_i always lower that arithmetic mean. This reflects evaluation based on the concept that the values of comfort properties close to unsatisfactory fabric are more important for expressing the IC than those close to optimum fabric.

For the case of thermophysiological comfort, selected properties and weights were extracted from properties characterizing utility value of clothing [168]. For practical expression of IC it is sufficient to replace standardization and nonlinear transformation to the partial comfort functions by the piecewise linear transformation [167].

For one side bounded properties the partial comfort function is monotone increasing or decreasing function of quality characteristic x The piecewise linear transformation of partial comfort function is here composed from three pieces (two are constant and the linearly increasing or decreasing dependence is placed between them).

For two side bounded comfort properties is partial comfort function monotone decreasing on both sides from optimal (constant) region and the piecewise linear transformation has form shown in the (Figure 4.137).

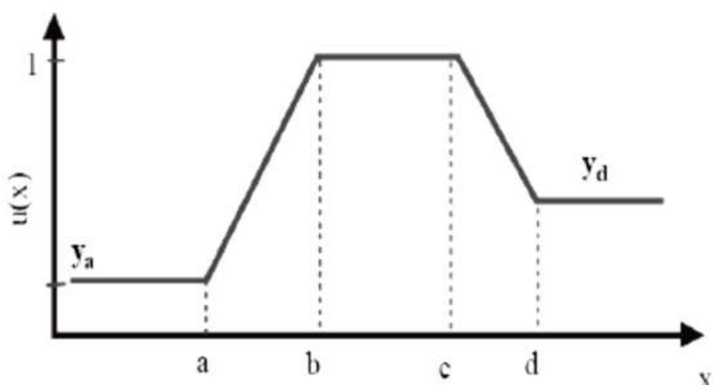


Figure 4.137 Transformation into to partial comfort functions

Physiological Index of Comfort IC is then weighted geometrical average simply calculated from the relation [167]:

$$IC = \exp(\sum_{j=1}^{k} b_j \ln(u_j)) \qquad (110)$$

Where a, b, c, d and b_j were previously calculated and experimentally concluded [167], and the value of u_j was calculated from (figure 4.137), when forming the aggregating function IC from experimentally determined values of individual comfort properties, the statistical character of the x_j quantities can be considered and the corresponding variance can be determined as well [169], (Figure 4.138) shows the index of comfort for the tested materials used in the selected tropical condition and it clearly explains the previous concluded results.

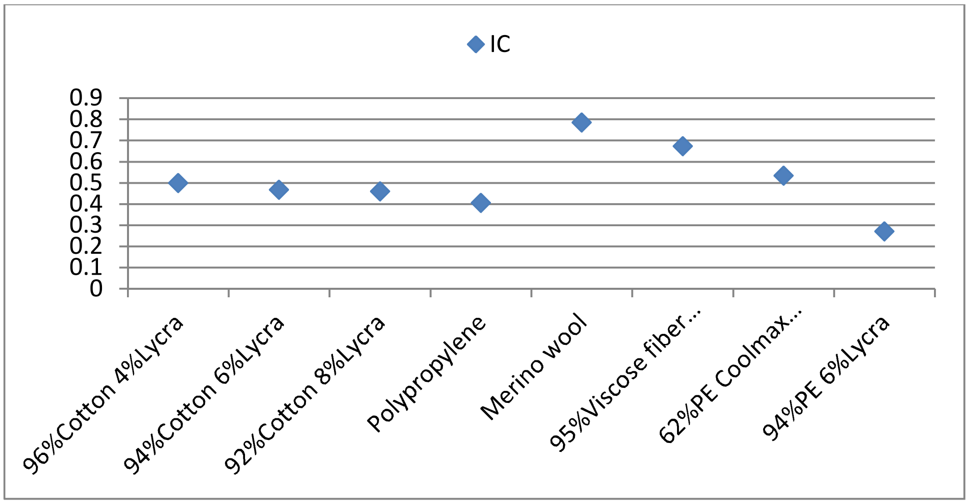


Figure 4.138 Index of comfort for the tested materials used in the selected tropical condition

CHAPTER V

THEORETICAL BACKGROUND AND ANALYSIS

Knitted fabrics are the preferred structures in many wear in which demand for comfort is a key requirement. Comfort is the perceived psychological feeling of a wearer under current conditions of the physical activities and the environment. Knitted fabrics are known for their excellent comfort properties. They possess high extensibility under low load allowing comfortable fit on any part it is pulled onto [170]. As clothing is directly in contact with the human body, it interacts with the skin continuously and dynamically during wear, triggering tactile, thermal and moisture related sensations. The process of transferring heat and moisture in the clothing determines the state of thermo-physiological comfort of the wearer [171]. To achieve the ideal comfort level, heat and sweat generation must be transported out and dissipated to the atmosphere. Porosity is one of the key properties influencing such behavior. While models exist for characterizing pore size and volume in woven and nonwoven materials [172], we are trying here to investigate water vapor transfer through pore spaces in the materials under study.

5.1 Pore Size Model

5.1.1. Plain Weft Knitted Structure

The model uses the knitted fabric structural parameters such as the courses per unit length, wales per unit length, stitch length and stitch density [173]. The basic element of a knit fabric structure is the loop intermeshed with the loops adjacent to it on both sides and above and below it. Loop length is the fundamental unit of weft knitted structure. The structure of a plain weft knitted fabric is given in (Figure 5.1) W and C represent the wales spacing and course spacing whereas w and c correspond to the number of wales per cm and number of courses per cm respectively.

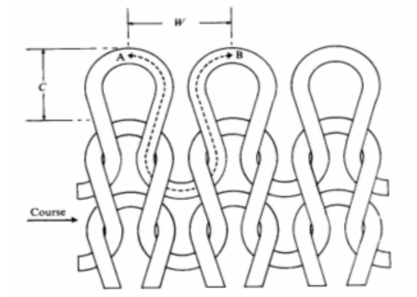


Figure 5.1 The structure of a plain weft knitted fabric

The prediction model only characterized a pore within the loop (Figure 5.2), which is the unit cell of a plain knitted structure.

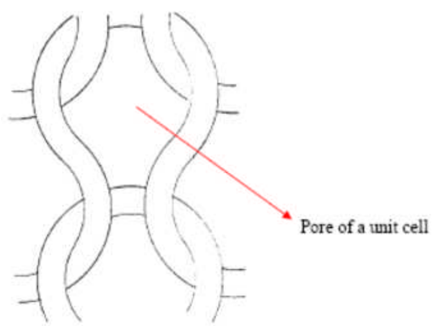


Figure 5.2 Pore space within one loop of a plain weft knitted fabric

The model characterized the pores within the yarn in one loop and was applied respectively on all loops existed. The loops are assumed to be composed of ideal yarns, which are circular in cross-section and have a constant diameter throughout their length so yarn deformation at crossover points is usually neglected.

In the past, researchers proposed models to characterize the loop of a knitted fabric. One of the first models in this area was proposed by Peirce in 1947 [174]. In his approach, the structure of a knitted fabric is reduced to a simple form in which the yarn axis follows a path composed of circular arcs and straight lines, on cylindrical surfaces following the direction of a course (Figure 5.3). He then flattened out the cylinders to a plane and considered the geometry of this planed loop structure in the development of his equations.

A formula was developed for the length of the stitch as a function of the wales and courses count, and the yarn size, Peirce defined the stitch (loop) length as follows [174]:

$$l = 2 / c + 1 / w + 5.94d \qquad (111)$$

Where;

l = length of yarn in one loop (cm)

c = number of courses per cm

w = number of wales per cm

d = diameter of the yarn (cm)

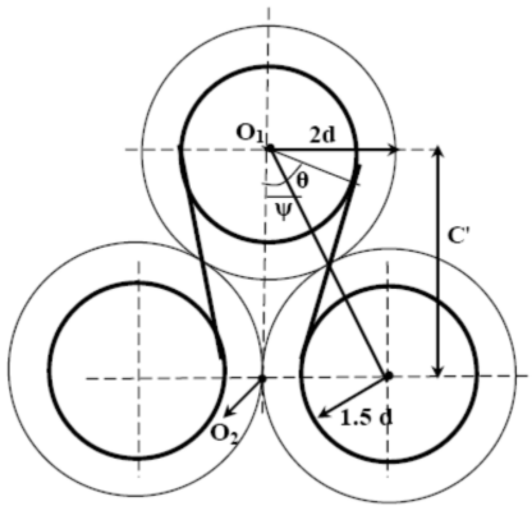


Figure 5.3 The path of the central axis of the yarn

S, the number of stitches/ cm^2 of fabric or stitch density is defined as follows:

$$S = c \times w \quad (112)$$

Assuming the yarn to be a cylinder (Figure 5.4), the volume of yarn in 1 cm^2 of fabric can be shown to be as follows:

$$\text{Volume of yarn in } 1\ cm^2 = S\, l\, \pi\, R^2 \quad (113)$$

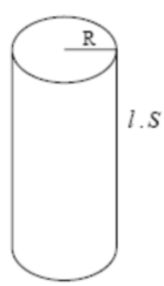


Figure 5.4 Assumed cylindrical shape of the yarn

The volume of fabric in 1 cm^2 is as follows:

Volume of fabric (cm^3) in 1 cm^2 area = fabric area (cm^2) x thickness of the fabric (cm)

The volume of free space in 1cm^2 of fabric is:

Volume of space (cm^3) in 1 cm^2 fabric area = Volume (cm^3) of fabric in 1 cm^2 area – volume of yarn (cm^3) in 1 cm^2 fabric

This is expressed as follows:

Volume of free space (cm^3), inter-yarn, in 1 cm^2 fabric = $1 x 1 x\ h - S\, l\, \pi\, R^2$

So we can tell that the volume of free space (cm^3), inter-yarn, in 1 cm^2 fabric = $h - S\, l\, \pi\, R^2$

Where h is the fabric thickness.

From this the area of free space in 1cm^2 can be calculated as follows:

$$\text{Area of free space } (cm^2) \text{ in} 1cm^2 \text{ fabric} = \frac{h - S\, l\, \pi\, R^2}{h} \qquad (114)$$

Since S is the number of stitches in 1 cm^2, the area of open space within one loop can be given as follows:

$$\text{Area of open space within one loop} = \frac{h - S\, l\, \pi\, R^2}{h\, S} \qquad (115)$$

The pores in a fabric are not circular. However, if the area occupied by a pore is transformed to that of a circle, pore radius can be estimated by:

$$\text{Pore radius} = \sqrt{\frac{h - S\, l\, \pi\, R^2}{\pi\, h\, S}} \qquad (116)$$

As indicated we can tell that as yarn diameter increases pore size values decreases. This equation can be used in calculation of pore size existed with in the fabrics.

The linear density (tex) of a yarn can be given as follows:

$$T = \frac{\pi d^2}{4}\, \rho_y 10^5 \qquad (117)$$

Where T is the yarn linear density (tex), d is the yarn diameter (cm) and ρ_y (g/cc) is the yarn density. Peirce used a value of 0.909 (g/cc) for ρ_y for cotton yarn [174].

From the previous equation, yarn diameter, d, can be shown to be as follows:

$$d = \sqrt{\frac{4\,T}{\pi\,\rho_y\,10^5}} \tag{118}$$

Or yarn radius (R) :

$$R = \sqrt{\frac{T}{\pi\,\rho_y\,10^5}} \tag{119}$$

When Equation (119) is substituted in Equation (116) pore radius can be shown to be as follows:

$$\text{Pore radius} = \sqrt{\frac{t\,\rho_y\,10^5 - S\,l\,T}{\rho_y\,10^5 \pi\,t\,S}} \tag{120}$$

The proposed theoretical model considered one repeating unit cell of a knitted structure. By determining the course (c) per cm, wale (w) per cm, thickness (h), yarn diameter (dy) and loop length (l), the porosity (ε) can be shown as [175]:

$$\varepsilon = 1 - \frac{\text{Yarn volume}}{\text{Total volume}} \tag{121}$$

$$\text{Yarn volume} = \frac{\pi\,d_y^2\,2l}{4} = \frac{\pi\,d_y^2\,l}{2} \tag{122}$$

$$\text{Total volume} = \frac{1}{c}\frac{1}{w}h = \frac{h}{cw} \tag{123}$$

Finally:

$$\varepsilon = 1 - \frac{\pi\,d_y^2\,lcw}{2h} \tag{124}$$

5.2 Measurement of Yarn Diameter

In order to come closer to the real geometric configuration of the stitch, the parameters of the mathematical functions were obtained from image processing of existing knitted loops. The yarn diameter was measured using the previous discussed method [159]. Twenty-five measurements were taken on each sample. The system consists of microscope, monitor and image processing system. The image analysis system was calibrated using special calibration graphs, the image of the fabric was displayed on a monitor. The fabric was placed under the microscope and it was adjusted to display the portion of the yarn on which the diameter measurements were to be carried out. The diameter of that portion of the yarn was read directly from the calibrated scale on the screen. This was done on several loops from different locations on each fabric to assure that we got the average reading which refers to the sample. The materials were left for 48 hours in the different climatic conditions to be sure that they were totally acclimatized then the microscopic photos were taken and the diameter was measured.

5.3 Water vapor diffusion through fabrics

Water vapor permeability is the ability to transmit vapor from the body. The ability of clothing to transport water vapor is an important determinant of physiological comfort [176, 177]. Sweat should be removed from the surface of skin to that of the fabric of the next-to-skin clothing. After the body has stopped sweating, the textile fabric should release the vapor held in the atmosphere in order to reduce the humidity on the surface of the skin. Air permeability is often used in evaluating and comparing the 'breathability' of various fabrics (coated and uncoated) for such end uses as raincoats, tents and uniform shirting. It helps evaluate the performance of parachutes sails, vacuum cleaners, air bags, sail cloth and industrial filter fabrics, and it is also a dominant factor in the process of water vapor transfer.

Due to the manner in which yarns and fabrics are constructed, a large proportion of the total volume occupied by a fabric is usually airspace. The distribution of this airspace influences a number of important fabric properties such as warmth and protection against wind and rain in clothing, and the efficiency of filtration in industrial cloths as well as the water vapor transfer, where it is an important factor in the comfort of a fabric as it plays a role in transporting moisture vapor from the skin to the outside atmosphere. The assumption is that vapor travels mainly through fabric spaces by diffusion in air from one side of the fabric to the other.

The porosity of a knitted structure will influence its physical properties, such as the bulk density, moisture absorbency, mass transfer, thermal conductivity and water vapor permeability. Vapor diffusion through textiles is mainly affected by the pore characteristics of fabrics. It is quite clear that pore dimension and distribution is a function of fabric geometry. The yarn diameter, surface formation techniques and the number of loop counts per unit area are the main factors affecting the porosity of textiles. The porosity of a fabric is connected with certain of its important features, such as air permeability, water vapor permeability, dyeing properties etc.

Establishing a more complex theory to express water vapor permeability related to all fabric parameters will have difficulties. To simplify the matter, certain important parameters such as the pore of the fabric were taken into account in the calculation of water vapor permeability [173]. Three factors are mainly considered that are related to the pores in fabrics.

1) Cross-sectional area of each pore,

2) Depth of each pore or the thickness of the fabric and

3) The number of pores per unit area or the number of courses and wales per unit area.

When considering water vapor diffusion through textiles, the shape arrangement and size distribution of voids through which the vapor diffuse are of great importance. The fabric thickness and differential pressure between the two surfaces of a fabric are the other dominant factors that affect water vapor permeability.

In the diffusion process, the vapor pressure gradient acts as a driving force in the transmission of moisture from one side of a textile layer to the other. The relation between the flux of the diffusing substance and the concentration gradient was first postulated by Fick [53].

$$J_{Ax} = D \frac{dC_A}{dx} \tag{125}$$

Where, J_{Ax} is the rate of moisture flux; $\frac{dC_A}{dx}$ is the concentration gradient; and D is the diffusion coefficient or mass diffusivity of one component, diffusing through another media.

Water vapor can diffuse through a textile structure in simple diffusion through the air spaces between the fibers and yarns [54, 55]

At a specific concentration gradient the diffusion rate along the textile material depends on the porosity of the material and also on the water vapor diffusivity of the fiber. The moisture diffusion through the air portion of the fabric is almost instantaneous whereas through a fabric system is limited by the rate at which moisture can diffuse into and out of the fibers, due to the lower moisture diffusivity of the textile material [56].

The water vapor transport, called diffusion, runs from the region of high concentration to the region of low concentration until the concentrations level out [178].

The rate of the transport of the diffusing substance across the textile material, and concentration gradient of water vapor pressure is given with the Fick's Equation stated above.

Several models [68], showed the importance of construction variables of textile materials on moisture vapor transmission characteristics of fabrics. The resistance to water vapor transmission Ret was then described in terms of fabric thickness h, optical porosity Ɛ and water vapour diffusivity in air D [68]. Water vapor resistance is then shown to be related to the fabric structure By :

$$R_{et} = \frac{h}{(1-\varepsilon)\frac{(D_f/D_a)}{(1-\gamma)+\gamma(D_f/D_a)}+\varepsilon} \qquad (126)$$

By modeling a fabric structure as yarns and pores are arranged in parallel while, within the yarn, while fibers and air are arranged in serial.

Here D_f and D_a refer to the diffusion coefficient of water in fiber materials and in air, respectively, and y is the volume fraction of air in the yarn. For a fabric from a blend yam which is the case in most of the produced fabrics, the water vapor resistance becomes:

$$R_{et} = \frac{h}{(1-\varepsilon)\{ (1-\gamma)x\left(\frac{D_a}{D_{f2}}\right)+(1-\gamma)(1-x)\left(\frac{D_a}{D_{f1}}\right)+\gamma\}^{-1}+\varepsilon} \qquad (127)$$

Generally, however, the ratio (D_f/D_a) is typically in the range of 10^{-6} to 10^{-8} and, for all practical purposes, is negligible [68]. Then Equations 8 and 9 reduce to

$$R_{et=} \frac{h}{\varepsilon} \qquad (128)$$

The variation of water vapor transfer rate value with blend level can also be explained in terms of the effect of fiber type on fabric geometry. The water vapor diffusivity D, in still air is reported to be about 0.25 cm^2/s and diffusivity in cotton for example along the fiber direction is reported to be 0.05 times the diffusivity value in still air [58].

In an actual fabric, fibers generally run perpendicular to the vapor diffusion path, and thus the longitudinal pore in fibers does not appreciably contribute to the diffusion [58]. In such a case, the value to be used in Equation 9 should be diffusivity through a nearly solid fiber material. Diffusivity in hydrophilic fiber materials is reported to be about $10^{-7}/cm^2/S$, while for hydrophobic polymer materials, it is about 10^{-9} cm^2/s [58].

When these values are plugged into Equation 9, it reduces to

$$R_{et} = \frac{h}{D\,\varepsilon} \qquad (129)$$

Since water vapor diffusion is highly dependent on the air permeability of the fabric which is mainly through pores [68]. Air permeability increases as the porosity of the fabric increases; which also results in higher moisture transfer through the air spaces within the fabric.

The diffusivity of water vapor in air can be given as a function of temperature and pressure [179,180] and it is represented in the following equation:

$$D = 2.20 \text{ X } 10^{-5} \left[\frac{\theta}{\theta_0}\right]^2 \left[\frac{P_0}{P}\right] \qquad (130)$$

Where D is the diffusivity of water vapor in air (m^2/sec), θ is the absolute temperature (K), θ_0 is the standard temperature of 273.15 K, P is the atmospheric pressure and P0 is the standard pressure (Bar).

The influence of temperature on water vapor permeability resistance have been investigated [181-184]. They report that the water vapor resistance of clothes depends on temperature variation. [185-189]. however, it was revealed that the effect of pressure on this resistance was more significant than temperature. The water vapor transfer rate depends on the water vapor concentration gradient and the diffusion coefficient of the substance. The effect of both temperature and pressure must be considered when designing a clothing system for high altitudes because the water vapor diffusion coefficient depends on both of them as related in relation (130).Since water vapor diffuse through non straight passes through pores within the fabric, it is then concluded that tortuosity of fabrics ξ have a great effect on vapor path depending on fabric thickness, water vapor resistance then becomes:

$$R_{et} = \frac{h \; 10^5 \, \xi}{2.20 \left[\frac{\theta}{\theta_0}\right]^2 \left[\frac{P_0}{P}\right] \left[1 - \frac{\pi \, d_y^2 \, lcw}{2h}\right]} \qquad (131)$$

In order to simplify the theoretical calculations, loops are assumed to be composed of ideal yarns but with great variability in pore size distribution. It is difficult to estimate the porosity of fabrics by calculating the pore dimensions and yarn diameter. As is known, yarns in the structure of the fabric do not have a smooth surface or a solid construction as there is also a lot of emptiness in the yarns.

The water vapor partial pressure was calculated for each of the nine different temperature and humidity conditions according to :

$$\text{Relative Humidity} = 100 \text{ X } \frac{pa}{psv} \qquad (132)$$

Where the relative humidity is the ratio of actual vapor pressure pa to the saturated vapor pressure psv at the same temperature [190]

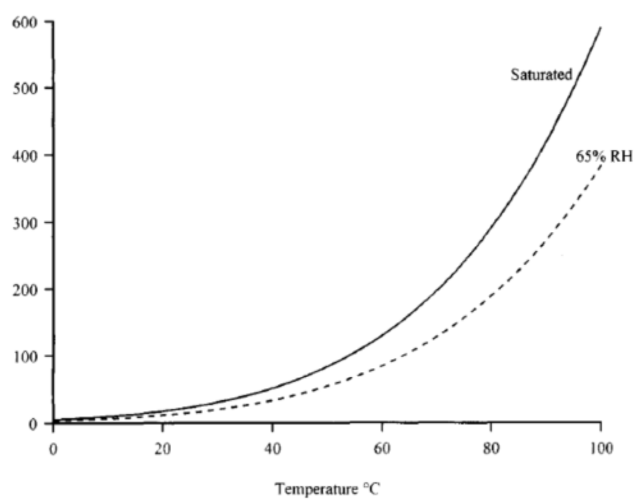


Figure 5.5 Relative humidity in accordance with mass of water vapor

Values of the porosity was calculated in accordance with Equation (124), the diameter was calculated as previously mentioned to get the actual values in order to compensate the real value in the theoretical model.

5.4 Theoretically calculated values

5.4.1 96%Cotton 4%Lycra

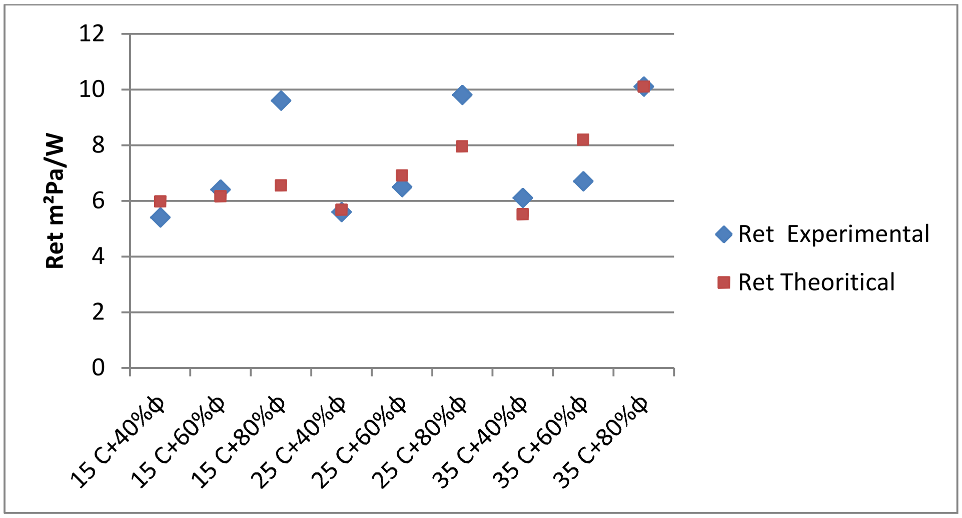


Figure 5.6 Experimental and theoretical Ret m²Pa/W in the different tropical conditions

5.4.2 94%Cotton 6%Lycra

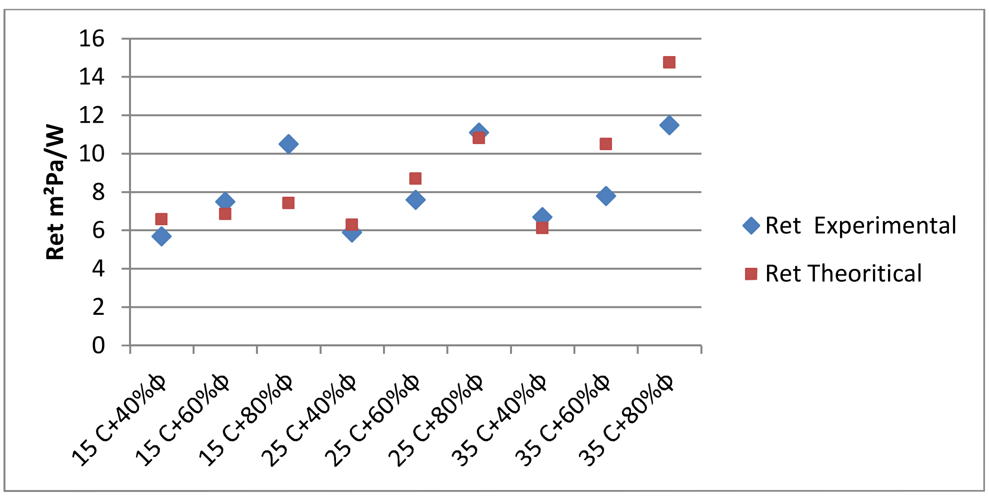


Figure 5.7 Experimental and theoretical Ret m²Pa/W in the different tropical conditions

5.4.3 92%Cotton 8%Lycra

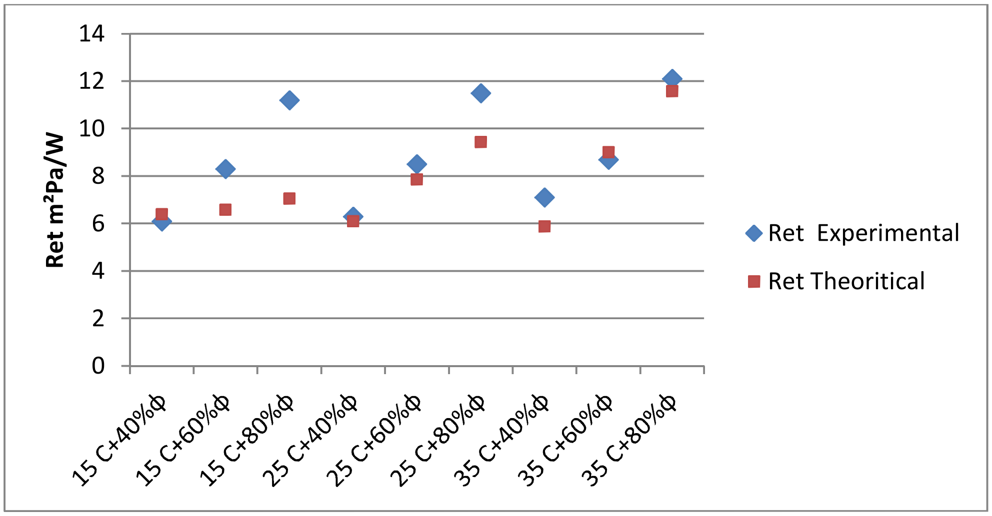


Figure 5.8 Experimental and theoretical Ret m²Pa/W in the different tropical conditions

5.4.4 Polypropylene

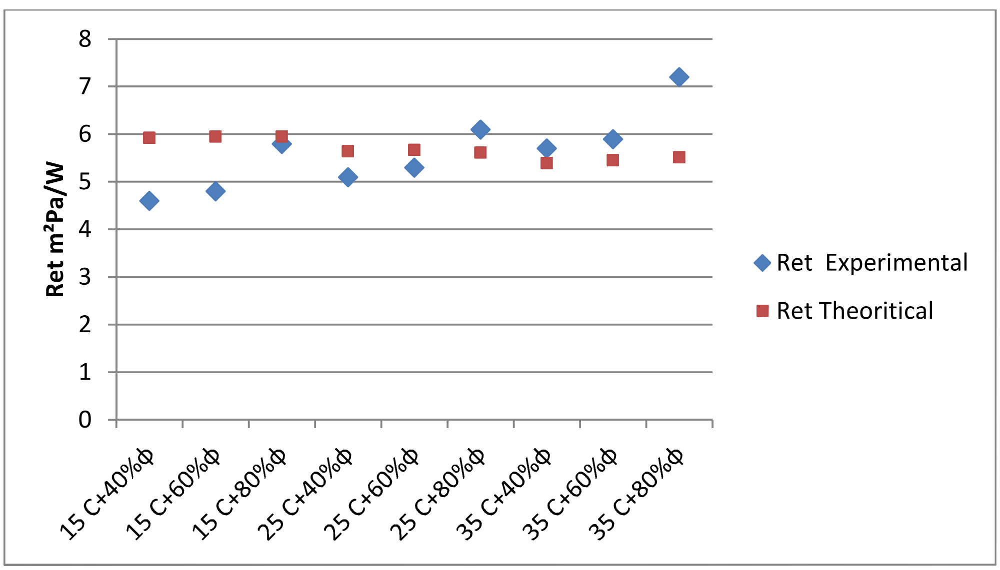


Figure 5.9 Experimental and theoretical Ret m²Pa/W in the different tropical conditions

5.4.5 Merino wool

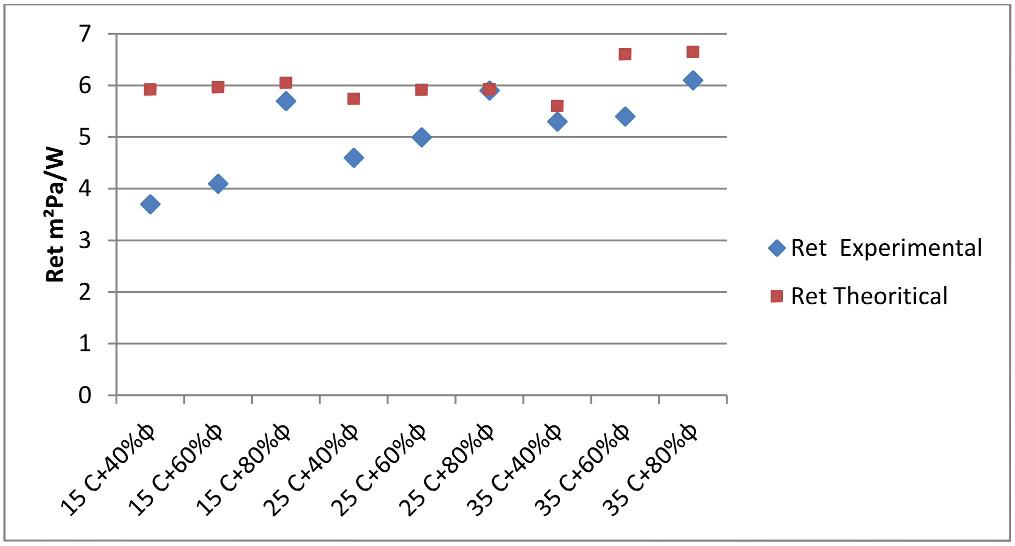


Figure 5.10 Experimental and theoretical Ret m²Pa/W in the different tropical conditions

5.4.6 95%Viscose fiber made from bamboo plants, 5%Lycra

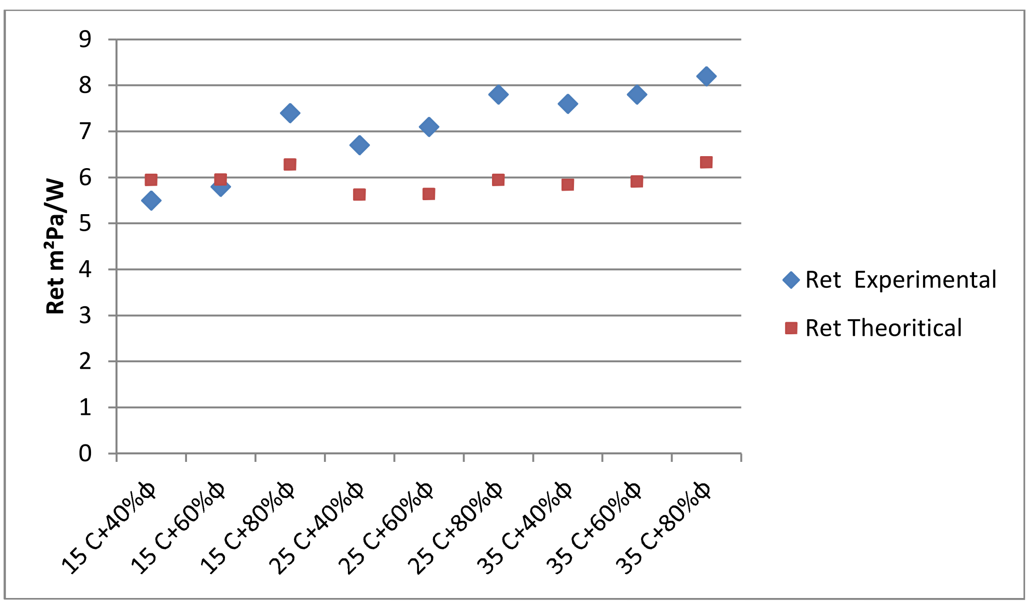


Figure 5.11 Experimental and theoretical Ret m²Pa/W in the different tropical conditions

5.4.7 62%PE Coolmax 32%PE micro 6%Lycra

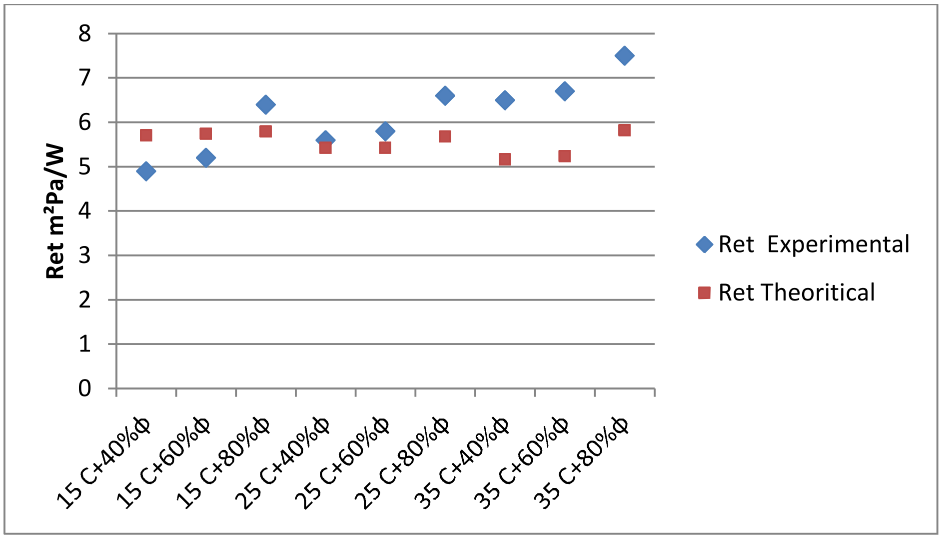


Figure 5.12 Experimental and theoretical Ret m²Pa/W in the different tropical conditions

5.4.8 94%PE 6%Lycra

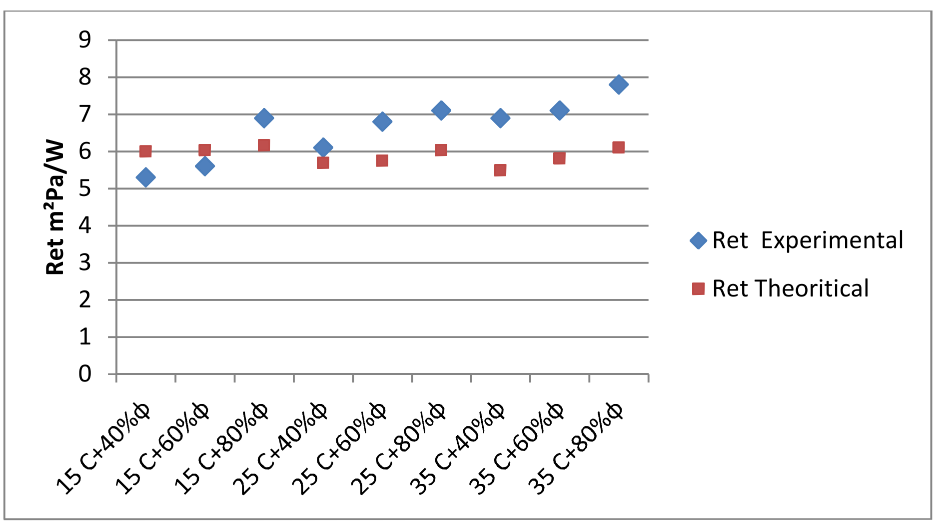


Figure 5.13 Experimental and theoretical Ret m²Pa/W in the different tropical conditions

It obvious from (Figure 5.6) to (Figure 5.13) that the theoretical water vapor resistance in the different tropical conditions for the tested garments in the different weather conditions is highly correlated with the experimental water vapor resistance Ret (m^2Pa/W) as shown in the last chapter, it is obvious that as the resistance increases for any of the reasons stated before, for example; less pore size or lower partial pressure or swelling of the fibers, it leads to the decrease of water vapor permeability. It is also clear that the total water vapor amount is changing with the change of the parameters under study and which represents the different climatic conditions, the results obtained by experiments are in a good correlation with the results obtained from the theoretical model , where we can find that the theoretical model combines between porosity and water vapor partial pressure of the fabrics under study and as was mentioned before , that porosity or void spaces with in the fabric in some cases is changing with the change of the humidity existing in the environment especially with materials from fibers that swell like cotton ones , while in the other materials it is clear that the change was mainly because of the different partial pressure of water vapor, it is obvious that the more humidity in the surrounding environment the more difficult for the fabric to get rid of the moisture content, whether it was absorbed by the material or it was by transferred to the surface of the material, and in the same time it makes it difficult for the body to release the sweat.

CHAPTER VI

CONCLUSION

This research studied the thermophysiological properties for garments used in tropical weather countries as well as measuring the comfortability of these different materials under different conditions of temperatures and humidity that actually exists in countries with hot weather like Egypt all around the year, and monitoring the factors that affects the thermal behavior of the garments used in this tropical weather.

It is well known that cotton is a very good material for absorbing humidity and it is widely used in that tropical condition, but is it really the best material to be used.

The results show the thermophysiological properties of the tested fabrics, and as we are studying here the hot condition, special properties are recommended, the cooler feeling was achieved by using Viscose fiber made from bamboo plants. About the conductivity, it is clear that; here as most of the times in that hot condition, the temperature of the environment is much higher that the human being and as the heat normally transfers from regions with higher temperature to others with lower one, it is desired here to have a material with lower heat conductivity so that the heat will not transfer rapidly from the environment through the clothing material to the wearer, and we can see that it is achieved with using 94%PE 6%Lycra, but it is the only property that is achieved with in that material , so it is not desired to use it in the hot condition. Insulation is not desired in material used here as we need the body to release heat easily if overheated, and we can see that this condition is achieved by using Viscose fiber made from bamboo plants, and here we can tell that is the second desired thermophysiologiacl property achieved by using Viscose fiber made from bamboo plants.

It is desired to have a material that doesn’t adjust its temperature with the environment quickly as it will get heated quickly from the high temperature surrounding, as it will cause the body to feel the surrounding heat even without doing any effort , and it was found also that Viscose fiber made from bamboo plants achieves this requirement, which is here the third desired thermophysiological property existing in that material.

While it was found that Polypropylene is not desired as it achieves only the highest air permeability , but it doesn't achieve any of the other desired thermophysiological properties, Merino wool achieves two of the most significant thermophysiological properties desired for materials used in such a hot condition, which are; the lowest water vapor resistance , and the highest water vapor permeability index, but while it achieves these two properties, we can find also that these two properties are accepted by using Viscose fiber made from bamboo plants.

Cotton is widely used in such hot conditions, but as we can see that Viscose fiber made from bamboo plants and merino wool which are not commonly used within that conditions, are more comfortable concerning the thermal behavior , and they are highly recommended to be used in that tropical condition , especially Bamboo because it is available in such regions and it is also naturally anti-bacterial which is good to wear in that conditions where the human being releases a lot of sweat, where it is a good media for bacteria to grow . It is naturally antibacterial, antifungal and anti-static because it has a unique anti-bacteria and bacteriostasis bio-agent named "bamboo kun" which bonds tightly with bamboo cellulose molecules during the normal process of bamboo fiber growth.

It is also UV protective and we can tell how important is this when it comes to that hot condition with long time of exposure to sun during long summer days, it is also green and biodegradable which means that it is safe to get rid of it without having any effect on the environment. It is also breathable , cool, strong, flexible, soft and has a luxurious shiny appearance, we can tell it is good to use viscose fiber made from bamboo plants instead of cotton not only because of its advantages but also may be because the cotton is good in absorbing sweat and humidity, but it is not that good when it comes to loosing that humidity , and in the same time that humidity when absorbed by the fibers causes the fibers to swell , leading to less air permeability , which is also a dominant factor in releasing the water vapor from the skin to the environment, also this humidity causes unpleasant feeling when wearing as it sticks to the body , leading to less comfort to the wearer.

It was also concluded that the total water vapor permeability becomes fewer as the water vapor resistance gets higher, leading to less comfort, and we can tell that the theoretical model used represents and clarifies the experimental results held for the different materials in the different experimental conditions.

We can find here that we can predict the water vapor resistance through garments depending on the fabric parameters and construction, and this information is very useful when it comes to designing a special functional garment for special use, where we could estimate the thermal behavior of the designed fabric. It is recommended for upcoming studies, to investigate the mass and heat transfer process through macro and micro structure of yarns and fabrics to help in more understanding for the thermal behavior as well as the heat and mass transfer through designed garments, and this will allow us to understand the factors which affect the comfort properties in the required conditions, leading us to develop garment properties that could be applied to enhance comfort properties.

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