EFFECT OF GARMENTS ON THERMOPHYSIOLOGICAL COMFORT

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To My Mother and my friends who supported me all the time…

ABSTRACT

This study investigates the effect of garment on human thermophysiological comfort. In this thesis simplified but effective model of heat transfer from human skin to the environment through clothing is proposed. A comprehensive and detailed literature search is provided. Thermal comfort models in literature are examined and based on the Fanger's comfort model, the simplified thermal comfort model is developed. The objective is improving an algorithm which is easy to calculate numerically yet gives best possible results by matching well with the experimental data in literature.

The objective is developing a thermal comfort algorithm that can be used in IOT applications such as smart phones and smart buildings, so that a user can control his/her thermal comfort state by changing his/her clothing according to outputs of the algorithm. Therefore, the algorithm has to give fast but good results that do not require any use of measurement instruments. In buildings, the use of PMV control showed 7.3 % less energy consumption than the dry-bulb air temperature control and showed 28.8 % less energy consumption for the annual cooling electricity consumption (Hong, 2018). Therefore, this study can be used for such building control applications. Fanger's Predicted Mean Vote model is adopted to scale comfort values for this application. Different case studies that are focusing on clothing thermal resistance, evaporative resistance and PMV, are investigated. Codes are simulated in MATLAB. The main output of the algorithm in this study is suggestions on how a person should change his/her clothing to feel comfortable at any time in any environment. This algorithm is used for different strategies.

ÖZETÇE

Bu tezde, kıyafet ile örtülü olan insanın derisi ile bulunduğu ortam arasındaki ısı transferinin basitleştirilmiş ama etkili modeli sunulmuştur. Çalışma, kıyafetin buradaki etkisini incelemektedir. İlk olarak, termofizyolojik konfor konusunda ayrıntılı bir literatür incelemesi yapılmıştır. Farklı termal konfor modelleri incelenmiş ve Fanger'ın termal konfor modeline dayanan, basitleştirilmiş bir termal konfor modeli oluşturulmuştur. Amaç, hesaplaması kolay olan fakat literatür ile iyi örtüşen matematiksel bir model geliştirmektir.

Amaç, akıllı binalarda veya telefon aplikasyonlarında kullanılabilecek bir algoritma geliştirip, kullanıcının giysilerini değiştirerek kendi termal konfor düzeyini kontrol edebileceği bir durum yaratmak. Bu sebeple, geliştirilen algoritma herhangi bir parametrenin ölçümüne ihtiyaç duyulmayan ve hızlı ama iyi sonuçlar veren bir algoritma olmalıdır. Binalarda, PMV kontrolün kullanılmasının, kuru-termometre sıcaklık kontrolüne göre enerji kaybını %7.3 azalttığı ve yıllık soğuma elektrik tüketimini de %28.8 azalttığı bulunmuştu (Hang, 2018). Bu edenle, Fanger'ın "Predicted Mean Vote" adlı konfor ölçüm modeli bu uygulama için adapte edilmiştir. Farklı durumlar incelenmiş ve kıyafetin nem ve ısıl geçirgenliği ile PMV değerine odaklanılmıştır. Kodlar MATLAB kullanılarak yazılmıştır. Bu algoritmanın ana sonucu "Bir kişinin bulunduğu herhangi bir ortamda ve herhangi bir zamanda, kendini konforlu hissedebilmesi için kıyafetinde ne gibi değişiklikler yapmalıdır?" sorusuna verdiği matematiksel cevaplardır. Bu uygulama değişik stratejiler için kullanılmıştır.

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I would like to express my gratitude to my supervisor, Prof. M. Pınar. Mengüç for supporting me very patiently from the beginning, always motivating me, and lifting me up whenever I feel like I am drowning.

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NOMANCLATURE

h	$[W/m^2K]$	Heat transfer coefficient
Q	$[W]$	Heat transfer
T	[℃]	Temperature
R	$[m^2K/W]$	Heat Resistance
L	$[W/m^2]$	Thermal load
M	$[W/m^2]$	Metabolic rate

Special Characters

Ed	$[W/m^2]$	Heat loss from skin surface by water vapor diffusion
k	$[W/mK]$	Thermal conductivity
C_{res}	$[W/m^2K]$	Heat loss during breathing
E_{rsw}	$[W/m^2]$	Heat loss due to sweating
A_{cl}	$[m^2]$	The area of clothing
h_c	$[W/m^2K^1]$	Convective heat transfer coefficient
h_r	$[W/m^2K^1]$	Radiative heat transfer coefficient
h_{comb}	$[W/m^2K^1]$	Combined heat transfer coefficient
T_{mr}	$[°C]$	Mean radiant temperature
T_a	$[°C]$	Air temperature
T_{cl}	$[°C]$	Mean temperature over the clothing surface
T_{sk}	$[°C]$	Mean skin temperature
R_{cl}	$[m^2K/W]$	Conductive resistance of clothing

CHAPTER I

INTRODUCTION

1.1 General Background

As one can imagine a typical person's expectations from garments he/she wears are not only to be covered and protected, but also to look and feel good. The garments are desirable to be compatible with the personality, appearance and status of the users, physical, social and psychological expectations. These expectations of consumers have revealed the concept of comfort and the studies aimed at meeting them have led to comfort research.

Garments play a major role in establishing the balance between the human body and the environment while performing various functions such as covering, adornment, status, protection, and modifying problems related to heat loss. In order for a fabric to be a garment, it must have the necessary comfort in terms of garment functions and human senses. However, the basic function of a garment is to protect the user from disturbing physical environmental conditions by means of fabric plies or layers. This protection means providing the thermal environment necessary for the body to continue its activities and performing functions such as impacting the body, injury due to impact, and resisting climatic forces such as wind, cold, heat and rain. These functions are also important in defining user comfort perceptions.

Clothing comfort is a complex concept; it is generally examined under four main headings (Bartels, 2005):

Thermal garment comfort: It involves the transfer of heat and moisture passing through the garment and directly affects the person's heat regulation. It is a parameter that depends on the heat and moisture transmission properties of garments (Saville, 2004).

Sensory comfort: Sensory comfort includes sensations when clothing touches the skin. As a result of contact of skin and clothing, various feelings expressed by wearer as a situation related to the satisfaction. The textile surface is desired to create a pleasant touch (softness, slippery) on human skin. Clothing should not stick to the skin and should not cause itching. When sweating is high, wetness and a feeling of adhesion to the skin create sensory discomfort (Kothari and Sanyal, 2003). These properties are determined by fiber properties, yarn and fabric construction, fabric finishing processes and garment construction (Yoo and Barker, 2005).

Body movement comfort: A textile product should be appropriate to the shape of the body and should not prevent body movements and should provide free movements.

Psychological comfort: Self-confidence of fashionability and environmental appreciation can be included in this group. It is also influenced by factors such as gender, age, season, environment, social situation, social life, clothing by place and time.

1.2 Literature Review

1.2.1 The concept of comfort

The starting point of the comfort researches was to define comfort and to determine the situations in which consumers feel good. In the 1939 and 1946 studies of DuBois, one of the first examples of these researches, it was stated that the fact that the user feels good depends on the balance between the metabolic energy he produces and the energy he transfers to his environment. This energy balance depends on the body's ability to feel heat or cool, and clothing sets the limits. In Kennedy's 1956 study of military clothing, clothing, body physiology and environmental conditions are given as three elements of continuous comfort (Hollies and Fourt 1970).

Many researchers define comfort as a neutral feeling. According to Sarkar (1994), comfort is a subjective concept that can only be defined individually. In addition, comfort status can be achieved by satisfactory harmony of many physical, physiological and psychological factors. The flow chart of these factors in the perception of comfort is shown in Figure 1.1. (Li 2001). According to the scheme, physical factors provide the sensory organs with the necessary warnings. These stimuli are sent to the brain with physiological signals and also cause body reactions such as sweating and pulse change. The brain uses the signals it receives to identify various subjective perceptions and makes an overall assessment by comparing it with previous experiences and psychological expectations.

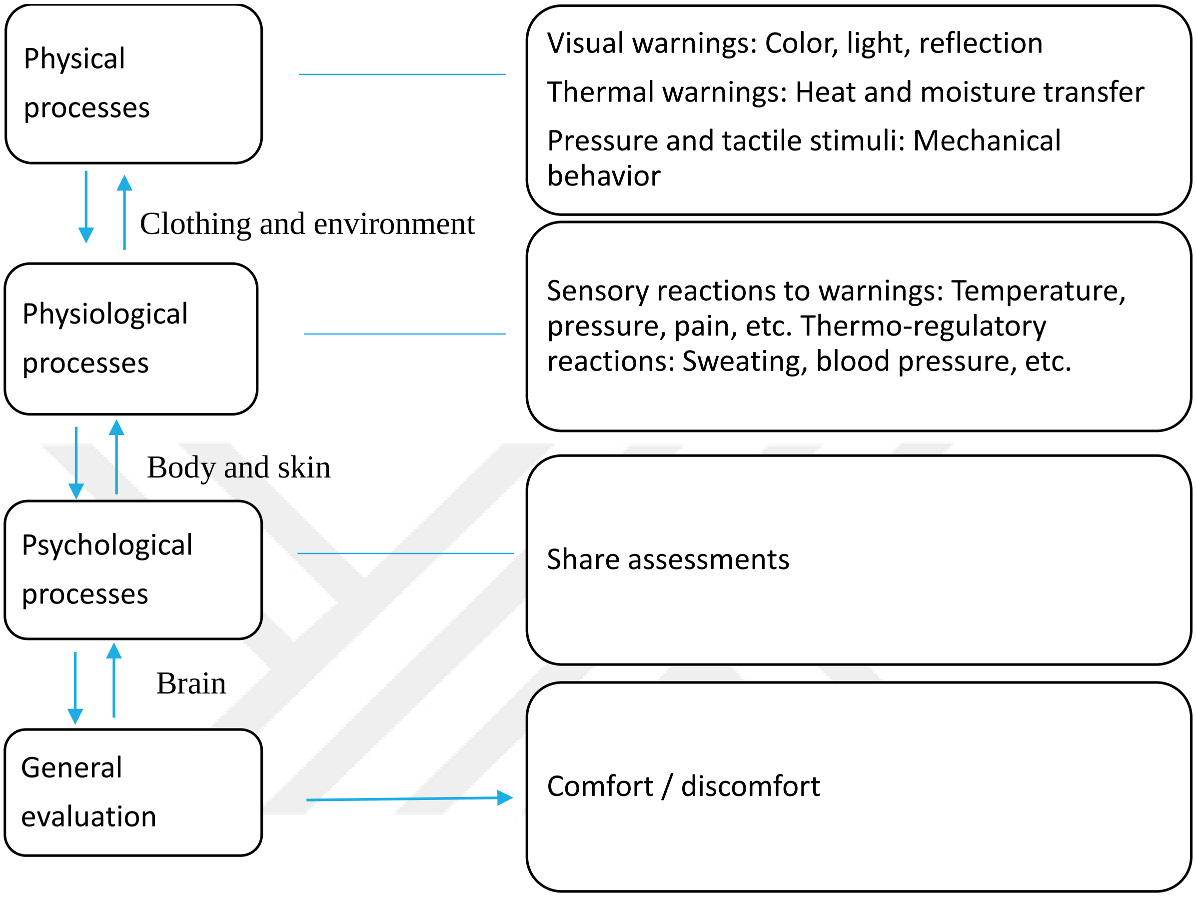


Figure 1.1. Comfort rating scheme (Li, 2001)

Hollies and Fourt (1970) examined comfort, thermal and non-thermal components (surface character, mechanical finishing processes, drapability, sewnability etc.), including the user's status (operating status, various activities, etc.) and environmental conditions. The physiological responses of the human body to specific clothing and environmental conditions can be used to define comfort. In order to make this definition, the environment must reach a stable state. This is calculated by measuring factors such as thermal resistance, moisture resistance of the garment, climate conditions of the environment, and activity level of the user.

Hes (2002) described comfort as the complex effect of heat / moisture transfer properties and mechanical properties of fabrics and garments. The physical properties of the garment, such as the force that comes into contact with the body, the deformability of the garment, the stiffness, stiffness, softness perceived when the fabric is touched, have an effect on the comfort assessment (Hes et al. 2001). There are several important aspects of all these definitions. They are;

- Comfort relates to the senses of various senses and is subjective.
- Comfort includes various aspects of the human sense, such as visual (aesthetic comfort), thermal (cold and hot), pain (stinging and itching), and touch (smooth, rough, soft, hard).
- Subjective feelings include psychological processes. This means that the person evaluates the present situation from past experience in order to define the comfort conditions he / she wants.
- Body-clothing interactions (both thermal and mechanical) play an important role in defining the user's comfort state.
- External environmental conditions (physical, social, cultural) are very effective on user comfort.

It is obvious that the perception of comfort is a complicated process that involves many stimuli from the garment and external environmental conditions, which go to the brain via neurons and are resolved there. Following is a more engineering definitions of comfort.

1.2.2. Comfort and Clothing

Clothing, the human body and the environment are the three elements that make up the concept of comfort. Garments are selected and used to interact more or less with the environmental conditions (temperature, humidity, etc.), as well as to provide the desired comfort. For example, fashionable and aesthetically appealing garments provide psychological relaxation to satisfy the user's motivation to be recognized in society (Hollies and Fourt 1970).

A covered body feels the current room air conditioning conditions on the skin and under the garment. When we wear a garment, the heat and moisture produced by the body wait in the air layer between the body and the fabric layer before it is released to the environment, thus determining the character of the microclimate on the body and consequently the feeling of comfort. Comfort in terms of clothing is not to be affected psychologically and physiologically by the clothes we wear, to feel comfortable in ourselves (Kalaoglu, 1995).

1.2.3. Thermophysiological Comfort

History of thermal comfort dates back to Blagden in 1775 and his evaluation that the ability of people to withstand high temperatures. In 1923, Houghton and Yaglou developed an index called “effective temperature” while trying to determine the effects of air temperature and humidity on thermal comfort (Katic, 2016). Givoni and Goldman developed an empirical one-node model in 1971. At the same time, Gagge et al. have developed the Pierce two-node model and separated human body as the core layer and skin surface layer.

During 70s, Fanger developed his own model to evaluate thermal environments. He depended the degree of discomfort on thermal load, which is defined as “the difference between internal heat production and the heat loss to the actual environment for a man hypothetically kept at the comfort values for skin temperature and sweat production at the actual activity level (Fanger, 1970). Fanger collected data from people at various metabolic rates considered themselves comfortable involved in climate chamber experiments. Then he developed an empirical equation (PMV) for the human sensation of thermal comfort. It was later adopted as an ISO standard. PMV is a 7 points scale ranging from cold (-3) to hot (+3), averaged by the assessment of the thermal comfort sensations of many users. In this scale, the value 0 represents the comfort / neutral state.

In cool environments, thermal comfort is best correlated with mean skin temperature and body temperature. However, in warm conditions, it was found that thermal discomfort is related to sweating rather than skin or body temperatures (Winslow et al. 1937, 1939; Gagge et al. 1967, 1969). In 1970, Hardy described the physiological conditions of general thermal comfort (at low activity levels) have been described as follows:

- internal body temperature 36.6 to 37.1 ℃,
- mean skin temperature 33 to 34.5 ℃ for man and 32.5 to 35 ℃ for women,
- local skin temperature is variable over the body but generally between 32 and 35.5 ℃
- temperature regulation is completely accomplished by vasomotor control of blood flow to the skin (no sweating/shivering present).
- Fanger (1970) also defined three conditions for a person to be in overall thermal comfort:
- the body is in heat balance;
- sweat rate is within comfort limits;
- mean skin temperature is within comfort limits.

Physiological or thermal comfort is defined as satisfactory compatibility with the thermal environment according to ISO 7730 established in 1994. Li, using the heat and moisture conduction properties of textile fabrics, defined comfort as the state of obtaining thermal and moist state (Li 2001). This concept includes the heat and moisture permeability properties of the fabric forming the garment and its role in maintaining the thermal balance of the fabric during different activities.

Grabowska (2001) associated physiological comfort with the establishment of the thermal energy balance between the human body and the environment; physiological comfort, air permeability, thermal insulation, vapor permeability, moisture sorption, moisture transmission is affected by fabric properties. The physiological comfort of people in their clothes is due to the evaporation of sweat and the prevention of overheating in hot climates or active conditions, and the body maintains its comfort by evaporating moisture when the external temperature or activity level increases. In some cases, the rate of evaporation of sweat from the wet body may be lower than the rate of sweat release. Accumulation of sweat and insufficient evaporation heat on the body (skin) gives a feeling of discomfort (Barnes and Holcombe, 1996).

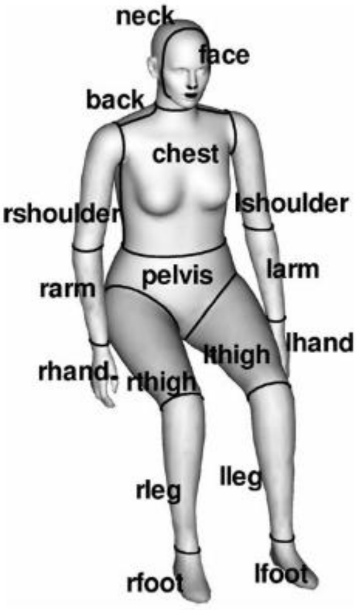


Figure 1.2. Scanned manikin body divided into sixteen segments. Face and neck constitute the head segment (Sørensen and Voigt, 2003)

Environmental factors that determine thermophysiological comfort are average radiation temperature, relative humidity and air velocity and air temperature. The average radiation temperature (MRT) indicates the uniform surface temperature of the black protective chamber (150 mm diameter copper chamber), which exchanges heat with the same amount of radiation as a non-uniform cavity with the object in it (Kaplan and Okur, 2005).

The average radiation temperature is an expression of the heat exchange that occurs in parallel with the temperature difference (even if there is no direct contact between the body). All matter with a temperature bigger than zero emit thermal radiation. Therefore, the average radiation temperature can also be expressed as the weighted average of the temperature of these objects according to their area. If the temperature of the objects is higher than the skin temperature, the average radiant temperature is positive, otherwise it is negative.

1.2.4. Thermophysiolocigal Models

The first two thermal models to evaluate the thermal comfort were Fanger’s steady state model and Gagge’s two-node transient model. In the Fanger’s PMV model the environment is assumed to be steady state however in reality environments are often non-uniform and transient. Still, Fanger’s empirical model is capable to predict the overall thermal sensation (Schellen et al., 2013).

In recent years different thermophysiological models were developed. Most commonly used multi-node thermal model was developed by Stolwijk in 1971. The passive system of

Stolwijk 25 node model consists of six segments that are head, trunk, arms, legs, hands and feet. Each segment is divided into four layers: the core, fat, muscles and skin (Katic, 2016). The active system consists of functions of signals. In the Table 1.1 main characteristics of thermophysiological models are summarized.

The main similarity of most models is the application of energy balance to a person and the use of energy exchange mechanisms, along with experimentally derived physiological responses, in order to predict thermal sensation (Huizenga, 2001). In 1971, "Effective Temperature Scale" was introduced by the study that Gagge and Nishi elaborated at the J.B. Pierce Lab (Fabbri, 2015). A real progress in clothing research was started to be made by Gagge and Goldman in 80s. McCullough and Lotens conducted studies that describing physical processes in clothing. Also Lotens focused on condensation and absorption of moisture for heat transfer (1993).

Improved multi-node thermo-physiological models like Berkeley Comfort (2001), Tanabe (2002) and ThermoSEM (2004) were developed based on the Stolwijk model, and take into account the asymmetric environmental conditions (Katic, 2016). The Tanabe model is able to predict the change of physiological conditions for different parts of the body (Tanabe, 2002). The Fiala model extensively simulates the predictions of overall and local physiological responses of the human body (Fiala et al., 1999). The environmental heat exchange was modelled by including evaporation of moisture from the skin, insulation effect of the clothing and local heat losses from body by free and forced convection (Fiala et al., 1999). The UC Berkeley model consists of 16 body segments with four concentric shells (core, muscle, fat and skin) and a clothing layer. Even though many models mentioned above can consider physiological differences between individuals, in practice most of them are using a single set of physiological data to represent an average person (Katic, 2014).

The mathematical thermoregulation model (ThermoSEM) which is based on the Fiala model, is a dynamic thermos-sensation model. The difference between Fiala model and ThermoSEM is in the ThermoSEM, neurophysiological concepts for thermoregulation in active part is considered. In this manner, in the model skin blood flow is based on neurophysiological concepts (Katic, 2014).

Table 1.1 Characteristics of recent thermophysiological models (Katic, 2014)

Model	**Characteristics**	**Constraints**
Gagge (1971)	-1 segment -2 layers (-*Easy to calcuation*)	-Can be applied to only uniform conditions -Moderate activity level -No local body part outputs
Stolwijk (1971)	-6 segments -4 layers -Have local skin temperatures	-Constant environmental conditions - Each segment has set point temperatures

Table 1.1 Continued

Fiala (1999)	-187 nodes -15 segments -7 layers -Steady state and transient conditions -Various activity levels	-Regression based
UC Berkeley (2001)	-Multi-node -5 layers: core, muscle, fat and skin + clothing -Steady state, transient and non-uniform environment conditions -Physical characteristics can be changed	-Simulated arm temperature is lower than the measured one during transient conditions.
Tanabe (2002)	-16 segments and 4 layers -65 nodes -Steady state and non-uniform transient conditions	-Based on set point temperatures of each segment
ThermoSEM (2004)	-Multi-node -19 segments -Based on neurophysiology -Individual differences	-Validated for mild conditions. Mild condition means neither extremely hot nor extremely cold.
Foda (2011)	-Two nodes: core and skin -17 segments -Individual body parts	-Steady state conditions -Average man with sedentary activity -Normal office clothing

Table 1.1 Continued

Lai & Chen (2016)	-Based on Fiala’s work -12 segments -An additional method for quantifying local clothing insulation.	-Transient and non-uniform -2 Dimensional -All measurements were conducted in indoor spaces.
Tang (2016)	-6 segments -3 tissue layers -Dressed human body	-Environment temperatures from -5℃ to 20℃ -Nude thermal model does not give accurate results under extreme environmental conditions.

1.2.5. Fundamental Heat Transfer Mechanisms in Clothing and Fabrics

The human body is a thermodynamic system that produces continuous heat through metabolic activities (biochemical breakdowns, muscle vibrations, physical activity, etc.). In order to achieve thermal equilibrium, an equal amount of heat must be removed from the resulting heat. Failure to maintain the thermal balance of the body can lead to comfort problems or even life-threatening conditions in parallel with fluctuations in skin temperature. The conditions that disturb the thermal balance of the body can be listed as follows (Kaplan and Okur, 2005):

- Relocation between two environments with very different temperature and humidity values;
- Disposal of large quantities of fluid from the body in a short time;

- Suddenly different physical activity.

Heat transfer takes place from the high temperature zone to the low temperature zone. This transition follows one of the four mechanisms:

1. Conduction: It is the most common mechanism of heat transfer in solid bodies. Heat conduction in solid bodies is due to the vibration of atoms and molecules interacting with the rapidly moving or vibrating neighboring atoms and molecules.

2. Convection: It is the energy transfer that occurs between a solid surface and the adjacent liquid or gas that is in motion. If there is no bulk fluid motion, the heat transfer is by pure conduction.

3. Radiation: It is the emitted energy by a matter in the form of electromagnetic waves due to the changes of configurations of atoms or molecules. It does not require any intervening medium between two surfaces, also it is the fastest mode of heat transfer which is at the speed of light. Radiation is the only heat transfer mechanism that can take place in vacuum. This is the explanation of how the energy of the sun reaches to the earth.

4. Condensation: This heat transfer phenomenon occurs when a vapor come into contact with a solid surface whose temperature is below the saturation temperature of the vapor. It can also occur on the free surface of a liquid or gas that the vapor is exposed when the temperature of liquid or gas is below the saturation temperature of the vapor (Çengel, 2015).

Under low activity conditions, 75% of heat loss from the skin surface occurs by convection, radiation and conduction (Holcombe and Hoschke 1983). The garment should be such that the heat generated will allow sweat to dissipate.

Below, each of these mechanisms are given in more details.

1.2.5.1. Conduction Heat Transfer

In homogeneous solids, heat transfer occurs only by conduction, and this transfer complies with Fourier's Law, which assumes that the heat flow in a given direction is parallel to the temperature difference.

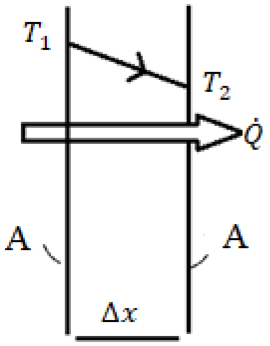


Figure 1.3. Heat conduction through a place wall of area A and thickness Δx

Assuming steady heat conduction through a large plane wall of thickness $\Delta x = L$ as shown in Figure 1.3. The rate of heat conduction through a plane layer is:

$$\dot{Q} = kA\frac{T_2 - T_1}{\Delta x} \quad \textbf{(1.1)}$$

Here, k is the thermal conductivity of the material which indicates the ability of a material to conduct heat. When $\Delta x \longrightarrow 0$, the Equation 1.6 reduces to the differential form:

$$\dot{q} = -k\frac{\mathrm{dT(x)}}{\mathrm{dx}} \quad \textbf{(1.2)}$$

where $\frac{\mathrm{dT(x)}}{\mathrm{dx}}$ is the temperature gradient. From the Equation 1.7 it is obvious that rate of heat conduction in a direction is proportional to the temperature gradient in that direction.

1.2.5.2. Convection Heat Transfer

Heat transfer from the unit surface area formed by convection between a surface at temperature T_s and a fluid having an average temperature T_f in contact with it is expressed as in Equation 1.3:

$$q = h_c(T_f - T_s) \quad \textbf{(1.3)}$$

where h is the convective heat transfer coefficient. Equation 1.14 is known as Newton's law of cooling (Kakaç 1990).

In garment systems, transport is a result of the movement of the air layer, which changes depending on body movement. The transfer of heat between the body and the garment depends on the forced transport, which varies depending on the amount of movement of the body, the natural transport around the body and the air velocity in the environment. Forced transport rate is more difficult to determine because this mechanism changes depending on the air flow rate and direction (Rupp, 1998, Kaplan and Okur 2005).

Hardy (1968) described convective heat loss as a function of many factors and listed these factors as in Equation 1.4 (Ruckman et al. 1999):

$$Q_c = f(D, V, \mu, \rho, \Delta T, \lambda, C_p, t) \tag{1.4}$$

Here, heat loss caused by Q_c convection, D is the dimensions of the material from which heat loss occurs (m), V is the velocity of the gas carrying heat (m/s), visk the viscosity of gas molecules (g/cms), ρ is the density of the gas (kg/m^3), ΔT is the temperature difference (K), λ is the heat conduction coefficient (W/mK), cp is the specific heat (J/kgK) and t is the time *(s).*

Heat loss due to forced convection from garments is greater than with natural convection. The movement of the arms and feet in the garment causes forced transport. According to Fanger (1970), the velocity of the air layer accompanying the body varies between 0.4 -1.8 m/s and the change in air velocity affects the convection heat transfer. As the temperature difference between body surface and air increases, heat loss increases with convection (Ruckman et al. 1999, Huizenga et al. 2001).

Hes et al. (2004) stated that convective heat transfer will increase with the square of the air velocity around the body, but the velocity of the air layer in the garment is very low in classical garment systems and that the openings such as arms, neck and cuffs in the garments accelerate the air around the body. It is contemplated that channels can be opened into the garment to accelerate the air layer. In the studies where the heat loss from a special garment design with long and vertical ducts covering the whole body was measured with a thermal mannequin, it was observed that more heat transfer took place than the channelled garment. The velocity of the air in the duct was also measured by anemometer and it was found that the air velocity was dependent on the dynamic viscosity of the air, expansion coefficient depending on temperature, duct diameter and air temperature.

1.2.5.3. Radiation Heat Transfer

Radiation heat transfer is explained by Stefan-Boltzman's Law. Accordingly, if an object at temperature T_1 is located in an environment at temperature T_2, the body will emit radioactive energy from the unit area at the rate of σT_1^4 and absorb energy at the rate of σT_2^4. The net radiation energy lost by the object:

$$q = \sigma(T_1^4 - T_2^4) \tag{1.5}$$

Here σ ($5.67x10^{-8}\ W/m^2K^4$) is the Stefan-Boltzman constant. This mechanism is more easily described in very high temperature objects such as solar, radiant heaters and fire. The heat loss or absorption of an object by radiation is affected by the color of the object. Black is the color that absorbs heat best and emits the best. White and dyed materials, on the other hand, have a low absorption and radiation performance because most of the energy is reflected.

Since the garment is the first circumferential layer surrounding the body and the temperature difference between the body and the environment is reduced by the garment, it has the effect of reducing the heat loss by radiation. It is not easy to determine the amount of heat lost by radiation from the body because it creates garment print zones and an uneven surface structure (Kaplan and Okur 2005).

CHAPTER II

DEFINITION OF CLOTHING PARAMETERS FOR THERMOPHYSIOLOGICAL COMFORT

In this chapter, thermal parameters of clothing that effect comfort will be discussed in detail. Thermophysiological wear comfort involves the process of heat and moisture transport through clothing and the mechanical behavior of fabric. Factors affecting the thermal behavior of clothing will include the dry thermal insulation, transfer of moisture and vapor through clothing (e.g. sweat, rain), heat exchange with clothing (conduction, convection, radiation, evaporation and condensation), pumping effects (e.g. caused by body movement), and air penetration (e.g. through fabrics, vents and openings). Parameters that decides the thermal behavior of fabrics are explained below.

2.1. Thermal Conductivity of Clothing

Thermal conductivity is one of the most important parameters affecting clothing comfort (Satsurnoto et al., 1997). This value is influenced by many factors such as fiber type, spinning technology, yarn count and twist, hairiness, fabric thickness, covering factor, porosity, amount of body surface area covered with clothing, garment design, fabric construction, number of layers and finishing processes applied to fabric (Varshney, 2010). Since a textile structure consists of a mixture of fibers, air and moisture, each of which has completely different thermal properties, the thermal behavior of the system depends on the collective and interactive result of these three components (Jirsak et al., 1998). According to Ukponmwan (1993) and Holocombe 1983 (1983), the factors affecting the thermal properties of textile structures are:

- Thermal conductivity of air contained in fiber and fabric,
- Specific heat of fiber,
- Fabric thickness,
- Fabric density (amount, size and distribution of air voids in fabric),
- The contact area between the fabric and skin,
- Heat loss through conduction from skin to fabric,
- Heat loss by convection from skin to fabric and fabric surface,
- Radial heat loss (radiant power of skin and fabric surfaces),
- Heat loss by evaporation of water from skin or fabric,
- Heat recovery due to water absorption by fabric,
- Outdoor conditions: temperature, relative humidity and air movement.

Thermal conductivity of a fabric can be calculated using Rule of Mixtures. It is between transverse and in-plane thermal conductivity values which are calculated using series and parallel rule of mixtures equations respectively. k_c as the thermal conductivity of a composite fabric, can be found as follows:

$$(\frac{v_f}{k_f} + \frac{(1-v_f)}{k_m})^{-1} \leq k_c \leq v_f k_f + (1 - v_f) k_{\,m} \qquad \textbf{(2.1)}$$

where v_f and v_m are the volume fractions of fiber and matrix, $k_f$and k_m are the thermal conductivity values of fiber and matrix.

The thermal conductivity of textile fibers is 5 to 20 times higher than that of stationary air ($k_{air} \cong 0.026\, W/\, mK$). The thermal conductivity of air increases by approximately $0.75x10 - 3\, W/mK$ at a $10\, K$ increase in ambient temperature. Therefore, the ambient temperature and thus the temperature of the air in the fabric has an effect on the thermal conductivity of the fabrics.

Marsh (1930) stated that there is a linear relationship between the thermal insulation value and the thickness of the fabric. Marsh revealed that there is a great deal of heat loss through conduction from the body when naked, and thin fabrics have a lower insulation value.

Morris (1953) examined the thermal properties of textile surfaces. He showed that density and thermal conductivity increased and the low density of two fabrics with the same thickness of thermal insulation value is lower than that stated. Higher thermal insulation can be achieved by using textreated or staple synthetic yarns instead of flat surface filament yarns.

McCullough and Jones (1984) explained the heat isolation mechanism of the garment through four mechanisms of heat transfer. The garment provides conductive heat loss with compressed air in and between the fabric layers, convective heat loss by providing a barrier to the surrounding air currents, radiation heat loss by limiting radiation heat loss and sweat evaporation produced in the body by limiting radiation sweat produced in the body.

According to Yoon and Buckley (1984), what determines heat transfer in the garment are as follows:

- Mechanism: dry heat transfer, water vapor and / or liquid heat transfer;
- Propulsion: temperature difference and water vapor pressure in the fabric, capillary forces;
- Adjustable fabric properties: thermal insulation, air permeability, water vapor resistance, free surface energy of fiber and yarn structure.

Various methods have been developed over the years to measure the thermal properties of textile surfaces (Pac et.al., 2001; Farmworth et al. 1990; Li and Wong, 2006a; Kawabata et al., 1989; Hes and Dolezal, 1989). Bomberg (1992) measured the thermal resistance of different fabrics using methods such as Guarded Hot Plate (ASTM C 177), Heat Flow Meter (ASTM CS 18) and Thin Heater (ASTM Cl114) and found differences between them.

Satsumoto et al (1997) measured dry heat transfer with a vertical heating plate simulating the human body and evaluated the usability of this plate instead of thermal manikin.

Table 2.1 shows the thermal conductivity values of various textile fibers. The higher the thermal conductivity of the fiber, the higher the thermal conductivity of the fabric. The thermal conductivity of textile fibers generally increases with increasing moisture content (Warner, 1995).

Table 2.1. Thermal conductivity values of textile fibers and air (Hashan, 2017)

Fiber Type	**Thermal conductivity** (W/mK)
100 % Nylon	0.129
Nylon 6, Nylon 6/6	0.25
100% Silk	0.083
100% Linen	0.188
Acrylic	0.036
Wool	0.031
Lycra	0.026
Viscose	0.031
Polyester	0.05

100% Cotton	0.047
100% Bamboo	0.042
Sheep wool	0.039
Polypropylene, PP	0.12
Air	0.026

Satsumoto et al. (1997), to determine the effect of garment construction factors on heat transfer, such as the size of openings and air voids in garments, measured the thermal conductivity of 100% cotton fabric by vertical hot plate and thermal manikin methods. The aim of these two methods is to imitate the clothed state of the human body. The material simulating the human body in the vertical hot plate method is a hot rubber plate that provides a constant heat flow of 100 W/m^2. The polymethylmethacrylate (PMMA) sheet with heat flow meter is attached to the rubber sheet surface. The measuring fabric, which is arranged in such a way that there is a certain thickness of air layer between the PMMA board and the outside, is outermost. The thermal manikin, on the other hand, is an aluminium block in the form of the upper part of the human body and the measuring fabric is dressed on the mannequin with an air layer between them. In both methods, the air gap between the fabric and the heat source surface (rubber plate/thermal mannequin) was gradually increased to determine the effect of openings in the garments. According to the results of the study, as the air layer between the body and the garment gets warmer with the body temperature, it is found that the amount of heat transfer through conduction decreases and the amount of heat transmitted by convection increases. With the measured conduction, the heat transfer coefficients decreased as the thickness of the air layer increased and the garment openings increased. According to this study, the vertical hot plate method gives more accurate results because it is easier to control the size of the air gap in situations that simulate dressing.

Jirsak et al. (1998), the thermal conductivity of textile surfaces measured by the dynamic and static method and compared the two methods. In the static method, a temperature difference is created between the two surfaces of the textile material and thermal conductivity is calculated directly from the temperature change measured by the thermocouple placed in the material. In the dynamic method, thermal conductivity is not found directly, first the thermal diffusion is measured from the heating process of the material. Thermal diffusion determines the temperature difference that occurs over time *t* at the distance *x* from the heat source and is defined as Equation 2.2:

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = a\,\frac{\partial^2 T}{\partial^2 \mathrm{x}}$$

(2.2)

In Equation 2.2, T temperature (℃), x distance to the heat source (m), t time (s) and a is thermal diffusion (m^2/s). Thermal conductivity, on the other hand, is calculated as a function of thermal diffusion, the specific temperature and density of the material. According to the measurements made according to both methods, the relationship between the thickness of the textile surface and thermal conductivity was observed in the measurements taken by the dynamic method; as the density of the sample increases, the effect of the thickness on the thermal conductivity increases. Under the same measurement conditions, the thermal conductivity values obtained by the dynamic method were generally higher. This was thought to be due to the convection of the temperature difference created temporarily in the porous sample during the measurement. As a result, it was stated that thermal conductivity was affected by the pore size and distribution of the materials.

Schacher et al. (2000), in the study of thermal properties of classical and micro fiber polyester fabrics found that higher thermal conductivity of classical polyester fabrics found. It has been suggested that this is due to the porosity difference between the two types of polyester fibers. Again, Li et al. (2002) showed that fabric thickness and porosity affect the heat conduction properties of fabrics with cotton and polyester fabrics.

Pac et al. (2001), heat transfer from the body to the clothing due to molecular interactions have defined the transfer of thermal energy. Accordingly, if the thermal conductivity of the textile fabric is high, the amount of heat transmitted will therefore be greater, the amount of thermal energy transferred from the body and absorbed by the garment. Pac et al. Measured two different types of cotton (Pima and Coarse S) and two different yarn structures (single ply and double ply) in different stitch lengths to measure the amount of thermal energy absorbed in Joule. loop, two-ply yarn, longer fiber length and fiber structure with better unevenness) absorbed energy is excessive; these fabrics have been found to exhibit higher thermal conductivity.

Schacher (2000) concluded that microfibers have low thermal conductivity and high thermal resistance properties. Majumdar et al. (2010) analyzed different knitted fabric structures which are cotton, cotton-bamboo blended yarns and bamboo. He found that generally, as the volume ratio of bamboo fibre increases, thermal conductivity of knitted fabrics decreases.

Frydrych et al. (2002), made a comparative study of insulation properties of cotton and Tencel fabrics. As a result of the study, it was found that the fabrics produced from cotton yarn had better conductivity and thermal absorption than the fabrics produced from Tencel yarns. They found that Tencel fabrics were better in terms of hot-cold feeling and air permeability.

Heat and mass transfer analyses of fabrics as well as insulation properties, has been made by many researchers in mathematical and experimental studies (Ukponmwan 1993, Fohr and Couton, 2002). Dias and Delkumburewatte (2007) examined the porosity, thickness and moisture content of different knitted fabric structures and developed a theoretical model to estimate their thermal conductivity. Stankovic (2008) examined the relationship between porosity, air permeability and thermal conductivity and designed a new method to test the thermal properties of knitted fabrics. This method has been developed to measure the cooling rate of the body, which is isolated from the environment with fabric and heated to a certain temperature.

Oglakcioglu and Marmarlı (2010) examined the thermal resistance and thermal absorbency properties of cotton knitted fabrics before and after perspiration in dry and wet conditions.

They found that wet fabrics give lower thermal insulation and cooler feel. They also determined that thermal resistance of fabrics decreased and thermal absorbency increased with mercerization process.

All studies on thermal comfort have shown that the amount of air held in the fabric during use is important. It provides good thermal insulation due to the presence of stagnant air in the structure of the fabrics having high compressibility and return ability after compression and the fabrics having high thickness.

- High thermal resistance for cold protection,
- Low water vapor resistance for efficient heat transfer under moderate thermal conditions,
- Fast fluid transfer characteristics and efficient removal of unwanted contact from the liquid to efficiently transmit heat under high thermal conditions.

2.2. Intrinsic Clothing Resistance, (I_{cl})

The most important thermal parameter considered in most clothing designs is the thermal resistance of fabrics to heat transfer. The thermal resistance of the unit area of fabric and garment is defined as thermal insulation, so the measurement of the thermal insulation (insulation) property of materials is possible, in particular by determining the thermal resistance. In addition, physical factors such as thickness, thermal conductivity, air permeability as well as structural factors such as design, cutting, draping and usage are also effective on the thermal insulation properties of the garments (Ukponmwan 1993, Satsumoto et al. 1997).

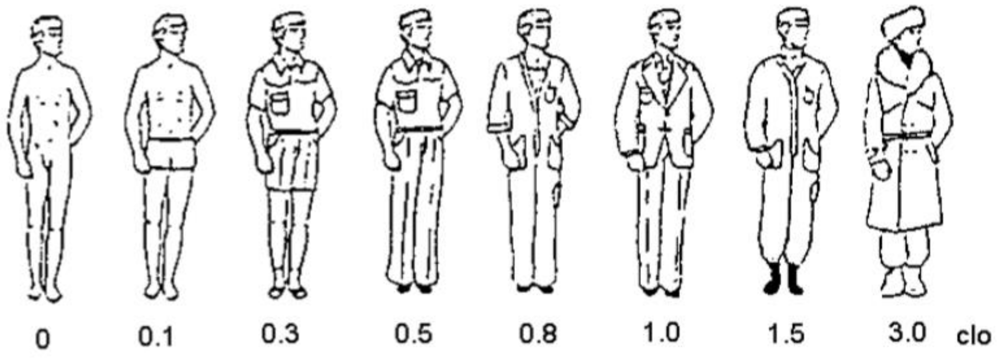


Figure 2.1. Thermal resistance values of classical clothing types (Li, 2001)

Intrinsic clothing insulation, I_{cl} is a property of clothing itself and represents the resistance to heat transfer between skin and clothing surface. Rate of heat transfer through clothing is by conduction and depends on fabric thickness and fabric conductivity. Gagge et al. (1941) defined 1 *clo* which equals to $0.155\,m^2W^{-1}$, it corresponds to the thermal resistance a garment must have for a person in a resting state (producing $1\,met = 58.2\,W/m^2$ of heat) in a room with 21℃ temperature, 50% relative humidity and 0.1 *m/s* air movement. Thermal resistance of different types of clothing in terms of *clo* is shown in Figure 2.1. (Li, 2001). It should be kept in mind that the *clo* value is estimated assuming that clothing was distributed evenly over the body. Even though the insulation of clothing is mainly expressed in *clo* units, in calculations SI units (R_{cl}) is used. A list of different clothing dry thermal insulation values in units of *clo* is given below.

Table 2.2. A list of different clothing dry thermal insulation values in units of *clo*

Garment Description	**Thermal insulation, *clo***
Underwear	
Panties	0.03
Underpants with long legs	0.10
T-shirt	0.09
Shirt with long sleeves	0.12
Half-slip	0.14
Full-slip	0.16
Shirts and blouses	
Short sleeves	0.15
Lightweight long sleeves	0.20
Normal long sleeves	0.25
Flannel shirt, long sleeves	0.15
Trousers	
Shorts	0.06
Straight trousers (thin)	0.15
Straight trousers (thick)	0.24
Sweatpants	0.28
Dresses and Skirts	
Skirt (thin)	0.14
Skirt (thick)	0.23
Light sleeveless dress	0.25
Winter dress long sleeves	0.40
Sweaters	
Sleeveless vest	0.12
Thin sweater	0.20
Sweater long sleeves with turtleneck	0.28
Thick sweater	0.35
Jackets	
Vest	0.13
Light summer jacket	0.25
Smock	0.30
Jacket	0.35
Double-breasted suit jacket (thin)	0.42
Double-breasted suit jacket (thick)	0.48

Table 2.2. Continued A list of different clothing dry thermal insulation values in units of *clo*

Garment Description	**Thermal insulation, *clo***
High insulative, fibre-pelt	
Boiler suit	0.90
Trousers	0.35
Jackets	0.40
Vest	0.20
Outdoor clothing	
Coat	0.60
Down jacket	0.55
Parka	0.70
Fibre-pelt overalls	0.55
Sundries	
Socks	0.02
Thin soled shoes	0.02
Thick soled shoes	0.04
Thick ankle socks	0.05
Boots	0.05
Thick long socks	0.10
Sleepwear and Robes	
Sleeveless short gown	0.18
Short-sleeve short robe (thin)	0.34
Short-sleeve pajamas (thin)	0.42
Long-sleeve long gown (thick)	0.46
Long-sleeve short wrap robe (thick)	0.48
Long-sleeve pajamas (thick)	0.57

$$R_{cl} = I_{cl}0.155 \tag{2.3}$$

The environment provides thermal resistance and environmental conditions affect heat transfer. For a clothed body, the surface area for heat transfer is increased by an amount depending upon the thickness of the clothing layer. This is taken into account using clothing area factor, f_{cl}. Thermal resistance of the environment on a naked person is

$$R_a = \frac{1}{f_{cl} h_{com}} \tag{2.4}$$

f_{cl} = clothing area factor, the surface area of the clothed body A_{cl}, divided by the surface area of the naked body A_D. h_{com} is the sum of heat transfer coefficients of convection and radiation.

$$f_{cl}=1+0.31 I_{cl} \tag{2.5}$$

The total thermal resistance of a clothing plus surface air layer is measured on a heated manikin (ISO, 2004; ASTM, 2005a). It is calculated as

$$R_t = \frac{A(T_s - T_a)}{H} \tag{2.6}$$

The intrinsic thermal resistance of a clothing is determined by subtracting off the ratio of surface air layer resistance to clothing area factor (f_{cl}) from total insulation value:

$$R_{cl} = R_t - \frac{R_a}{f_{cl}} \tag{2.7}$$

Since an air layer is always accompanied by the garment layer during clothing, a resistance value of 0.8 *clo* from the air layer in the indoor environment should also be added to the total insulation. This value shows that in most garment systems, the air layer provides more than half of the total insulation. Fibrous materials serve this purpose perfectly thanks to their capacity to trap large volumes of air. In other words, a textile-based thermal insulator is one that has the maximum air trapping capacity; The contribution of the fiber to thermal insulation is secondary. A garment consisting of more than one layer provides a higher insulation value than a single layer garment because more air is trapped between the layers. On the other hand, the insulation due to the weather outside is not constant and depends on the wind speed. Increasing wind speed adversely affects thermal insulation. Removing the relatively inert, static air on and in the outer surface of the fabric causes the thermal insulation value to decrease. *Clo* values of the air layer at different wind speeds are shown in Table 2.1 (Özipek and Sadıkoğlu 1999, D'Silva and Anand 2001, Önder and Sarıer 2003, Kaplan and Okur 2005).

Stuart and Denby (1983), in the study of heat and water vapor transfer mechanisms in garments under the conditions of changing the speed of air movement, stated that the air flow around the covered body causes pressure difference on the surface of the garment. If the pressure in the garment (around the body) is constant and does not flow into or out of the garment, then the pressure value outside the garment is high at some points and low at some points. If the garment has air permeability, this pressure difference affects the air flow through the garment. If the air flow is proportional to the pressure difference, the pressure value in the garment must be equal to the average outside pressure so that the net total flow is not zero. The inward flow will carry cooler and dry air to the skin, while the air carried out will be moist to the extent permitted by the skin temperature and the equilibrium conditions of the skin.

Table 2.3. Thermal resistance values of air layer (D'Silva and Anand, 2001)

Wind Speed *(m/s)*	***clo***
0.34	0.85
0.4	0.8
0.57	0.7
0.85	0.6
1.37	0.5
2.39	0.4
4.85	0.3
11.9	0.2
22.7	0.15
51	0,1

Heat and water vapor loss will occur as the skin is usually warmer and humid than the environment. In this way, the effect of the wind on the air plate accompanying the garment manifests itself as heat loss. Schacher et al. (2000) in the study of thermal insulation and thermal properties of classical and microfiber polyester fabrics compared, the relationship between the wind speed and the heat loss from the fabric, tight fabrics or fine-textured or fine-textured fabrics will reduce the heat loss by making the passage of fabrics. It has been found that there is a relationship between air flow rate and heat loss when wet and wet fabric gives more heat loss at the same speed value.

In porous materials such as fabrics, the thermal conductivity of the fluid filling the cavity is an important element determining the insulation. If this fluid is air, a good insulation effect is obtained because of the very low heat conductivity of the air. If the voids are filled with water having a high coefficient of thermal conductivity, the thermal insulation of the material will deteriorate. Filling the cavity by fibers improves thermal insulation by further reducing convective heat loss.

2.3. Evaporative Resistance of Clothing, (R_{ecl})

Human skin is always wet to some extent so that there is always an insensible heat loss. The vapor permeation properties of clothing are very important for comfort. The intrinsic evaporative resistance of a clothing (R_{ecl}) is calculated similar to the intrinsic thermal resistance as follows:

$$R_{ecl} = R_{et} - \frac{R_{ea}}{f_{cl}} \qquad \textbf{(2.8)}$$

where R_{et} is the total evaporative resistance and R_{ea} is the evaporative resistance of surface air layer. Evaporative heat transfer coefficient h_e and the convective heat transfer coefficient h_c is related with the Lewis number defined as the ratio of mass transfer coefficient by evaporation to heat transfer coefficient by convection. At sea level for air LR is 16.5 $K\text{-}kPa^{-1}$ and it is affected by the physical properties of gases involved and by atmospheric pressure.

$$h_e = \frac{1}{R_{ea}} \;\; or \; R_{ea} = \frac{1}{16.5h_c} \qquad \textbf{(2.9)}$$

2.4 Vapor Permeability Index, (i_m)

Water vapor permeability refers to the ability to transfer water vapor emitted by the body, also known as unconscious sweating. The relative water vapor permeability is the ratio of the percentage of water vapor transmitted from the fabric sample to the percentage of air vapor passing through the equivalent thickness. The rate of water vapor transmission through the fabric generally decreases with increasing fabric thickness.

Many researches have carried out research studies to determine the water vapor transfer capacity and mechanism that determines thermal comfort properties of sports garments. Hatch et al. (1990), hot and humid environment, the parameters that determine the level of heat dissipation from the body air, heat, water vapor and liquid transmission capacity is stated.

Moisture permeability index i_m was defined by Woodcock (1962) and it is an indicator of the evaporative performance of a clothing. The moisture permeability index is the ratio of total dry resistance to total steam resistance and is an indicator of the evaporation performance of water in the garment. It is defined by ASHRAE (1997) as the ratio of the actual evaporative heat flow capability between the skin and the environment to the sensible heat flow capability as compared to the Lewis Ratio (LR).

$$i_m = \frac{R_t}{LR \times R_{et}} \tag{2.10}$$

where R_t is the total heat resistance and R_{et} is the total evaporative resistance of the garment. In theory i_m ranges from 0 (impermeable) to 1 (completely water vapor permeable). The high permeability index is required for maximum steam cooling and comfort. The i_m value is not a value intrinsic to clothing as it is affected by external environmental conditions. A value of 0.5 is a typical value for a naked subject, 0.4 for normal clothing and 0.2 for impermeable type clothing such as nylon.

2.5. Air Permeability in Clothing and Fabrics

Air permeability is defined as the volume of air flow through the unit fabric surface when there is a certain pressure difference between both sides of the fabric. Air permeability is the mass transfer property most affected by the fabric structure. According to the model in which Yoon and Buckley (1984) associate air permeability with the fabric structure, the air flow occurs in particular through the inter-yarn pores, which are assumed to have cylindrical voids perpendicular to the fabric surface (Tarafdar 1995, Kaplan and Okur 2005).

The air permeability of a fabric affects the comfort property in many ways. Firstly, a material which is permeable to air is generally used for water in vapor or liquid phases. Therefore, the water vapor permeability and liquid water conductivity are closely related to air permeability.

Second, air permeability effects the thermal resistance of a fabric. High air permeability fabrics lose more heat by convection in windy environment.

Larose (1947), in his work on air permeability, wind speed and thermal resistance of garment systems, showed that the decline in thermal resistance caused by the increase in wind speed is higher in systems with high air permeability (Hollies and Fourt 1970). Goodings (1964) examined the air flow mechanism in garments in terms of hydrodynamic flow and found that air flow was laminar and turbulent. The properties of the air flow are influenced by a wide range of dimensions of the pores in the fabric, and changes in the air flow through the permeable fabrics can be formulated by logarithmic correlation. Sudden changes in the direction of air flow in most fabrics cause turbulent flow (Hollies and Fourt 1970).

The study by Epps and Lehonas (1997) on woven fabrics showed that air permeability was highly correlated with minimum pore size and was also related to fabric covering factor. Olsauskiene and Milasius (2001), in their work on air filters produced from 100% polyester fabrics, it was mentioned that air permeability is one of the important parameters of filter fabrics; The relationship between air permeability and fabric structural properties of such technical textile fabrics was also investigated. In the study conducted with plain weave fabrics made from different numbers of multifilament polyester yarns at different frequencies, it was found that air permeability increased as the percentage of relative porous area increased and decreased with increasing stiffness factor. Yarn twist and number of plies had no effect on air permeability.

Zhang et al. (2001) examined the effect of air permeability of garments on the body's thermal balance during exercise. In sequence, they applied the program consisting of 2.5 hours of rest and 1 hour of light exercise in a controlled air-condition of room. During the program, rectal and skin temperatures, relative humidity of the microclimate on the garment and surface temperature of the garment were measured. Mass losses were determined by weighing the subjects before and after the program. Exercises and measurements were repeated under a windless speed of 1.5 *m/s*. As a result of the study, no effect of air permeability on the changes in rectal and skin temperatures seen in exercise in windless environment was found, while in windy environment, it was found that the skin temperatures of those who had high air permeability were much lower. The same tendency was observed at the relative humidity of the microclimate and the surface temperatures of the garment. When exercising with this garment, less mass loss was detected, indicating lower sweat production.

Militky et al. (2003) wrote an algorithm that tries to estimate the air permeability of woven fabrics by using artificial neural network method and used yarn smoothness and weft - warp densities as data to estimate air permeability of fabrics. The program gave a high correlation between measured and predicted air permeability.

2.5.1 Fiber Porosity, (*P*)

Porosity is the ratio of the volume of voids to the total volume of nonwoven fabric. It can be calculated as follows:

$$\varphi(\%) = \frac{\rho_{fabric}}{\rho_{fibre}} \times 100\ \% \qquad \textbf{(2.11)}$$

$$P(\%) = (1 - \varphi) \times 100\% \qquad \textbf{(2.12)}$$

where P is the fabric porosity (%), φ is the volume fraction of solid material (%), ρ_{fibre} is the fiber density and ρ_{fabric} is the fabric bulk density. When porosity is 100% then the fabric is totally open and this cannot be. When porosity is 0% then the fabric is solid without any pore volume.

2.5.2. Permeation Efficiency Factor, (f_{pcl})

Permeation efficiency factor f_{pcl} is defined by Nishi and Gagge (1970) with the aim of describing the cooling efficienct of sweating of the skin surface for a clothed human body.

$$f_{pcl} = \frac{1}{1+0.143\times h_c\times I_{cl}} \qquad \textbf{(2.13)}$$

The relationship between f_{pcl} and i_m is governed by Nishi and Gagge (1970):

$$f_{pcl} = \frac{i_m}{h_c\times(I_{cl}+I_a)} \qquad \textbf{(2.14)}$$

where I_{cl} and I_a are in clo.

2.6 Fabric Structure and Thermal Comfort

There are many studies on the effect of different fabric structures on comfort properties. Onofrei et al. (2011) proposed knitted fabric structures suitable for users' activity levels. If the user's activity level is moderate, the fabrics with high air permeability and low thermal resistance properties are suitable as the moisture of the skin will be very low. In more intense activities, skin temperature and wetness increase rapidly. In this case, the fabrics are expected to have high air and water vapor permeability, low thermal resistance, high diffusion and fast drying properties. For high density activities, they suggested single jersey fabrics with high air and water vapor permeability and low thermal resistance.

Comfort zone definition was first attempted to be made by Houghten and Yagloglou (1923) at the ASHRAE (American Society of Heating and Ventilating Engineers) laboratories in 1920s. (Auliciems and Szokolay, 2007) Missenard (1931) and Buettner (1934) made studies to express the heat and mass transfer from humans to the environment analytically. In the following years during World War 2, clothing used in wars tried to be developed by military laboratories to meet the challenging environmental conditions. A new development was the thermal manikin that led the invention of *clo* unit (Gagge et al., 1941) which was the measurement of the insulation of clothing.

Improvement of the clothing science was started with the manikin and continued with the work of Newburgh (1949). About the same time, Pennes (1948) modeled the single element of the human body and developed the BIO-HEAT equation to be able to calculate the steady state temperature distribution in human arm, which was taken as a cylinder. The model consists of conduction in the radial direction of the cylinder, metabolic heat generation in the tissue, convection occurs due to circulating blood, heat loss from the surface of the skin by convection, radiation and evaporation. Furthermore, Gagge modeled human body as a single cylinder that is divided into two concentric shells which are core and skin. According to the assumption Gagge made, the temperature of each layer is uniform and heat is transferred from core to the skin through the blood and tissue conduction. Energy balance equations were written and convection due to blood flow, conduction through tissue layers, respiration and shivering were included. The heat transfer between skin and the environment was also included in the model. Gagge model is used to predict thermal comfort for moderate activity levels and uniform environmental conditions meaning that dry bulb temperature is between 5°C - 45°C and humidity is down to 10% (Yıldırım, 2005).

Gulsevin (2005) studied on high performance clothing for athletes, and used leather in contact with the inner layer of polyester, acrylic, nylon and polypropylene, which has good moisture transmission properties of synthetic materials. He stated that double-layered fabrics using materials are ideal structures. The sweat accumulated in the microclimate formed on the skin surface is transferred from the inner surface of the fabric to the outer surface and absorbed by the fibers in the outer layer. When high absorbency fibers are used on the inner surface of the fabric, the skin constantly comes into contact with the wet fabric and creates an uncomfortable feeling for the user (Çeken, 2004). Higgins and Anand (2003) proposed double-ply fabrics with polyester on the inner surface and hydrophilic or fine filament yarns on the outer surface.

Oğlakçıoğlu and Marmaralı (2007) compared the thermal properties of different knitted fabrics. As a result, they found that interlock braids had higher thermal conductivity and lower water vapor permeability than rib braids. They also found that flat weaves are better suited for sportswear and summer wear with better moisture transmission properties. Majumdar et al. (2010) compared 100% cotton, 50/50% cotton/bamboo and 100% bamboo ring yarns produced in various knitting structures and reached the following results; Interlock fabrics have the highest thermal conductivity, thermal conductivity decreases with increasing amount of bamboo fiber, and thermal conductivity decreases with decreasing yarn count.

Mavruz et al. (2009) found that air permeability decreases with increasing frequency, thickness and weight in single jersey fabrics. Srinivasan et al (2007) showed that fabrics made of microfibers are suitable for sportswear production due to their high draping, better dimensional stability, quick drying, high moisture and water absorbency and excellent moisture transmission properties.

Marmaralı et al. (2009) stated that sparsely structured knitted fabric gives warmer feeling with higher insulation and air permeability and low thermal absorbance value, and frequent and medium density fabrics have better water vapor permeability. Ozdil et al. (2007) worked on 100% combed cotton yarn knitted rib fabrics. When thin yarn is used thermal conductivity is seen to be lower and water vapor permeability is seen to be higher. As the yarn twist increased, the thermal resistance of the fabrics decreased while the thermal absorbency and water vapor permeability increased. The effect of yarn twist on thermal conductivity was not observed. Onofrei et al. (2011) found that 2x2 and 3x3 rib knitted fabrics for cold weather sportswear have higher thermal resistance and satisfactory liquid moisture conduction property. Flies et al. (2004) rib knit sections, fiber and fabric structure due to air gaps due to conductive heat loss, heat loss due to air flow is more important and convective heat loss is more than woven fabrics stated. As the air trapped in the fabric increases, the loss of heat decreases as rib lines decrease.

Oğlakçıoğlu et al. (2009) investigated the thermal properties of 100% cotton and angora/cotton blended ring and rotor spinning yarns in three different ratios 1x1 rib fabrics. The results showed that yarn hairiness, fabric thickness and thermal resistance values increased as angora fiber ratio increased; showed that thermal absorbency and relative water vapor permeability values decreased. Fabrics knitted with ring yarns give warmer feel, higher thermal resistance and lower water vapor permeability at the first contact. In addition, angora fibers with high thermal resistance values are reported to be more suitable for use in winter clothing.

Wu and Zhang (2009), polypropylene fibers and other hydrophilic fibers produced by using the knitted fabrics have high moisture transmission properties and stated that it may be advantageous to work with thin polypropylene fibers. It was found that viscose fiber, which was used with polypropylene fiber, had the best moisture conduction property, followed by cotton fiber. In addition, moisture transmission of fabrics such as single jersey having a very porous surface and low covering factor was found to be quite high.

Bivainytė et al. (2011), cotton and regenerated bamboo yarns for the outer layer; examined two-ply knitted fabrics using PP, PA, PES and Coolmax® (four-channel polyester fiber) yarns for the inner layer. As a result of the study, the air permeability of the double layered knitted fabrics was mostly determined by the stitch yarn length; found that the water vapor permeability is affected by the material used. Marmaralı et al. (2009) compared knitted fabrics containing three different ratios of elastane yarn, and found that as the amount of elastane increases, fabric density and thermal resistance increases while the value of air and water vapor permeability decreased.

CHAPTER III

PROBLEM STATEMENT AND MODEL

3.1 Introduction

Heat and moisture are dissipated from the skin of human body. Heat may be transferred from the exposed skin to environment either by convection or radiation. It is also possible that heat may be transferred into the clothing microclimate. In the clothing microclimate, some energy is transferred away by ventilation; the remainder goes through clothing materials. Finally, heat goes out from the outer surface of clothing ensembles to the environment.

Moisture follows the pathway from skin to clothing and clothing to environment. Nevertheless, in the clothing materials, the mechanisms of heat and moisture transfer are very different. It involves very complex processes. Conduction, convection, and radiation are the mechanism of heat transfer; diffusion, absorption/desorption, condensation/evaporation and wicking are the mechanism of moisture transfer. Absorption/desorption and condensation/evaporation are accompanied with heat releasing and absorbing. So the moisture transportation is coupled with heat transfer**.**

Assuming that there is no condensation and absorption of moisture vapor in the clothing layer, the heat generated by body will be transferred to the environment as sensible and evaporative heat by convection, radiation, conduction, air ventilation and penetration.

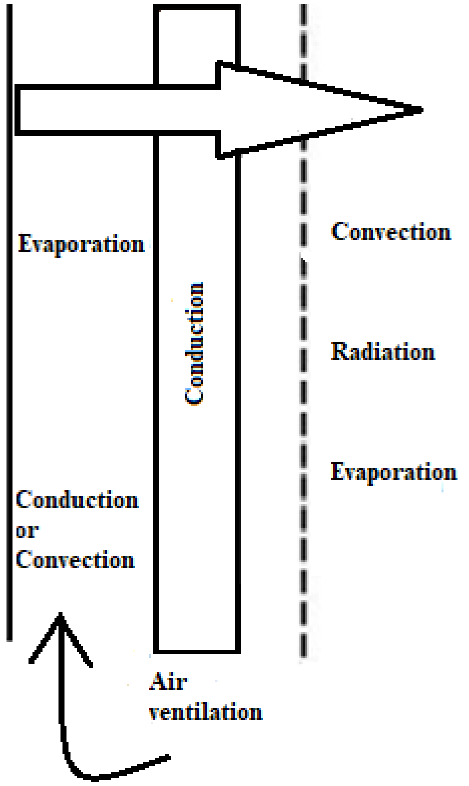


Figure 3.1 Model scheme for skin-clothing-environment system

3.2 Governing Equations and Boundary Conditions

The human body has always uniform internal temperature of about 37 °C. This means that there is a heat transfer between the body and environment. Heat generation within the body and heat losses from the body should be balanced to keep the body at the required temperature.

Body surface area can be found as:

$$A_D = 0.202w^{0.425}h^{0.725} \quad \textbf{(3.1)}$$

A_D is in square meters, body weight (*w)* in kilograms and height (h) in meters.

The heat exchange equation between human body and environment was given by ASHRAE (1989a) as follows:

$$S = M - W - (R + C + K) - E \quad \textbf{(3.2)}$$

For heat balance $S = 0$,

$$M - W - E_{diff} - E_{rsw} - E_{res} - C_{res} = K = R + C \quad \textbf{(3.3)}$$

$$Q_{dry} = K + C + R \quad \textbf{(3.4)}$$

$$Q_{latent} = E_{diff} + E_{rsw} + E_{res} + C_{res} \quad \textbf{(3.5)}$$

where all terms have units of Wm^{-2} and

$S =$ the body heat storage rate

M = rate of metabolic energy production

W = rate of mechanical work

(*M*−*W*) = rate of heat production within the body

$E =$rate of evaporative heat loss

C = rate of convective heat loss from the skin (positive value is heat loss, negative value is heat gain)

R = rate of radiative heat loss from the skin

$K =$rate of conductive heat transfer

E_{rws} = rate of evaporative heat loss from the skin through sweating

E_{dif}= rate of evaporative heat loss from the skin through moisture diffusion

Q_{sk} =(C+R+E_{sk})= heat loss at the skin

C_{res} = rate of convective heat loss from respiration

E_{res}= rate of evaporative heat loss from respiration.

3.3 Typical Skin Temperatures

The skin temperature may change to keep the core temperature in a range of 36-38℃. In neutral conditions, typical skin temperature values for 16 body segments were provided a by UC Berkeley (Zhang, 2003). Olesen and Fanger (1973) also provides data taken from subjects wearing office clothing (Arens, 2006). Both data can be seen in Table 3.1

When the skin temperature is 33.4℃, it is thought to be the most comfortable feeling. The comfort feeling continues when the skin temperature in any part of the body varies from this ideal temperature by 1.5-3℃. If the difference is more than ± 4.5℃, the human body feels uncomfortable. In addition, an increase or decrease in skin temperature of 1.5℃ compared to 36.5℃ can be life-threatening. Hypothermia can occur when the skin temperature drops below 35℃. The constant skin temperature can be expressed as approximately 34-36.5℃ for the trunk, 25.5-27.5℃ for the hands and feet, and 27-30℃ for the arms and legs (Önder and Sarıer 2003).

Table 3.1 Local skin temperatures for neutral conditions ℃

Segment	Skin temperature ℃ Zhang’s UC Berkeley Model (2003)	Skin temperature ℃ by Olesen and Fanger (1973)
Forehead	35.8	34.2
Cheek	35.2	–
Front neck	35.8	–
Back neck	35.4	–
Chest	35.1	34.5
Back	35.3	34.4
Abdomen	35.3	34.9
Upper arm	34.2	33.5
Lower arm	34.6	32.7
Hand	34.4	33.5
Left finger	35.3	–
Thigh	34.3	33.7
Shin	32.9	32.6
Calf	32.7	32.2
Foot	33.3	32.2
Average	34.45	33.38

3.4 Dry Heat Transfer

Unless the clothing is skin tight, there is a microclimate between skin and clothing. Spencer-Smith (1977) found in his measurements that convection was negligible if the air gap is less than 0.8 cm. If it exceeded 0.8 cm than natural convection would occur within the microclimate. In this paper microclimate thickness is assumed to be less than 0.8 cm. Therefore, the thermal resistance network for dry heat transfer is shown in the figure 3.2 and it is drawn by assuming skin is in contact with the clothing.

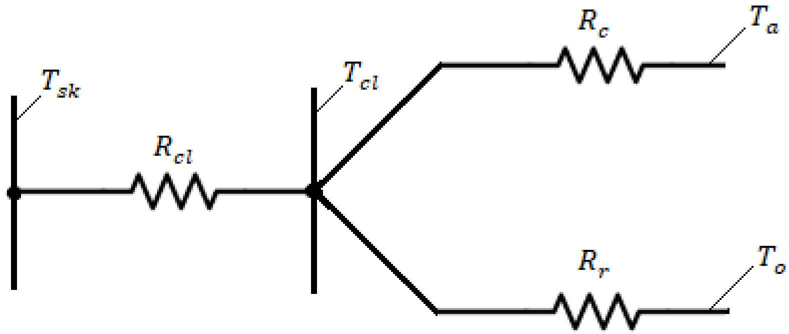


Figure 3.2. The thermal resistance network for dry heat transfer

$$R_t = R_{cl} + (\frac{1}{R_c} + \frac{1}{R_r})^{-1} \tag{3.6}$$

$$R_c = \frac{1}{f_{cl} \cdot h_c} \tag{3.7}$$

$$R_r = \frac{1}{f_{cl} \cdot h_r} \tag{3.8}$$

The actual transfer of heat through clothing (conduction, convection, and radiation) is combined into a single thermal resistance value to find total thermal insulation of the clothing system.

$$R_t = R_{cl} + \frac{1}{f_{cl} \cdot (h_c + h_r)} \qquad \textbf{(3.9)}$$

where f_{cl} is the clothing area factor. It is used to take into account that increase of the surface area of the body due to the thickness of the clothing layer. Also, it equals to the surface area of the clothed body A_{cl}, divided by the surface area of the nude body A_D. From McCullough et al. f_{cl} relates to R_{cl} as below:

$$f_{cl}=1+0.31I_{cl} \qquad \textbf{(3.10)}$$

$$R_{cl} = I_{cl}0.155 \qquad \textbf{(3.11)}$$

I_{cl} is intrinsic clothing insulation, that is a property of the clothing itself. Gagge et al. proposed the Clo unit for clothing insulation and one Clo can be said to be thermal insulation needed for keeping an inactive person comfortable at 21 °C. One Clo has an average value of 0.155 m^2°CW^{-1}. It should be kept in mind that the Clo value is estimated assuming that clothing was distributed evenly over the body. Even though the insulation of clothing is mainly expressed in Clo units, in calculations SI units (R_{cl}) is used.

ASHRAE (1997) gives the following derivation for conduction, radiation and operative temperature, respectively:

$$K = \frac{(T_{sk} - T_{cl})}{R_{cl}} \qquad \textbf{(3.12)}$$

$$C = f_{cl} h_c (T_{cl} - T_a) \qquad \textbf{(3.13)}$$

$$R = f_{cl} h_r (T_{cl} - T_r) \qquad \textbf{(3.14)}$$

$$T_o = \frac{(h_r T_r + h_c T_{a)}}{h_r + h_c} \quad and \quad h_{com} = h_r + h_c \qquad \textbf{(3.15)}$$

The total dry heat transfer of a clothing system is as follows:

$$Q_{dry} = \frac{A_{cl} \cdot (T_{sk} - T_o)}{R_t} \qquad \textbf{(3.16)}$$

where

A_{cl}= the area of the clothing (m^{-2})

h_c = convective heat transfer coefficient (W$m^{-2}K^{-1}$)

h_r = linear radiative heat transfer coefficient (W$m^{-2}K^{-1}$)

h_{comb} = combined heat transfer coefficient (W$m^{-2}K^{-1}$)

T_o = operative temperature (°C)

T_{mr} = mean radiant temperature (°C)

T_a= air temperature (°C)

T_{cl}= mean temperature over the clothed body (°C)

T_{sk}= mean skin temperature (°C)

R_{cl} =conductive resistance of clothing (m^2KW^{-1})

Convective heat transfer coefficient, h_c can be calculated using the expressions that developed through manikin experiments in wind tunnel by Oguro et al. (2002b) and deDear (1997) separately. The expressions are for the moving air and can be seen below:

Table 3.2 Convection heat transfer coefficients of moving air

	DeDear (1997)	*Oguro (2002b)*
Standing	$h_c = 10.4V^{0.56}$	$h_c = 9.41V^{0.61}$
Seated	$h_c = 10.1V^{0.61}$	$h_c = 9.43V^{0.63}$

Oguro et al. (2002a) used the same manikin to find the still air (velocity <0.1 m/s) convective coefficients between skin and air. For the overall body seated and standing coefficients can be calculated respectively as follows:

$$h_c = 0.78(T_{skin} - T_a)^{0.56} \tag{3.17}$$

$$h_c = 1.21(T_{skin} - T_a)^{0.43} \tag{3.18}$$

The radiation heat transfer coefficient between clothing surface and environment is as follows:

$$h_r = 4\varepsilon\sigma \frac{A_r}{A_D}\left[273.2 + \frac{T_{cl}+T_o}{2}\right]^3 \tag{3.19}$$

where ε is the area weighted emissivity of the clothed body, A_r is effective radiative area of the body and the ratio A_r/A_D can be estimated 0.73 for a standing person (Fanger, 1967), σ is the Stefan-Boltzmann constant and its value is 5.67×10^{-8} $W/\mathrm{m}^2\mathrm{K}^4$. According to ASHRAE (1997), h_r can be taken as 4.7 $Wm^{-2}K^{-1}$ for unclothed body at ‘typical indoor conditions’.

3.5 Evaporative Heat Loss

Evaporation of sweat is a form of heat release on the surface of the skin during transpiration. Sweat on the skin evaporates at the skin surface and reaches to the environment by passing through the clothing. The total evaporative (latent) heat (Holmér and Elnäs 1981; Gagge and Gonzalez 1996) may be given as follows:

$$E = E_{sk} + E_{res} = \dot{m} \cdot \frac{h_{fg}}{A_D} \qquad \textbf{(3.20)}$$

where E_{sk} and E_{res} are the evaporative heat loss from skin and respiratory heat loss, respectively, $\frac{W}{m^2}$, $\dot{m}$ is the body weight change per unit time, h_{fg} is the latent heat of sweat evaporation (40.8 Whg^{-1}).

Evaporative heat loss from the skin is important for clothing comfort. It is calculated using clothing vapor resistance and necessary for determining the sweat secretion and accumulation on the skin surface which is also based on evaporation transfer through the clothing layers. Thermal resistance network can be used to calculate total evaporative resistance from skin to clothing.

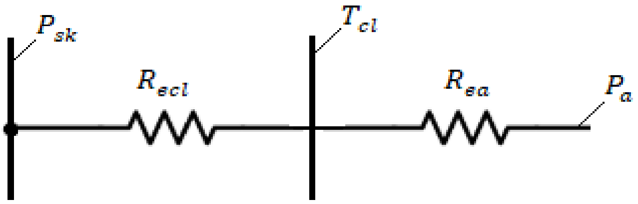


Figure 3.3. Evaporative resistance from skin to clothing

$$R_{e,tot} = R_{ecl} + R_{ea} \tag{3.21}$$

$$R_{ea} = \frac{1}{h_e} \tag{3.22}$$

The sum of latent heat transfers from skin to environment for steady state condition is given as follows (ASHRAE, 1997):

$$E_{sk} = \frac{w \cdot (P_{sk,s} - P_a)}{(R_{ecl} + {}^{1}/{}_{f_{cl} \cdot h_e})} \tag{3.23}$$

$$E_{max} = h_e \cdot (P_{sk,s} - P_a) \tag{3.24}$$

$$P_{sk,s} = \frac{1}{10} \exp\left(18.956 - \frac{4030}{T_{sk} + 235}\right) \tag{3.25}$$

$$\varphi = \frac{P_a}{P_{sa}} \tag{3.26}$$

with

$$E_{sk} = E_{sw} + E_{dif} \tag{3.27}$$

where E_{sk} is the evaporative heat loss from skin (W/m^2), E_{rsw} is the regulatory sweat evaporation heat loss and E_{dif} is the heat loss through moisture diffusion from skin, w is the skin wettedness, P_{sk} and P_a are the water vapor pressures on the skin and in the air (kPa), φ is the relative humidity in the air, R_{ecl} is the clothing intrinsic evaporative resistance and h_e is the evaporative heat transfer coefficient (W/m^2kPa) and is linked to h_c with Lewis Relation (ISO11079; ISO 9920; ISO 7933; Havenith et al., 1990b; Lotens and Havenith, 1991; McCullough et al., 1989). It can be expressed as follows:

$$h_e = LR \cdot h_c = 0.0165 \cdot h_c \tag{3.28}$$

$$LR = 0.0165 \ {}^\circ C/Pa \tag{3.29}$$

$$h_e = \frac{LR \cdot i_m}{I_{cl} \cdot 0.155} \tag{3.30}$$

$$i_m = \frac{R_t}{R_{et}} \times 60.6 \tag{3.31}$$

$$R_{et} = 60.6\left(\frac{1}{h_c} + 0.344 I_{cl}\right) \tag{3.32}$$

where i_m is the moisture permeability index which is a property proposed by Woodcock (1962). ASHRAE (1997) defines the moisture permeability index of a material as the ratio of evaporative heat transfer capability between skin and environment to the sensible heat transfer capability as compared to the Lewis Ratio. Moisture permeability index ranges from 0 to 1 and it is 0 for a material that impermeable to water vapor and 1 for air. For clothing permeability index ranges from 0 for impermeable to 0.5 permeable clothing. Zuo and

McCullough (2004) found that not the fiber material but the fabric structure can significantly affect the moisture permeability.

$$F_{cl} = \frac{I_a}{I_T} = \frac{1/(h_c + h_r)}{I_T} \tag{3.33}$$

$$F_{pcl} = \frac{i_m}{h_c \times (I_a + I_{cl})} \tag{3.34}$$

where F_{cl} is Burton's clothing efficiency factor, F_{pcl} is the permeation efficiency factor described by Nishi and Gagge (1970) and I_a is the insulation of boundary air layer in clo, I_T is the heat resistance in clo.

Skin wettedness is another significant factor for thermal comfort. It can take values from 0.06 which is when only natural diffusion of water occurs on skin (E_{dif}), to 1.0 which is when maximum evaporation occurs (E_{max}). There is always an insensible heat loss from skin through diffusion, therefore it would be correct to say that human skin is always wet to some extent. This makes the vapor permeation properties of clothing very significant. For a clothed person to feel comfortable w should be less than 0.2. Calculation of skin wettedness is as follows:

$$w = 0.06 + 0.94 \cdot \frac{E_{rsw}}{E_{max}} \tag{3.35}$$

$$E_{max} = \frac{(P_{sk,s} - P_a)}{(R_{ecl} + {}^{1}/_{f_{cl} h_e})} \tag{3.36}$$

w_{dif} is skin wettedness required for diffusion of water from skin and w_{rsw} is the wettedness due to regulatory sweat.

$$w_{dif} = 0.06 \cdot (1 - w_{rsw}) \quad \textbf{(3.37)}$$

$$w_{rsw} = \frac{\dot{m}_{rsw} \cdot h_{fg}}{E_{sk}} = \frac{E_{rsw}}{E_{sk}} \quad \textbf{(3.38)}$$

Moreover, in ISO 7730, for a comfort state required skin temperature and required sweat evaporation is given as a function of metabolic rate *M* as follows:

$$T_{sk,req=}35.7 - 0.0275(M - W) \quad \textbf{(3.39)}$$

$$E_{rsw} = 0.42 \cdot (M - W - 58) \quad \textbf{(3.40)}$$

And evaporation due to skin diffusion as:

$$E_{dif} = 0.00305 \cdot (256 \cdot T_{sk} - P_a - 3370) \quad \textbf{(3.41)}$$

Using ISO 7730, Havenith et al. (2002) provides following figure which shows the relation between metabolic rate and skin wettedness for different vapor resistance values with equal heat resistance (0.6 clo) of clothing.

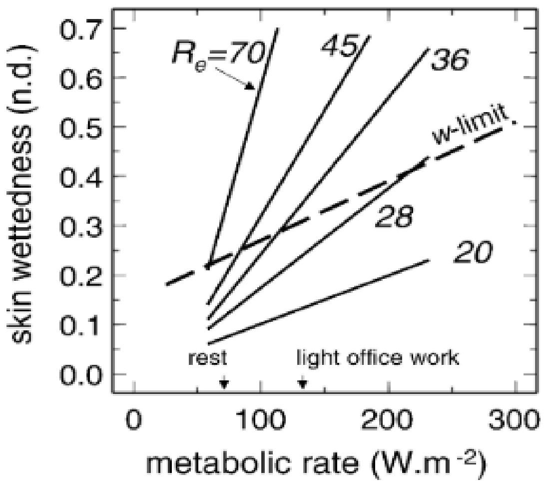


Figure 3.4. Relation between metabolic rate and skin wettedness for various clothing types with equal heat resistance (0.6 clo), but differing in vapor resistance. The dashed line gives the skin wettedness limit for comfort as defined by Nishi and Gagge (1977). (from Nishi and Gagge, 1997).

The dashed line is the skin wettedness limit to reach a comfort state and it is defined by Nishi and Gagge. In the figure it can be seen that skin wettedness and activity level are directly proportional. (Havenith, 2002) Using the estimation of skin temperature for comfort based on metabolic rate (ISO 7730), Havenith et al. use the following equation to calculate w:

$$w = \frac{E_{sk}}{E_{max}} = 0.06 + \frac{E_{sw} \cdot R_e}{p_{sk} - p_a} = \frac{0.42 \cdot (M - 58) \cdot R_e}{5770 - 7.2 \cdot M - p_a} + 0.06 \qquad \textbf{(3.42)}$$

Nishi and Gagge (1970) proposed that there is a limit of *w* for thermal comfort depending on metabolic rate (*M*):

Comfort requirement: $w < 0.0012 \cdot M + 0.15$ **(3.43)**

In hot conditions sweat secretion rate becomes the most critical heat transport mechanism. Umeno et al. (2001) states in his proposal that the sweat accumulated on the skin surface cannot exceed a limit of 35 g/m^2. The excess amount of sweat either should be absorbed by the clothing or dripped down at skin surface. Therefore, for a clothed body part, sum of moisture evaporation transferred through clothing and moisture absorbed by the clothing $\dot{m}_{clo,cloth}$ is equal to the moisture production from skin sweating $\dot{m}_{sw}$ kg/m^2s . (Jones and Ogawa, 1992):

$$\dot{m}_{sw} = \dot{m}_{clo,cloth} + \frac{(P_{sk,s} - P_a)}{\lambda_{H_2O} \cdot R_{e,tot}} \tag{3.44}$$

where λ_{H_2O} is the enthalpy of water vaporization 2256 kJ/kg. There are different sweating secretion rate calculations developed by different researchers in literature. Sweat secretion is required to model the sweat accumulation on the skin, as well as sweat evaporation from the skin and sweat transport through the clothing (Wan, 2008). Tanabe et al (2002) develops the 65-node model which consists of sixteen segments and four layers, based on the Stolwijk model. He calculates sweating secretion rate and heat loss by evaporation of sweat for each body segment as follows:

$$\dot{m}_{rsw}(i, 4) = \{C_{sw} \cdot Err(1,1) + S_{sw} \cdot (Wrms - Clds) + P_{sw} \cdot Wrm(1,1) \cdot Wrms\} \cdot SKINS(i) \cdot 2^{Err_{(i,4)}/10}/\lambda \tag{3.45}$$

$$E_{sw}(i,4) = \lambda \cdot \dot{m}_{rsw}(i,4) \qquad \textbf{(2.46)}$$

where, λ is the latent heat of evaporation of water (Jkg^{-1}), $SKINS(i)$ is fractional distribution over the skin area for sweat, and $Err(i,j)$ is error signal. C_{sw}, S_{sw} and P_{sw} are control coefficients taken from his experiment.

Smith (1991) suggests an equation using core and skin temperatures to calculate sweat rate. He states that there is a threshold, t_{sweat}, which the core temperature reaches and sweating begins and after this level, the sweat rate shows a linear dependence to core temperature. If the core temperature exceeds this threshold or 37.1℃ sweating occurs. The sweating threshold is calculated based on the mean skin temperature t_{skin}:

$$t_{sweat} = \begin{cases} 42.084℃ - 0.15833 t_{skin} \; for \; t_{skin} < 33℃ \\ 36.85℃ \; for \; t_{skin} \geq 33℃ \end{cases} \qquad \textbf{(3.47)}$$

Therefore, $\dot{m}_{sw}$ is approximated by Smith (1991):

$$\dot{m}_{sw} = \frac{45.8℃ + 739.4 \cdot (t_{core} - t_{sweat})}{3.6 \cdot 10^{6} ℃ \, s/kg} \; for \; t_{core} > t_{sweat} \qquad \textbf{(3.48)}$$

Between the sweating rates 0 g/h and 696 g/h skin wettedness increases linearly:

$$w = 0.06 + \frac{1 - 0.06}{0.000193 kg/s} \dot{m}_{sw} \qquad \textbf{(3.49)}$$

Shapiro et al. (1982) predicted the sweat loss of the clothed human body in hot environment under a specific activity:

$$\dot{m}_{sw} = 27.9 \cdot \frac{E_{req}}{(E_{max})^{0.455}} \quad \textbf{(3.50)}$$

where m_{sw} is the sweat loss (g/m^2h), E_{req} is required evaporative heat loss and E_{max} is maximum evaporative heat loss in Wm^{-2}. This equation is limited to 50$<$ E_{req} $<$360 Wm^{-2} and $20 < E_{max} < 525$ $Wm^{-2}$and evaluated between 20 °C and 54°C. Later independent researchers showed that this equation often over predicts sweating rates. Gonzales and co-workers initiated a new research and updated the equation by taking into account effects of heavy work, clothing factors and different environments:

$$\dot{m}_{sw} = 147 + 1.527 \cdot E_{req} - 0.87 \cdot E_{max} \quad \textbf{(3.51)}$$

When body produces less sweat than it can evaporate from body surface, meaning that evaporation is not restricted by clothing, then

$$E_{sk} = \dot{m}_{sw} \cdot h_{fg} \quad \textbf{(3.52)}$$

where $\dot{m}_{sw}$ is sweat rate in *g/h* and h_{fg} is the heat of vaporization for sweat at 35°C. When the evaporative capacity of the body is lower than the amount of sweat produced, part of the sweat drips off and the evaporative heat loss is:

$$E_{sk} = LR \cdot 6.45 \cdot A_D \cdot (\frac{i_m}{I_t}) \cdot (P_{s,sk} - P_a) \quad \textbf{(3.53)}$$

In literature there are various ways of predicting sweat rate of human body developed by researchers through experiments. In Table 3.3 the sweat rate formulas can be seen.

Table 3.3. Sweat rate formulas

Author	$\dot{m}_{sw}$ **Equation**	**Assumptions**	**Observations**
J.A.J. Stolwijk (1971)	$\dot{m}_{sw,i} = (EB(i,4) + SKINS(i) \cdot SWEAT \cdot 2^{\frac{T(i,4)-T_{set}(i,4)}{4}})/\lambda$ where $EB(i,4)$ is diffusion heat loss from skin, $SKINS(i)$ fraction of sweating for skin of segment i , $SWEAT$ is total efferent sweat command, $T_{set}(i,4)$ is set point temperature for receptors on skin segment.	-An averaged man with a body weight of 74.1 kg and surface area of 1.89 m^2. - $EB(i,4)$ is the heat loss through sweat by water vapor diffusion and given as a constant	-25 node -6 body segments -Limited to constant environment conditions -Control system equations are functions of two tissue temperature signals, hot/cold and rate of tissue temperature change signal. -Does not take into account the clothing insulation.
Y. Shapiro (1982)	$\dot{m}_{sw} = (27.9) \cdot \frac{E_{req}}{(E_{max})^{0.455}}$	-Derived for a clothed human body in environments that is between 20℃ and 54℃ - limited to 50< E_{req} <360 Wm^{-2} and $20 < E_{max} < 525\ Wm^{-2}$	-Independent evaluations indicate that this equation over predicts sweating rates.

Table 3.3 Continued

C. Smith (1991)	$\dot{m}_{sw} = \frac{(45.8)℃ + (739.4)\cdot(t_{core} - t_{sweat})}{(3.6\cdot 10^{6})℃\, s/kg}$	-Sweating starts after the core temperature reaches a threshold, $\boldsymbol{t_{sweat}}$. Therefore it is valid for $\boldsymbol{t_{core} > t_{sweat}}$	-15 segments -Transient, 3-D KSU thermal model -The higher the skin temperature, the lower the sweating threshold. -For core temperatures higher than or equal to 37.1℃ sweating always occurs regardless of skin temperature
R.R. Gonzalez (2001)	$\dot{m}_{sw} = 147 + 1.527\cdot E_{req} - 0.87\cdot E_{max}$	-Valid for; -Metabolic rates (rest to $\leq 450 W/m^2$) -Ambient temperature between 15 ℃ and 46℃, -Wind speed, 0.4-2.5 m/s	-Wide range of environmental conditions and metabolic rates
S. Tanabe (2002)	$\dot{m}_{sw,i} = \{C_{sw}Err(1,1) + S_{sw}(Wrms - Clds) + P_{sw}Wrm(1,1)Wrms\}SKINS(i)2^{Err(i,4)/10}/\lambda$ where C_{sw}, S_{sw} and P_{sw} are sweat control coefficients, $Wrm(i,j)$ is warm signal (℃), $Wrms$ is integrated warm signal (℃),$Clds$ is integrated cold signal (℃), and $Err(i,j)$ is error signal (℃).	An averaged man with body weight of 74.430 kg and the body surface area 1.870 m^2.	-Based on Stolwijk -16 body segments -65 node -Transient and non-uniform conditions -Able to predict physiological conditions for different parts of the body -Control equations contain sensor signals relating to the head core signal, skin thermoreceptor signals and signals related with both.

3.6 Heat Loss from Respiration ($C_{res} + E_{res}$)

Respiration heat loss consists of evaporative (latent) heat loss and sensible heat loss. C_{res} is heat loss due to breathing cool air and exhaling heated air to the environment and is proportional to the water vapor pressure gradient between the lung and the ambient air. E_{res} is mass transfer from body to environment occurring when exhaled. According to ASHRAE (1997) total respiratory heat loss:

$$C_{res} + E_{res} = [0.0173M(5.87 - P_a) + 0.0014M(34 - T_a)] \tag{3.54}$$

where P_a in *kPa*, M in Wm^{-2} and T_a in °C.

3.7 Effects of Air Movement on Clothing Thermal and Vapor Resistances

The air movement around the body or the movement of body itself cause thermal insulation and vapor resistance of clothing to be reduced. ISO 9920 (2009) provides correction equations for air movement and walking that are valid for relative air velocities bigger than 0.15 m/s. The equations apply to the entire body.

$$I_{clo,corr} = k_{clo,corr} \cdot I_{clo} = \exp[-0.281 \cdot (v_{air} - 0.15) + 0.044 \cdot (v_{air} - 0.15)^2 - 0.492 \cdot v_w + 0.176 \cdot v_w^2] \cdot I_{clo} \tag{3.55}$$

$$R_{ecl,corr} = [0.3 - 0.5 \cdot k_{clo,corr} + 1.2 \cdot k_{clo,corr}^2] \cdot R_{ecl} \tag{3.56}$$

where $I_{clo,corr}$ and $R_{ecl,corr}$ are the thermal and vapor resistances of clothing after correction for air speed. $k_{clo,corr}$ is the correction factor for the thermal insulation of clothing, v_{air} is the relative air velocity and v_w is the walking speed, m/s.

If this method is used, the thermal resistance circuit can be drawn as follows:

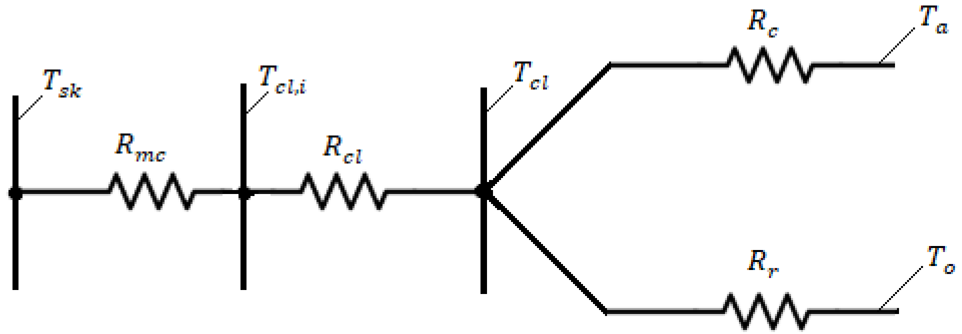


Figure 3.5: Thermal Resistance Network

R_{mc} is the conductive resistance of air layer within the microclimate and $T_{cl,i}$ is the temperature of the innermost layer of fabric. Table 3.4 shows correction factors for air movement that was provided by Havenith et al. through his measurements. If the relative air velocity is less than 1 *m/s*, the difference of the $k_{clo,corr}$ was found very small (Havenith, 2013).

Table 3.4 Corrections value of thermal insulation for air movement (Havenith, 2013)

Segment	**Correction factor for thermal insulation (Equation (3.5))**			
	Relative air velocity (*m/s*)			
	0.4	1	1.5	2
Chest	0.92	0.81	0.76	0.72
Back	0.94	0.86	0.82	0.79
Pelvis	0.94	0.85	0.81	0.79
Upper arm	0.91	0.78	0.73	0.69
Lower arm	0.91	0.79	0.74	0.70
Thigh	0.92	0.81	0.76	0.72
Lower leg	0.93	0.85	0.81	0.78
Foot	0.96	0.91	0.89	0.87
Whole body	0.92	0.81	0.77	0.73

3.8 Ventilation and Air Penetration Induced Heat and Mass Transfer

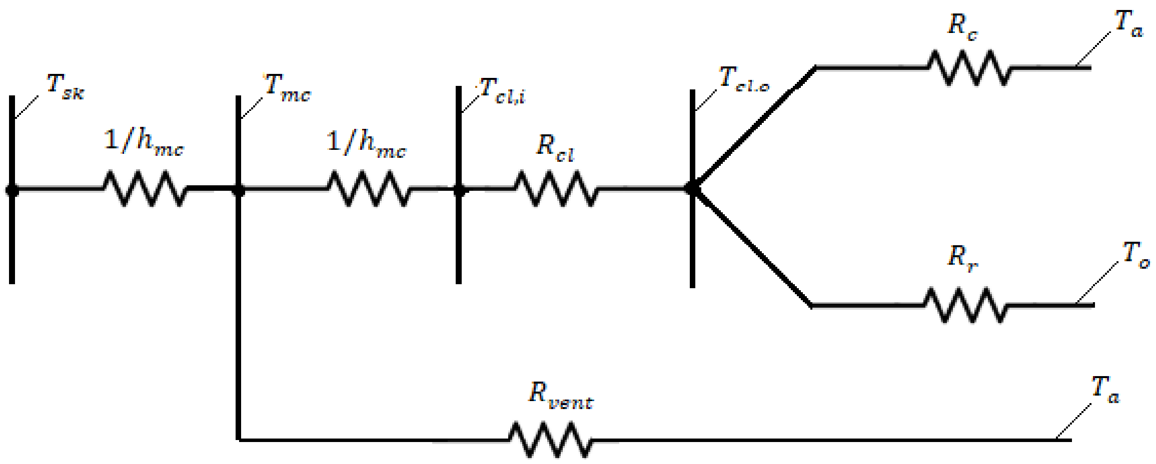


Figure 3.6: Steady state model of clothing system

Heat and mass transfer between the body-clothing-environment get very complicated especially when the microclimate is taken into account. When a clothed person walks in wind, the loose outer garment may flap and therefore pump out warm air and moisture vapor from the air gap between the skin and the garment and replace it by cooler air from the environment. Also, at the same time wind may penetrate through outer garment and create heat and mass exchange. Air ventilation can be in two ways called direct and indirect ventilation. First one is refers to the air exchange between microclimate and ambient air through the openings of the garment. Second one refers to air exchange by passing through the material from which the garment is made.

A concept relating the amount of heat and mass exchange to the amount of air ventilation is firstly proposed by Crockford et al. (1972, 1974 and 1978). He measured the clothing ventilation using a trace gas dilution method. After that different theoretical analyses were developed. Harter (1981) studied thirteen fabrics that are different from each other in weight, fiber content and construction. He found that there is a linear relationship between wind velocity and rate of air penetration through the fabric.

$$U_{pen} = a + b \cdot (V_{wind} \cdot \sqrt{ap}) \tag{3.57}$$

where ap is the air permeability of the fabric and a and b are constants.

Reischi et al. (1987) evaluated the ventilation effect on walking. According to the results ventilation is proportionally increased with walking speed (Figure 3.7).

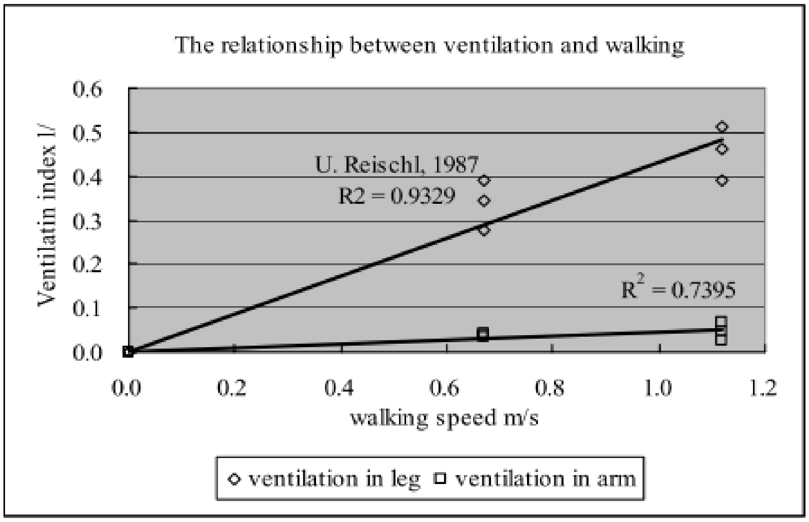


Figure 3.7. Ventilation as a function of walking speed (Reischi, 1987)

More studies were done on researching the ventilation effect by Havenith (1990b), Lotens and Wammes (1993), and Danielsson (1993) who stated that the convective heat transfer coefficient between clothing layers varied linearly from 5.25 $W/m^2°C$ when standing to 11 $W/m^2°C$ when walking at a speed of 2 m/s in still air.

Based on the previous findings and experimental data, Qian (2005) proposed the following empirical formulas to predict heat and mass transfer coefficients by wind penetration and air ventilation for a clothed person walking under windy conditions:

$$h_{dev} = KVI \cdot (V_{wind} + 2 \cdot V_{walk} - v_0) \tag{3.58}$$

$$h_{eev} = KVR \cdot (V_{wind} + 2 \cdot V_{walk} - v_0) \tag{3.59}$$

$$v_v = V_{wind} + 2 \cdot V_{walk} - v_0 \tag{3.60}$$

where KVI and KVR are constants that depend on garment fitting, design and construction of the clothing. KVI and KVR values range from 0.6 to 2.0 and 0.005 to 0.015 respectively and they are given in Appendix A. V_{wind} is the velocity of wind blowing towards a person, V_{walk} is the walking speed, v_v is the equivalent wind velocity taking into account the effect of walking speed. v_0 is the air current in the "still air" condition and taken as $0.22\,m/s$ (Qian, 2005). $h_{dev} = h_{eev} = 0$ when there is no air exchange by walking and wind motion, in other words at the still air condition. From the Equations (2.64) and (2.65) ventilation heat and mass loss are as follows:

$$Q_{vent,i} = KVI \cdot (V_{wind} + 2 \cdot V_{walk} - v_0) \cdot \left(T_{mc,i} - T_a\right) \quad \textbf{(3.61)}$$

$$m_{vent,i} = \frac{KVR}{\lambda} \cdot (V_{wind} + 2 \cdot V_{walk} - v_0) \cdot (P_{mc,i} - P_a) \quad \textbf{(3.62)}$$

where *KVR* and *KVI* are in Appendix A. The following equations are for predicting the total dynamic clothing thermal and moisture insulations:

$$R_{tdyn} = R_{tci} + \frac{1}{KVI \cdot (V_{wind} + 2 \cdot V_{walk} - v_0) + \frac{1}{R_{tco} + \frac{R_{ta}}{f_{co}}}} \quad \textbf{(3.63)}$$

$$R_{edyn} = R_{eci} + \frac{1}{\frac{KVR}{\lambda} \cdot (V_{wind} + 2 \cdot V_{walk} - v_0) + \frac{1}{R_{eco} + \frac{R_{ea}}{f_{co}}}} \quad \textbf{(3.64)}$$

where f_{co} is the clothing area factor for the outer garments, R_{tdyn}, R_{tci} and R_{tco} are the total dynamic clothing thermal insulation, the intrinsic thermal insulation of the inner garment(s) and the intrinsic thermal insulation of the outer garment(s), respectively. R_{edyn}, R_{eci} and R_{ea} are for the moisture resistances in the same way.

An empirical formulate to estimate the value of KVR and KVI, was proposed by Qian (2005) by considering the electric circuit analogy for the following clothing system.

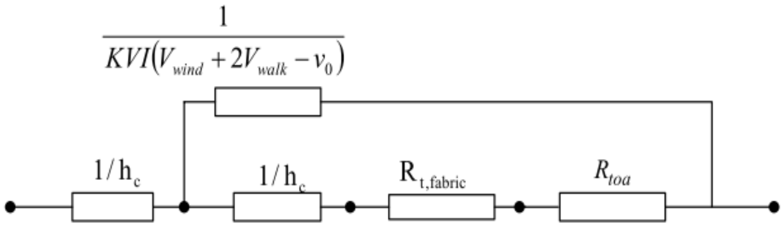


Figure 3.8. Steady state model of clothing system (Wan, 2008)

According to the clothing system above, the convective heat transfer coefficient in the microclimate h_{mc} can be calculated by:

$$\frac{1}{h_{mc}} + \frac{1}{KVI\cdot(V_{wind}+2\cdot V_{walk}-v_0)+\frac{1}{1/_{h_c}+R_{t,fabric}+R_{ta}}} = R_{t,clo} \tag{3.65}$$

Also mass transfer coefficient in the microclimate h_m can be calculated in the same way:

$$\frac{1}{\lambda h_m} + \frac{1}{KVR\cdot(V_{wind}+2\cdot V_{walk}-v_0)+\frac{1}{1/_{\lambda h_m}+R_{e,fabric}+R_{ea}}} = R_{e,clo} \tag{3.66}$$

where $R_{t,clo}$ and $R_{e,clo}$ are total thermal and vapour resistances of the clothing ensemble respectively. $R_{e,fabric}$ and $R_{t,fabric}$ are evaporative and thermal resistances of the fabrics in clothing ensemble respectively (Wan, 2008). Tables that Qian (2005) provides average KVI and KVR values for different clothing ensembles can be found in appendix A.

Qian (2005) developed a relationship using nonlinear regression between $KVI\ and\ KVR$ and the clothing index, air permeability and the thickness of outer clothing. For a clothing consisting of jackets and pants without underwear following equation applies:

$$KVI = 0.0649 \ln\left(\frac{Fit^2\sqrt{ap}}{th^2}\right) + 0.5897 \qquad R^2 = 0.84 \tag{3.67}$$

$$KVR = 0.0006 \ln\left(\frac{Fit^2\sqrt{ap}}{th^{0.2}}\right) + 0.0036 \qquad R^2 = 0.81 \tag{3.68}$$

where, Fit is the fit index value of clothing, and th is the fabric thickness of the jackets. Similar relations apply when there is an underwear extra:

$$KVI = 0.1519 \ln\left(\frac{Fit^2\sqrt{ap}}{th}\right) + 1.018 \qquad R^2(percentage\ of\ fit) = 0.63 \tag{3.69}$$

$$KVR = 0.0019 \ln\left(\frac{Fit^2\sqrt{ap}}{th^{0.5}}\right) + 0.0026 \qquad R^2 = 0.91 \tag{3.70}$$

$Fit\ index\ and\ ap$ values can be assumed using following table which was provided by Qian (2005):

Table 3.5. Categorization of clothing ensembles based on garment fit and air permeability (Qian, 2005)

Air permeability category	***ap* value**	**Fit category**	**Fit index**
Low	$< 1\ l/sm^2ap$	S	2.9~5.2
Moderate	$1{\sim}4\ l/sm^2ap$	M (fit to body)	8.7~14.5
High	$> 4\ l/sm^2ap$	L	20.3~24.3

These categorizations are made for clothing ensembles that Qian has used in experiments. However, they are not applicable to every clothing ensemble and parameters are not widely available.

3.9 Development of Simplified Model

3.9.1 Assumptions for Simplification of the Problem

Calculation of the parameters in the microclimate is very complicated and requires some parameters to be measured. In this thesis, a simplified numerical method is aimed to be developed which agrees well with the empirical studies available in the literature. Therefore, some assumptions are needed to be made to simplify the problem. These assumptions are listed as follows:

- When a person gets into an environment, a transient heat transfers between the body and the environment occurs. However, after some time, it reaches to steady state. The aim is the measure the feeling of comfort done after the time that steady state is reached. Therefore, the problem is solved at steady state.
- This thesis only deals with the heat transfer from skin through clothing to the environment.
- Microclimate thickness is less than 0.8 cm so that convection is neglected and there is only conduction through the air in the microclimate.
- Air between layers of the clothing is neglected.
- Effect of air movement and ventilation will be included by calculating the dynamic thermal and evaporative resistances of clothing.
- Radiation in the microclimate and between the clothing layers is neglected but radiation to the environment is included.
- The problem will be solved using only widely available properties of clothing.
- Comfort Prediction will be done for different strategies using PMV by Fanger (1970).

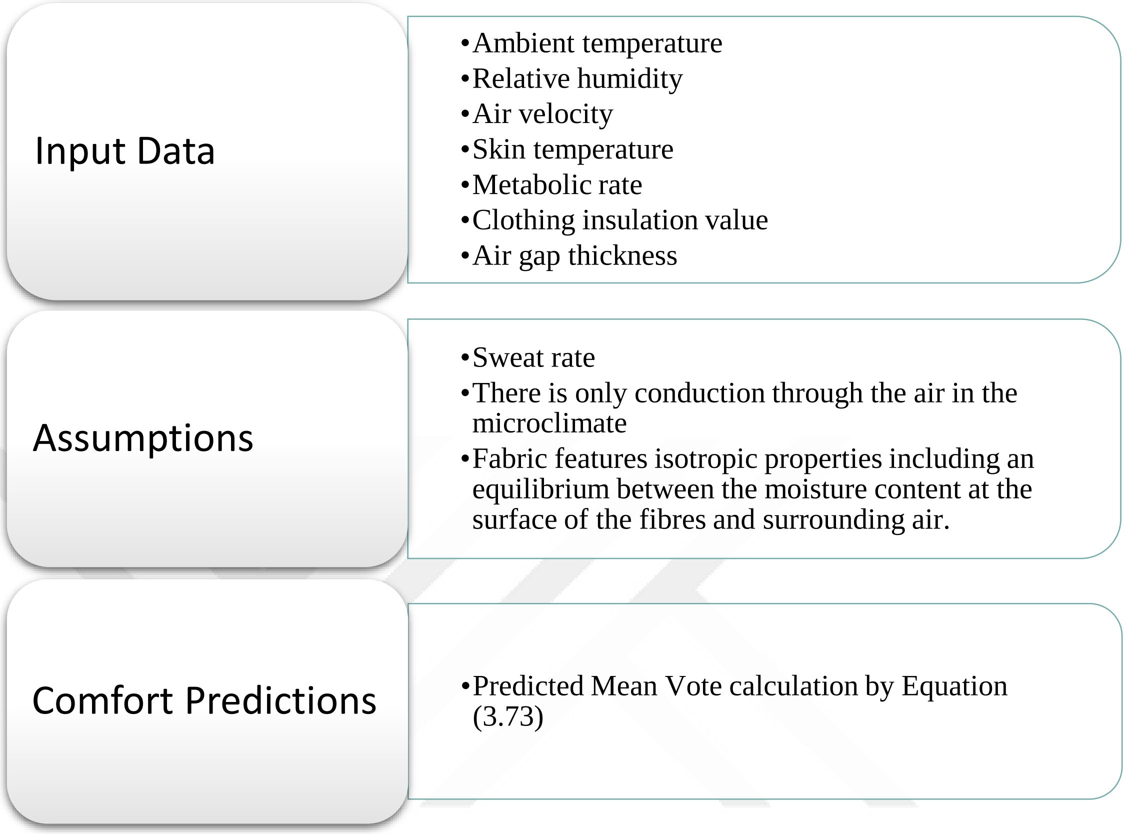


Figure 3.9 Modelling procedure for the solution of problem presented in this study

3.9.2 Finite Difference Formulation of the Dry Heat Transfer

The problem can be treated as 1D steady heat conduction with combined convection and radiation with a specified heat flux boundary condition. Metabolic heat minus the work is the total heat that reaches the skin and taken as the heat flux at the skin. The plane with length L between skin and environment is divided into M sections with equal thickness $\Delta x = L/M$ and starting from point 0 at the skin to M+1 at the surface of the clothing.

$$(M - W) + kA\frac{T_1 - T_0}{\Delta x} = 0 \tag{3.71}$$

$$\frac{T_{m-1} - T_m}{\Delta x} + \frac{T_{m+1} - T_m}{\Delta x} = 0 \tag{3.72}$$

$$\vdots$$

$$kA\frac{T_M - T_{M+1}}{\Delta x} + h_{combined}A(T_a - T_{M+1}) = 0 \tag{3.73}$$

If the conductivity of clothing that consists of n $(j = 1, n)$ layers, changes then the heat balance equations for each layer is as follows:

$$0 = (M - W) - \frac{T_{cl,1} - T_{cl,2}}{R_{cl,1}} \tag{3.74}$$

$$0 = \frac{T_{cl,1} - T_{cl,2}}{R_{cl,1}} - \frac{T_{cl,2} - T_{cl,3}}{R_{cl,2}} \tag{3.75}$$

$$\vdots$$

$$0 = \frac{T_{cl,n-1} - T_{cl,n}}{R_{cl,n-1}} - \frac{T_{cl,n} - T_0}{R_c + R_r} \tag{3.76}$$

These equations need to be solved to determine temperature at each node which is on the surface of each layer of clothing ensemble.

3.10 Thermal Comfort Calculations

3.10.1 Predicted Mean Vote (PMV)

Predicted Mean Vote is the comfort index that was introduced by Fanger (1970). It predicts human responses for the thermal sensation and is a function of thermal load and activity level. Fanger defined thermal load as the difference between the heat production of the body and heat loss to the environment for a man kept at the comfort values of the mean skin temperature and sweat secretion. In order comfort condition to be obtained, thermal load should be equal to zero. Thermal sensation scale for PMV:

Table 3.6. PMV Standards

PMV Value	**Feeling**
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

$$PMV = (0.303 \cdot e^{-0.036 \cdot M} + 0.028) \cdot [(M - W) - 3.05 \times 10^{-3} \cdot \{5733 - 6.99 \cdot (M - W) - P_a\} - 0.42 \cdot \{(M - W) - 58.15\} - 1.7 \times 10^{-5} \cdot M \cdot (5867 - P_a) - 0.0014 \cdot M \cdot (34 - T_a) - 3.96 \times 10^{-8} \cdot f_{clo} \cdot \{(T_{clo} + 273)^4 - (T_r + 273)^4\} - f_{clo} \cdot h_c \cdot (T_{clo} - T_a)] \quad \textbf{(3.77)}$$

where T_{clo} is found by iteration:

$$T_{clo} = 35.7 - 0.028 \cdot (M - W) - 0.155 \cdot I_{clo} \cdot [3.96 \times 10^{-8} \cdot f_{clo} \cdot \{((T_{clo} + 273)^4 - (T_r + 273)^4\} + f_{clo} \cdot h_c \cdot (T_{clo} - T_a) \quad \textbf{(3.78)}$$

Fanger (1970) presents a table that shows the relationship between the percentage of dissatisfied and the predicted mean comfort vote. In tests, He examined that 5% of the people would be dissatisfied even at the PMV=0 condition which is the best condition.

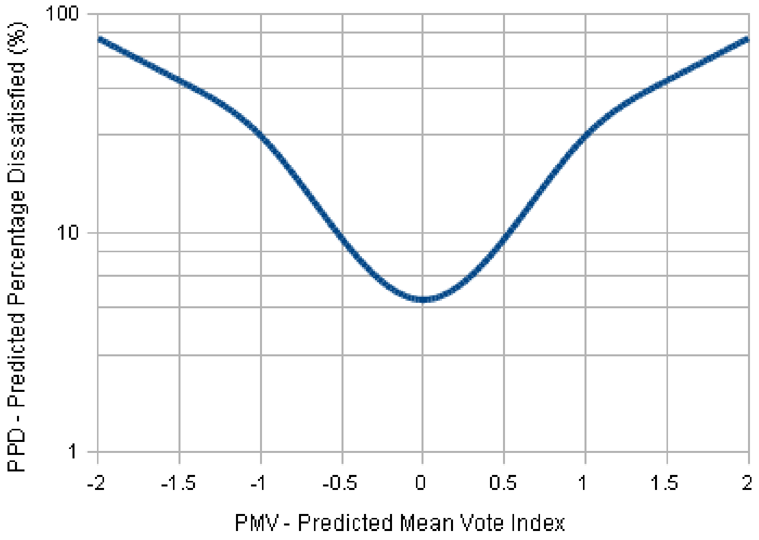


Figure 3.10. PMV rate (ASHRAE, 2013) where 0 indicates neutral state, left side of the 0 is cold feeling and right side is warm feeling.

3.10.2 Standard Effective Temperature

Standard Effective Temperature (SET) was defined by Gagge et al. (1972). It is defined as the temperature of an isothermal environment with air temperature equal to mean radiant temperature. It also assumes 50% relative humidity, and still air, meaning that the air velocity is less than $0.15\ m/s$, is the same as that from a person in the actual environment with clothing level of 0.6 *clo* and activity level 70 W/m^2 (Parsons, 2003). In thermal equilibrium state, SET and average body temperature is related as follows:

$$\begin{aligned} &\text{For } T_b < 23℃ && SET = 23 - 6.13(36.4 - T_b)^{0.7} \\ &23℃ < T_b < 41℃ && SET = 34.95T_b - 1247.6 \\ &41℃ < T_b && SET = 41 + 5.58(T_b - 36.9)^{0.87} \end{aligned} \qquad \textbf{(3.79)}$$

where T_b is average body temperature. The relationship between SET index levels and thermal sensation is shown in Table 3.7.

In this thesis, PMV is used instead of SET because SET requires average body temperature as an input and PMV calculates the heat losses and gains of the body due to different environmental conditions.

Table 3.7. Relationship between SET index levels, PMV votes and thermal sensation. (Auliciems, 2007)

SET (℃)	**Vote**	**Sensation**	**Physiology**
>37.5	>3	Very hot, great discomfort	Increase in failure of evaporative regulation
37.5-34.5	+2 to +3	Hot, very unacceptable	Profuse sweating
34.5-30	+1 to +2	Warm, uncomfortable, unacceptable	Sweating
30-25.6	+0.5 to +1	Slightly warm, slightly unacceptable	Slight sweat, vasodilation
25.6-22.2	-0.5 to +0.5	Comfortable, acceptable	Physiological thermal neutrality
22.2-17.5	-1 to -0.5	Slightly cool, slightly unacceptable	Initial vasoconstriction
17.5-14.5	-2 to -1	Cold, unacceptable	Slow body cooling
14.5-10	-3 to -2	Cold, very unacceptable	Beginning of shivering

CHAPTER IV

CASE STUDIES AND RESULTS

4.1 Introduction

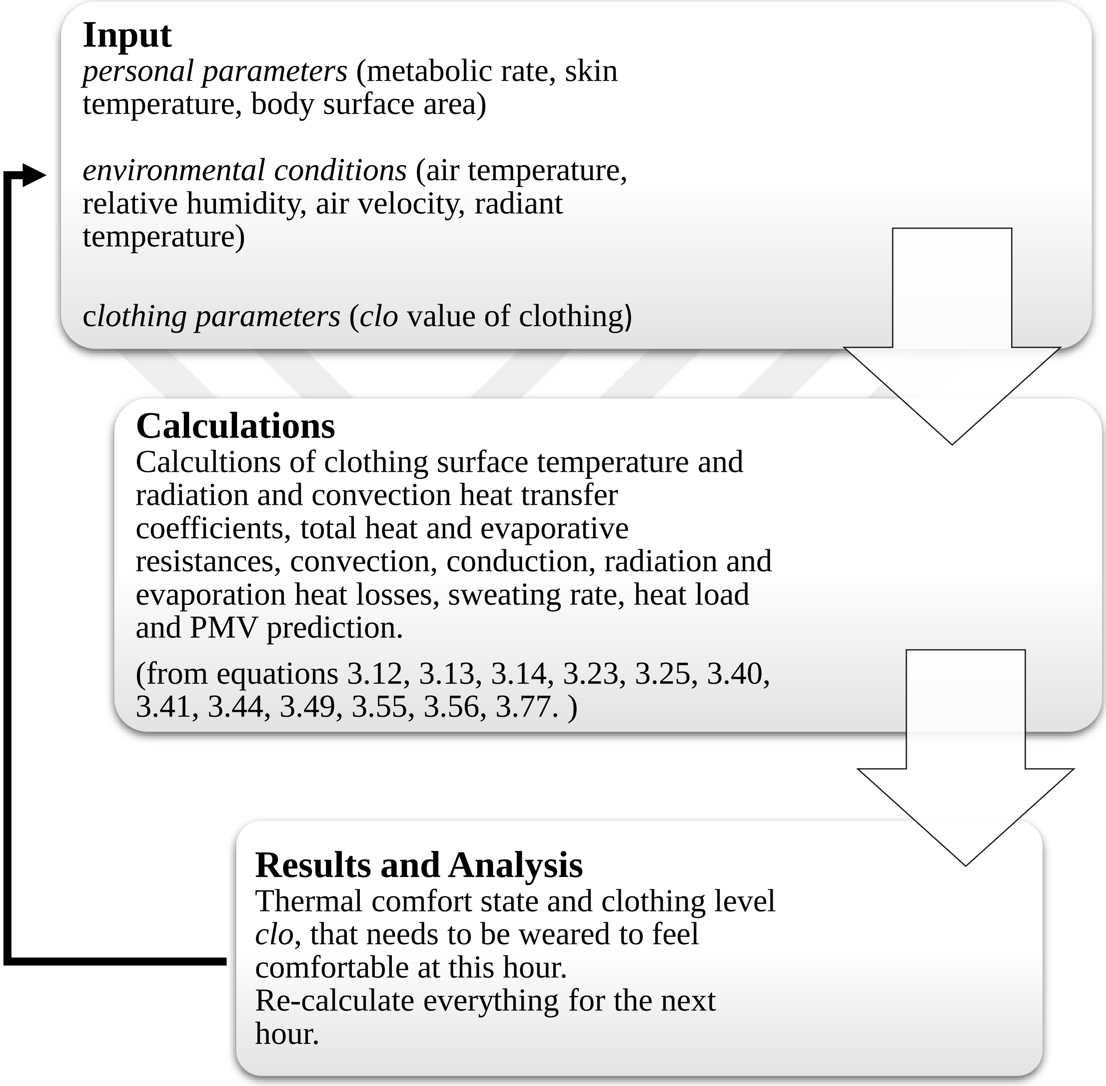
Based on the models and discussion given in the previous Chapters, now it is possible to investigate different realistic problems. In this chapter different cases will be solved by the presented model. First three parametric studies are conducted and results compared with the different experimental data from the literature. This is done for two reasons. First, parametric study is performed to evaluate impact of each parameter on overall thermal comfort. By seeing that, the most effective parameters can be chosen to improve clothing thermal comfort. Second, the presented model in this study is numerical, therefore it needs to be verified by making comparisons with experimental data in literature.

In the cases, Predicted Mean Vote is used to scale comfort feeling of a person. As it was discussed in the previous Chapter, the equation for the PMV is:

$$PMV = (0.303 \cdot e^{-0.036 \cdot M} + 0.028) \cdot [L] \tag{4.1}$$

where L is the thermal load. In general, all cases are examining the parameters that effect thermal comfort and searching for the answer of how one can reach to a thermophysiological comfort in an environment.

Below, a flowchart explaining the procedure followed in the algorithm, is provided.



Input

personal parameters (metabolic rate, skin temperature, body surface area)

environmental conditions (air temperature, relative humidity, air velocity, radiant temperature)

clothing parameters (*clo* value of clothing)

Calculations

Calcultions of clothing surface temperature and radiation and convection heat transfer coefficients, total heat and evaporative resistances, convection, conduction, radiation and evaporation heat losses, sweating rate, heat load and PMV prediction.

(from equations 3.12, 3.13, 3.14, 3.23, 3.25, 3.40, 3.41, 3.44, 3.49, 3.55, 3.56, 3.77.)

Results and Analysis

Thermal comfort state and clothing level *clo,* that needs to be weared to feel comfortable at this hour.
Re-calculate everything for the next hour.

Figure 4.1: Flowchart for the developed algorithm

4.2 Evaluation of Methodology

The key parameters are compared with the available data in the literature to determine if the equations provide reliable results. Predicted Mean Vote against the metabolic rate was originally plotted by Havenith (2002). A comparison was made using the same environmental conditions and the clothing parameters (see Figure 4.2). As it can be seen in Chapter 4 for Case 1, the results predicted with the current algorithm matches perfectly with the model of Havenith (2002). After gaining confidence in the presented methodology, other Cases given in this chapter are studied.

Collins and Hoinville (1980) performed their experiments with 32 subjects which are seated and in a relaxed fashion and wearing about 1 clo clothing in an environment with temperature 21.1 ℃. They concluded that subjects feel comfortable under this conditions. When the same conditions applied to the algorithm in this study, PMV value is found as 0.006 which very close to the optimum value (0.00) for comfort (Parsons, 2003).

Another set of comparison was made against the results provided by Qian (2006) on the evaporative resistance of clothing versus wind velocity. As it can be seen from Case 2, the results predicted with the presented model matches well with those of Qian.

4.3 CASE 1: Relationship Between PMV and Metabolic Rate

In this case, the relationship between metabolic rate and PMV (Predicted Mean Vote) values for typical office climates ($T_a = T_r = 22℃, v = 0.15\ m/s, P_{air} = 1\ kPa$) is compared with the values from the model of Havenith (2002). This case is done for a person with a clothing of 0.6 *clo* and 1 *clo*. In the same environmental conditions, the metabolic rate of the person increases and PMV, scale of comfort feeling, increases accordingly.

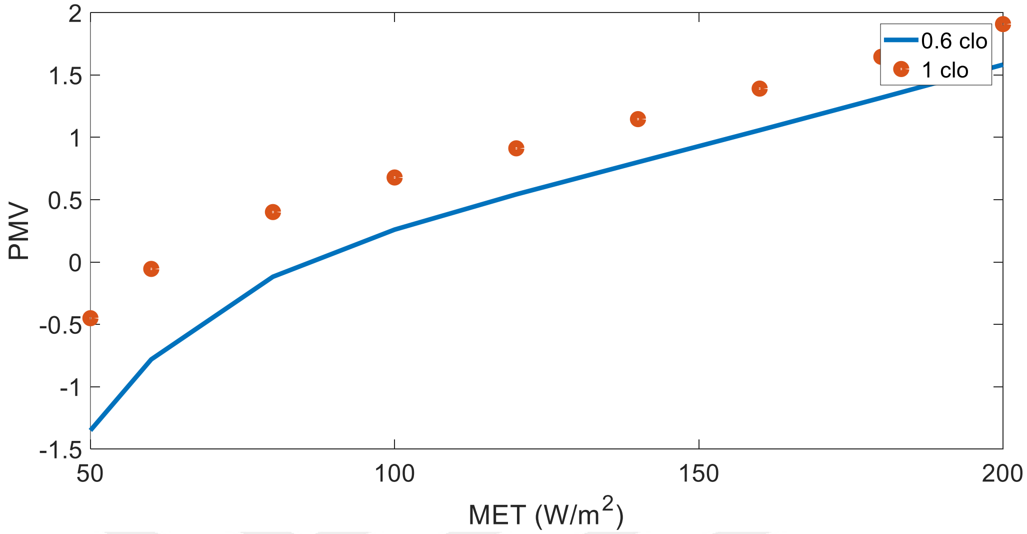


Figure 4.2: Relationship between PMV and Metabolic rate according to calculated results

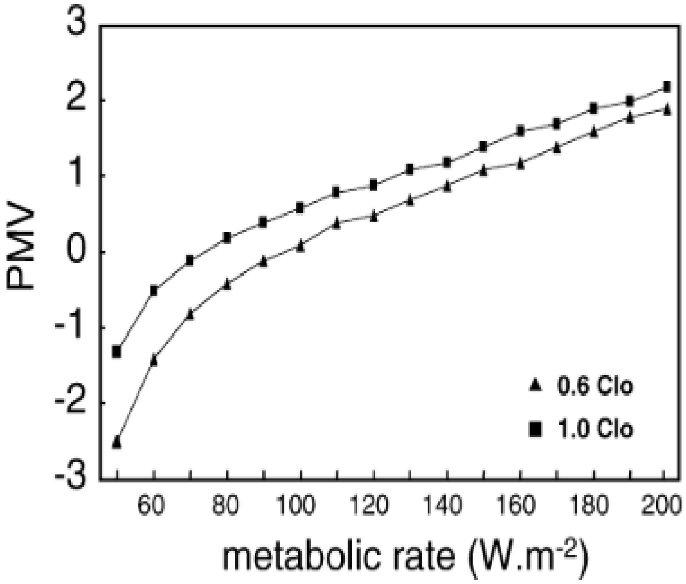


Figure 4.3: Relationship between PMV and Metabolic rate by Havenith (2002)

Figure 4.2 is the predicted result and Figure 4.3 is what Havenith provided as experimental result. As it is seen, the plot of the current model matches well with the experimental data provided by Havenith et al. (2002). It can be observed that from metabolic rate 50 W/m^2 to 200 W/m^2; for a clothing level 0.6 clo, PMV changes from about -1.5 (between slightly cool and cool) to +1.5 (between slightly warm and warm); and for a clothing level 1 clo, PMV changes from -0.5 (between slightly cool and neutral) to 2 (warm). The person feels warmer when he/she wears a clothing of 1 *clo* instead of 0.6 *clo*. Also, increase in internal heat storage (metabolic rate) causes person to feel warmer.

4.4 CASE 2: The Effect of Air Movement on Thermal Comfort

The effect of air movement on clothing heat transfer resistance is shown on the following graphs. The correction factor is used to calculate the new clothing heat resistances with respect to changed wind velocities and a constant walking speed of a person. The calculation of the correction factor and the corrected evaporative resistance were as follows:

$$k_{clo,corr} = \exp[-0.281 \cdot (v_{air} - 0.15) + 0.044 \cdot (v_{air} - 0.15)^2 - 0.492 \cdot v_w + 0.176 \cdot v_w^2] \cdot I_{clo} \tag{4.2}$$

$$R_{ecl,corr} = [0.3 - 0.5 \cdot k_{clo,corr} + 1.2 \cdot k_{clo,corr}^2] \cdot R_{ecl} \tag{4.3}$$

where $k_{clo,corr}$ is correction factor, v_{air} is wind velocity, v_w is walking speed, I_{clo} is clothing heat resistance in *clo* and $R_{ecl,corr}$ is the dynamic evaporative resistance of clothing.

In this case, the temperature of the environment is 25℃ with relative humidity of 38%. The skin temperature held constant at 34℃, and metabolic rate is 100 $\frac{W}{m^2}$. Clothing evaporative resistance versus wind velocity is compared with the experimental result provided by Qian (2006). In his experiment he used a manikin to observe the effect of wind speed on vapor resistance of different clothing ensembles. The experiment was done for a standing person under different wind velocities which are $V_{wind} = 0.22,\ 0.85,\ 1.69,\ 2.48,\ 3.12,\ 4.04\ m/s$. As it can be seen from the Figures 4.4 and 4.5, the result of this study can be verified with a tolerable error due to its well agreement with an experimental data of Qian (2006).

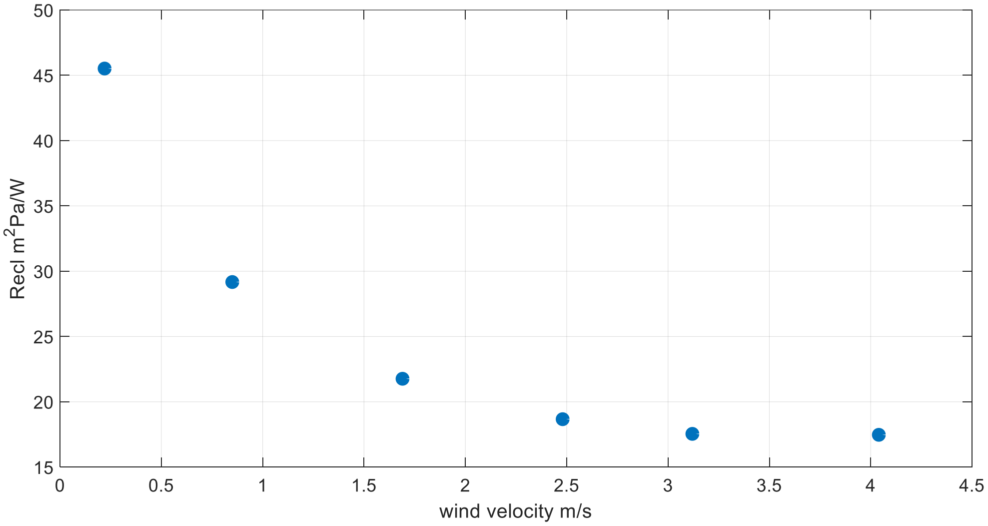


Figure 4.4: Change of evaporative resistance of clothing (R_{ecl})with respect to wind velocity simulated in this study.

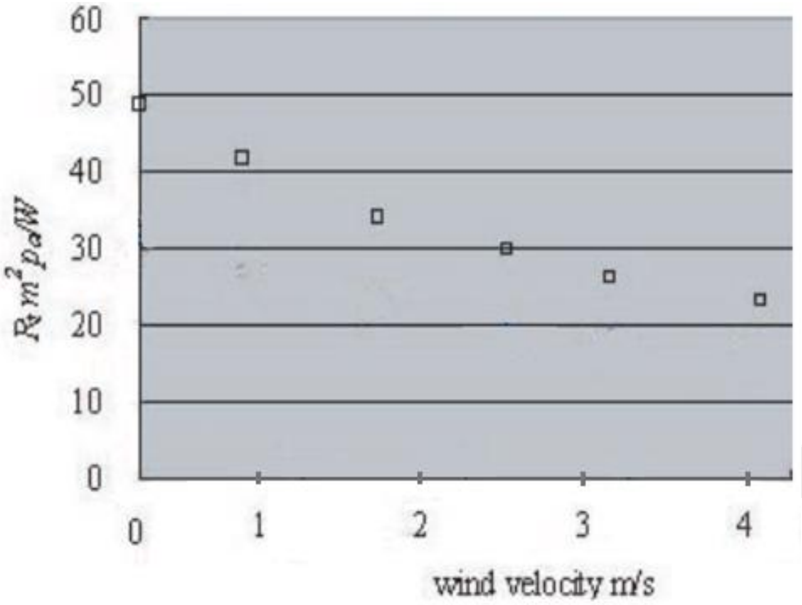


Figure 4.5: Clothing vapour resistance versus wind velocity as given by Qian (2006)

In Figure 4.6, the change of feeling is plotted based on the PMV calculation at various wind speeds. As expected, the increase of wind speed decreases the resistance of clothing to heat transfer. These predictions are done by calculating dynamic heat resistance of clothing which is used to include the effect of air motion. It should be kept in mind that the temperature and the humidity of the air are held constant and wind velocity is the only variable parameter. This case is as a parametric study which shows the effect of one parameter on overall comfort feeling. Therefore, increase of wind speed results in decrease of PMV values which can be interpreted as increase of cold feeling.

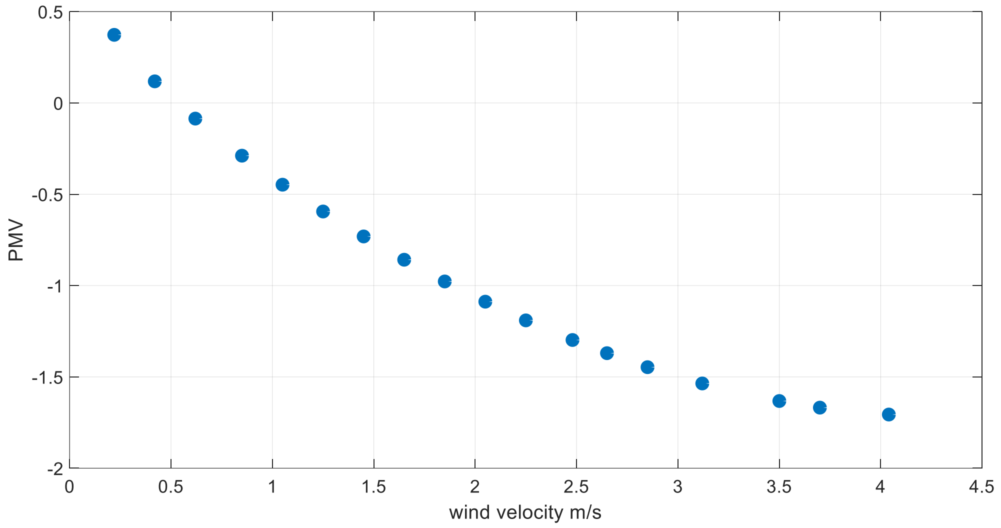


Figure 4.6: The change of PMV with respect to increase in wind velocity.

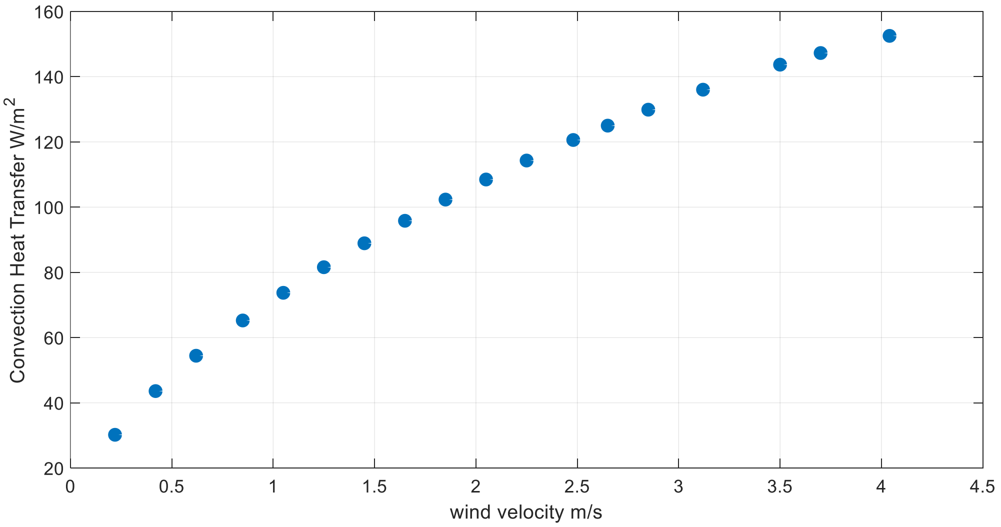


Figure 4.7: Increase in convective heat transfer with an increase in wind speed.

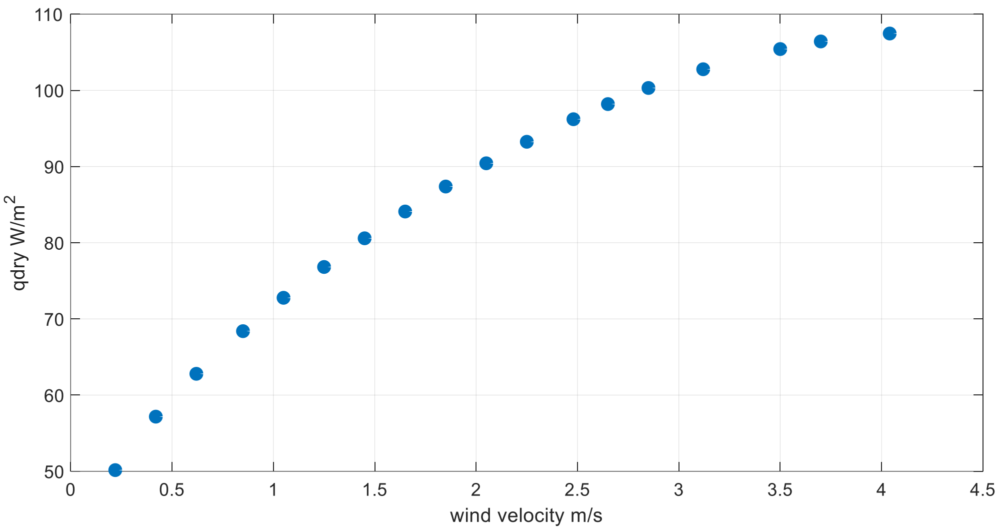


Figure 4.8: Increase in total dry heat transfer (q_{dry}) with an increase in wind speed.

In the Figure 4.7 above, the convective heat transfer increases as the wind velocity increases. This is obviously because heat transfer coefficient and wind velocity directly proportional to each other as it can be understood from the following equation (Oguro, 2002b) which can be remembered from Chapter 3:

$$h_c = 9.41V^{0.61} \tag{4.4}$$

where h_c is convective heat transfer coefficient and V is the wind velocity. Due to increase in convective heat loss, total dry heat loss q_{dry} increases as the wind velocity increases in Figure 4.8.

4.5 CASE 3: Relationship Between Clothing Resistance and Sweat rate

In Case 3, objective is to observe the effect of changing clothing thermal resistance on total dry heat transfer, clothing surface temperature, and sweat rate. Also, in this case the environment is hot $t_a = 25℃$ and $t_r = 25℃$ with relative humidity 60 % and wind velocity $v = 0.15\ m/s$. The person is standing still, the metabolic rate is $58.2\ W/m^2$ and the skin temperature is $t_{sk} = 33$ ℃ . Increasing thermal resistance of clothing, R_{cl}, causes a increase in total heat resistance (resistance of the clothing plus the resistance of air layer near to the surface of the clothing). As it can be seen from the equations (4.4) and (4.5) and from the Figure 4.9, heat resistance and heat transfer is inversely proportional and decrease in clothing resistance, results in an increase in total dry heat transfer. Moreover, increasing the heat resistance of clothing causes prevention of heat loss from the body which results in heat load on the skin and increase in sweat rate which can be observed in Figure 4.10.

$$R_t = R_{cl} + \frac{1}{f_{cl} \cdot (h_c + h_r)} \qquad \textbf{(4.5)}$$

$$Q_{dry} = \frac{A_{cl} \cdot (T_{sk} - T_o)}{R_t} \qquad \textbf{(4.6)}$$

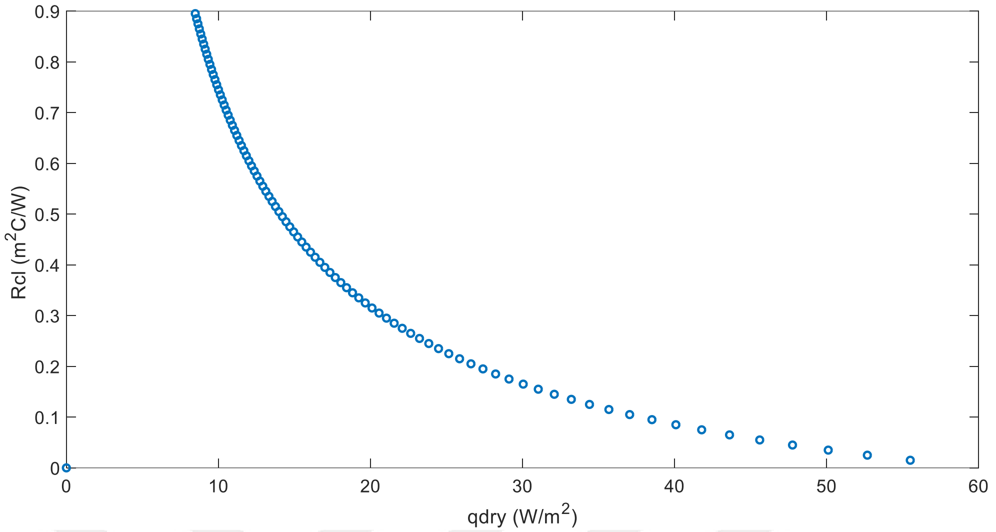


Figure 4.9: Total dry heat transfer (q_{dry}) is increasing while clothing resistance decreasing (R_{cl}).

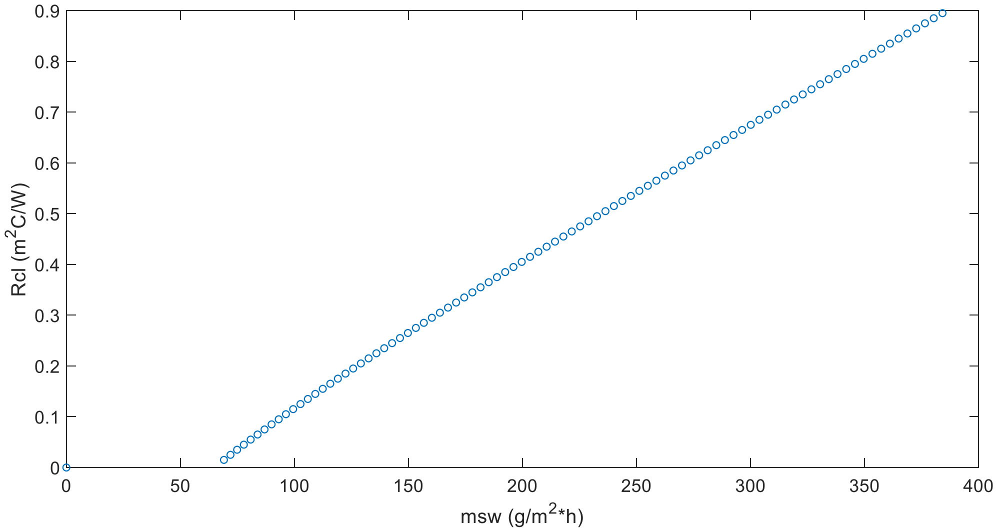


Figure 4.10: Increasing sweat rates (m_{sw})due to higher clothing resistances (R_{cl}).

In Figure 4.11 the temperature of clothing surface increases as the heat resistance of clothing decreases. This is due to as the heat resistance decreases, the difference between the skin temperature and clothing surface temperature decreases. Yet, the higher resistance limits the heat transfer between skin and clothing, and clothing surface temperature approaches to the environment temperature.

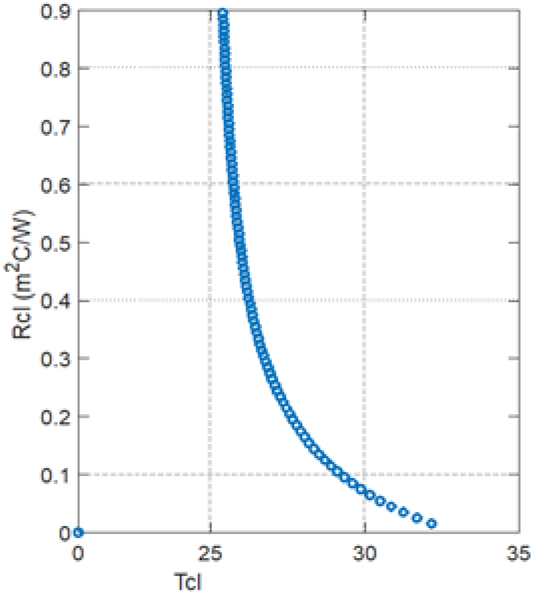


Figure 4.11: Relationship between clothing thermal resistance (R_{cl}) and clothing surface temperature (T_{cl} °C).

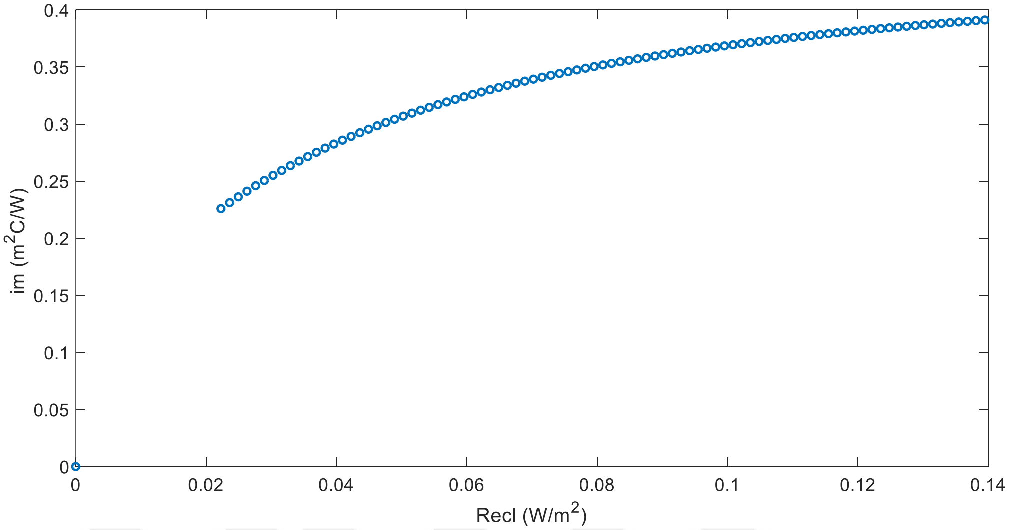


Figure 4.12: Relationship between moisture permeability index (i_m) and evaporative resistance of clothing (R_{ecl}).

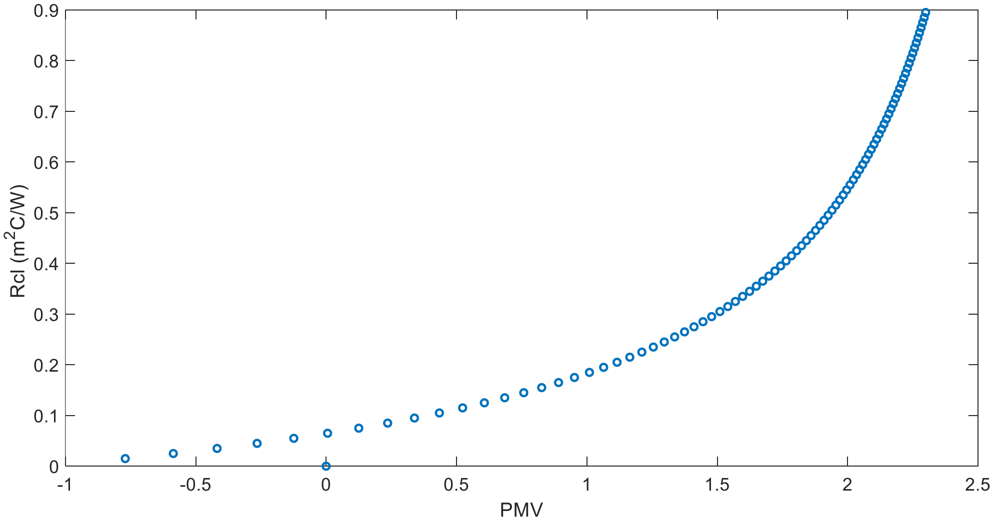


Figure 4.13: Increase in PMV value due to increase in clothing thermal resistance (R_{cl})

As seen in Figure 4.13 increasing PMV values, show that the person's feeling of warm discomfort increases as the heat resistance of clothing increases.

4.6 CASE 4: Relationship Between Porosity and Thermal Conductivity of a Fabric

In this case, the relationship between pore volume fraction and thermal conductivity of a fabric is analyzed. As it can be remembered from the Chapter 2, the equation for porosity and thermal conductivity of a fabric were as follows:

$$\varphi(\%) = \frac{\rho_{fabric}}{\rho_{fibre}} \times 100\ \% \tag{4.7}$$

$$P(\%) = (1 - \varphi) \times 100\% \tag{4.8}$$

$$k_c = \varphi k_f + (1 - \varphi) k_{\,a} \tag{4.9}$$

where P is the fabric porosity (%), φ is the volume fraction of solid material (%), k_f is the conductivity of solid material, k_a is the conductivity of air, ρ_{fibre} is the fiber density and ρ_{fabric} is the fabric bulk density. The environmental conditions for this case is considered as $t_a = t_{mr} = 20℃, RH = 60\%, v_a = 0.25\ m/s$ for a person with $t_{sk} = 34℃, M = 100\ W/m^2$.

In Figure 4.14, the change of effective thermal conductivity with respect to pore volume fraction of fabric made of 15% wool and 85% cotton, is shown. It is clear that increasing the pore volume fraction results in a decrease in thermal conductivity of the fabric. This is because the increase in total pore volume fractions means decrease in solid fiber content and increase in air content of garment. Air has a low conductivity which is 0.026 W/mK and when the higher the porosity of garment the more surrounding air penetrates to the voids of garment.

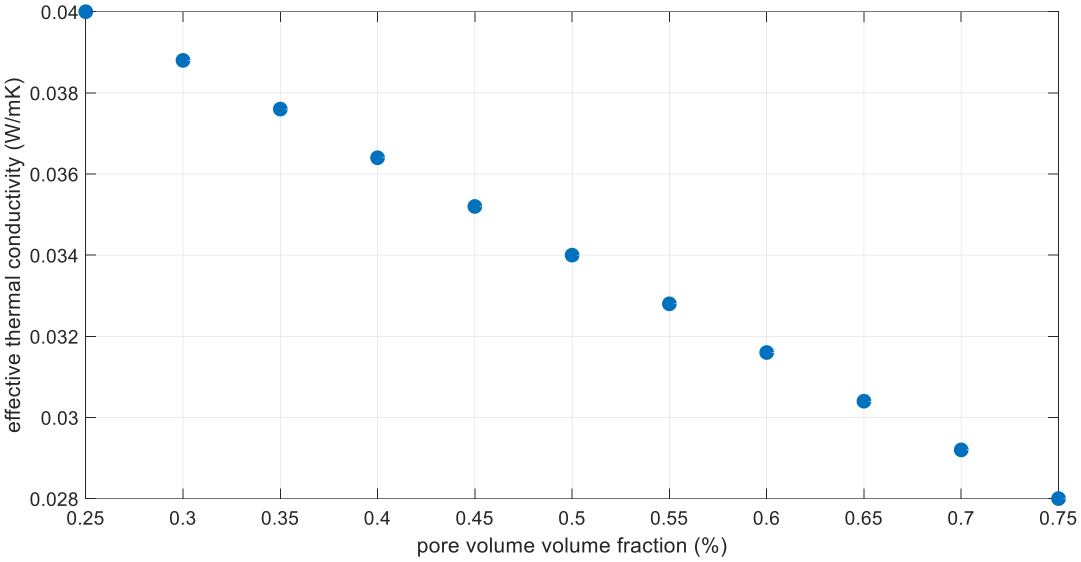


Figure 4.14: Analytical prediction of effective thermal conductivity as a function of the pore volume fraction of 15% wool+ 85% cotton fabric (Equation (4.8)).

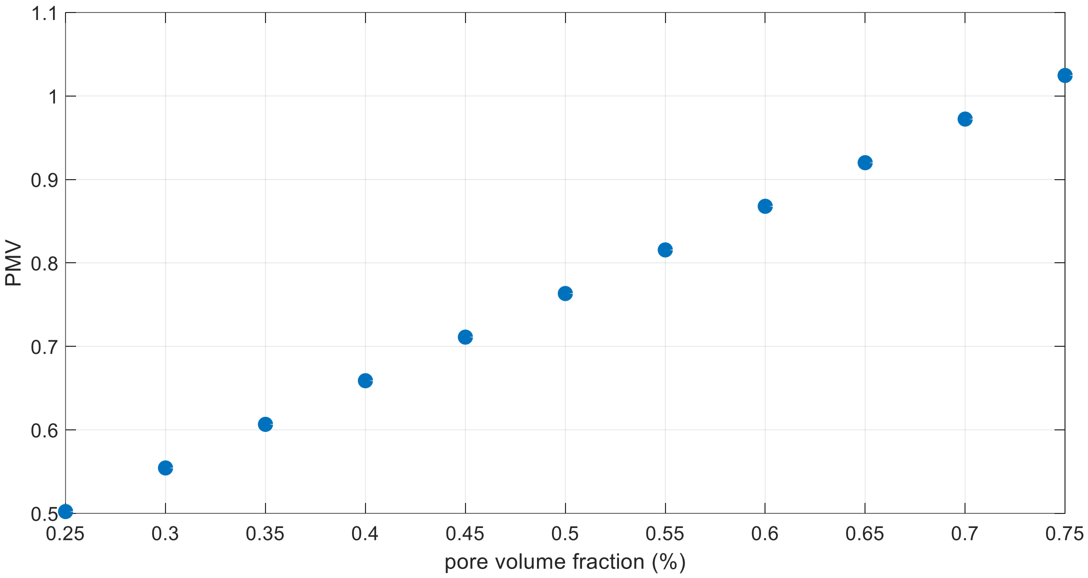


Figure 4.15: PMV versus pore volume fraction of 15% wool+ 85% cotton fabric in a static environment.

In the environment where air temperature is 20℃, if the porosity of a clothing increases, PMV increases due to the decrease of effective thermal conductivity of 15% wool+ 85% cotton because of the lower conductivity value of air. Generally, to improve the insulation value of a textile structure, volume of still air in the textile can be increased this way to keep the body warm. In this case study, it is assumed that the person stands still. Therefore, there is no air penetration through fabric openings and only the effect of pores to the effective thermal conductivity is displayed. However, during walking air penetrates in and out of the clothing system and causes a reduction in resistances of heat and moisture transfer. The air flow between the body surface and the environment through pores is noteworthy if the wearer is in windy conditions. Direct relationship between porosity and air penetration can only be observed through experiments or simulations made by scanning a manikin.

4.7 CASE 5: Thermal Conductivity of Blended Fabrics

In this case, different volumetric combinations of lycra and cotton fabrics are examined. For each combination, heat transfer resistance and evaporative resistance of 1 *cm* thick blended fabric is calculated from the Equation 4.9. It can be seen that when the lycra content in the fabric is increased, the resistance to transfer of heat and evaporation increase as well. This is due to lower thermal conductivity of lycra. Also, PMV value increases which means that a person starts feeling warm due to removal of heat from skin to the environment gets harder. In this case the following conditions are assumed: $t_{sk} = 34℃, t_a = t_r = 22℃, RH = 60\%, v_{wind} = 0.15\ m/s$.

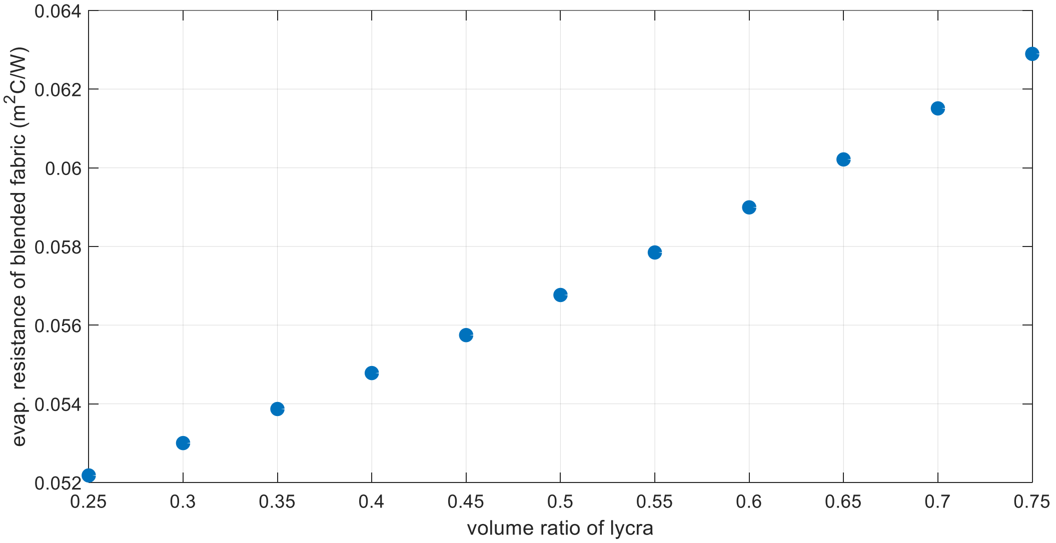


Figure 4.16: Relationship between evaporation resistance(R_{ecl}) of a blended fabric and volume ratio of Lycra.

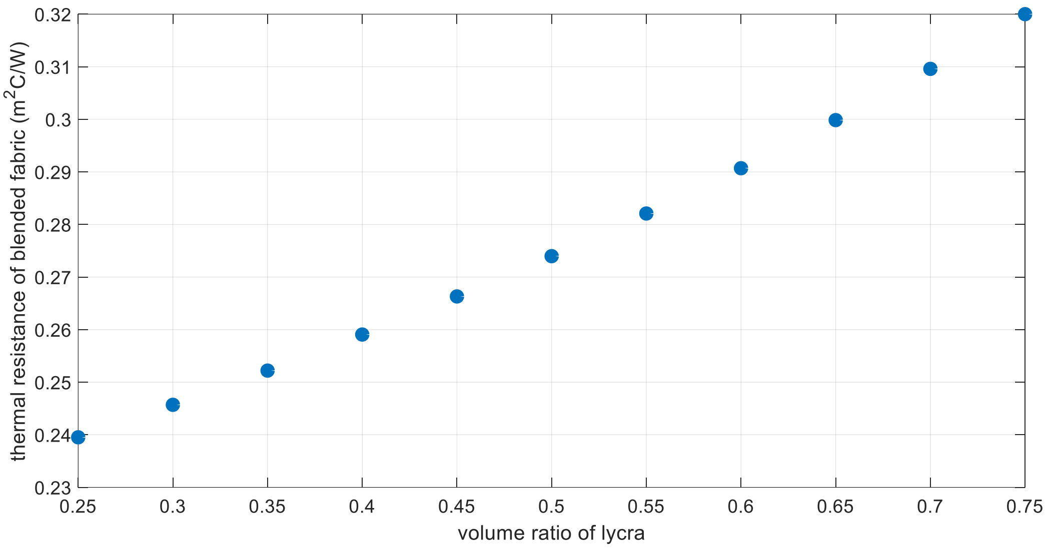


Figure 4.17: Relationship between heat resistance (R_{cl}) of a blended fabric and volume ratio of Lycra.

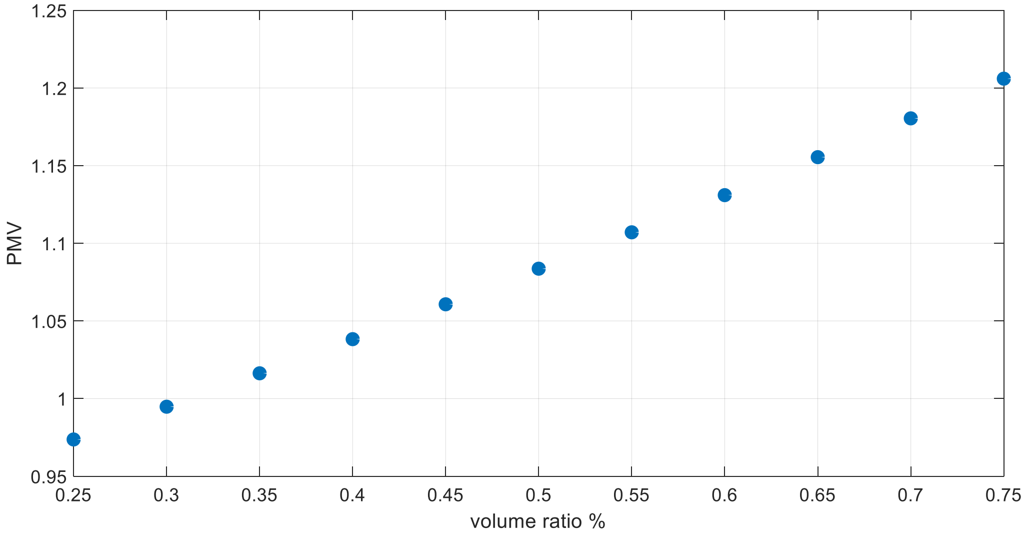


Figure 4.18: Relationship between PMV and volume ratio of lycra of a blended fabric.

The thermal conductivities of lycra and cotton are taken as 0.026 W/mK and 0.047 W/mK, respectively. This implies that lycra can conduct less heat than cotton; in other words, the resistance to the heat is higher for lycra than for cotton. The same applies for evaporation resistance. As seen in the Figure 4.16, increasing volume ratio of lycra increases the evaporation resistance of blended fabric. Below, in Table 4.1 there are different fabrics blended in different ratios and their thermal conductivities can be observed. As one can remember from the Chapter 2, the effective thermal conductivity of a blended fabric can be calculated as follows:

$$k_{eff} = v_f k_f + (1 - v_f) k_m \qquad \textbf{(4.10)}$$

where v_f is the volume ratio of the fiber, k_f and k_m are the thermal conductivities of fiber and matrix respectively. The thermal resistance values in Table 4.1 are calculated by assuming the thickness of the fabric is 1 cm.

Table 4.1. Calculated results of blended fabrics

Composition	**Thermal Conductivity** (W/mK)	**Thermal Resistance** (m^2K/W)
%15 Wool + % 85 Cotton	0.0446	0.224
%30 Wool + % 70 Cotton	0.0422	0.236
%30 Silk + % 70 Cotton	0.0578	0.173

Table 4.1. Continued Calculated results of blended fabrics

Composition	**Thermal Conductivity** (W/mK)	**Thermal Resistance** (m^2K/W)
%70 Silk + % 30 Cotton	0.0722	0.138
%45 Lycra + % 55 Cotton	0.0375	0.266
%75 Lycra + % 25 Viscose	0.0272	0.36697
%70 Lycra + % 30 Polyester	0.0332	0.3012
%70 Bamboo + % 30 Nylon	0.0681	0.1468
%70 Sheep wool + %30 Cotton	0.0414	0.2415
%40 Linen + % 60 Silk	0.125	0.08

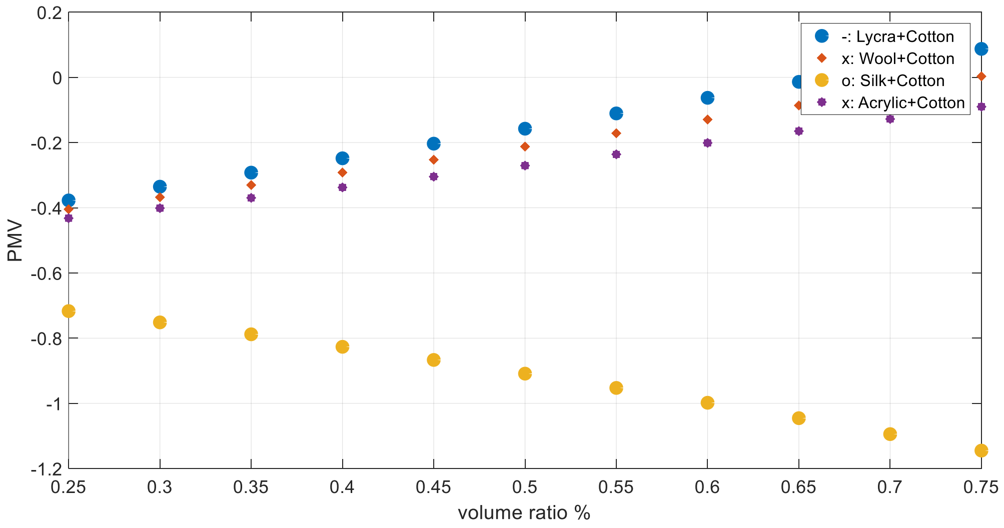


Figure 4.19: Comparison of PMV versus volume ratio of Lycra + Cotton, Wool + Cotton, Silk + Cotton, ad Acrylic + Cotton.

In the Figure 4.19 the Lycra and Cotton blended fabric shows the highest PMV values which can be associated with the highest thermal resistance in other words, lowest transfer of heat from skin to the environment and highest heat load on the skin.

4.8 CASE 6: Heat Loss due to Changing Weather Conditions

In this case, a typical day in Istanbul is considered. A person with the clothing resistance of R_{cl} =0.093 m^2kPa/W and the internal heat storage ($M = 100\ W/m^2$) are assumed as in the previous case. The objective of this case study is to explore how the heat loss from human skin to the environment through clothing changes with respect to changing weather conditions. Note that the person is assumed to have the same clothing all day with no exercise.

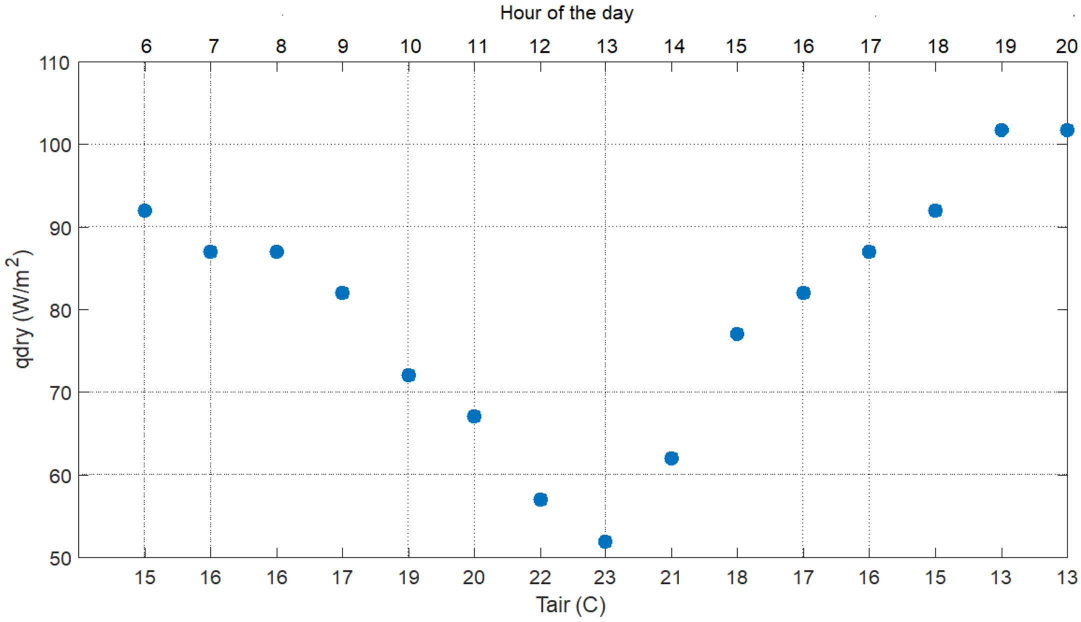


Figure 4.20: Change of total dry heat loss (q_{dry}) from skin through clothing with respect to change of air temperature and the hour of day.

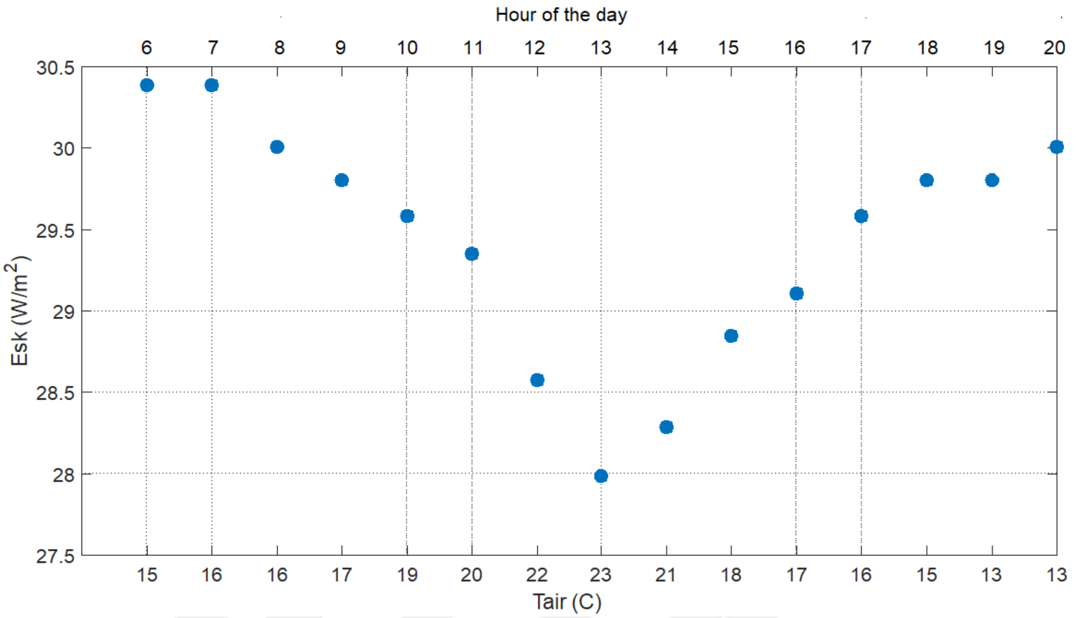


Figure 4.21: Change of evaporation heat loss (E_{sk}) from skin through clothing with respect to change of air temperature and the hour of the day.

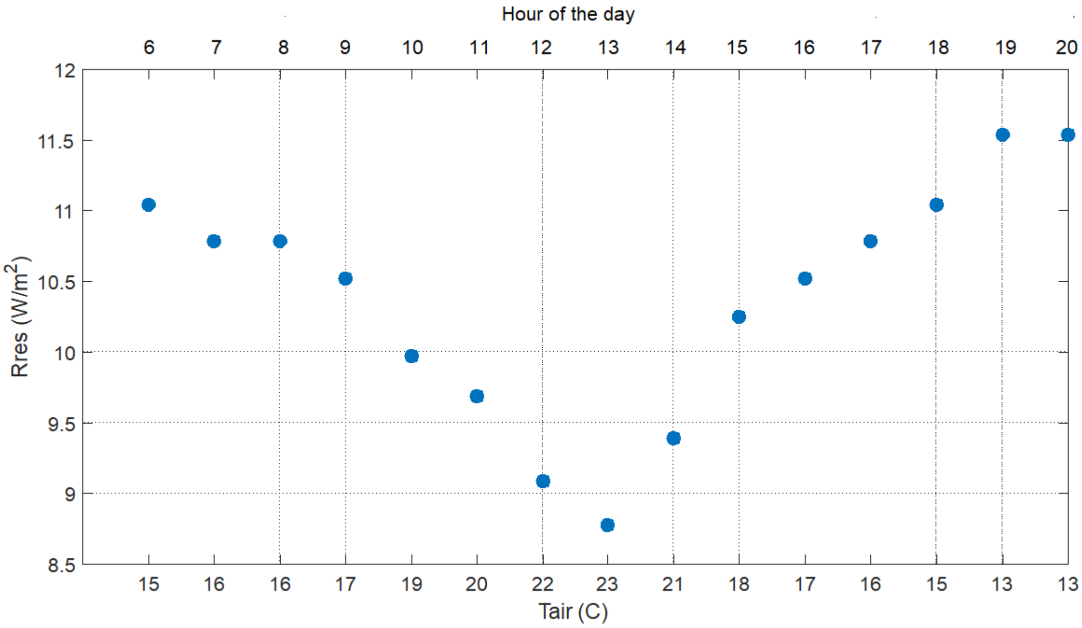


Figure 4.22: Change of respiratory heat loss *(Res)* from skin through clothing with respect to change of air temperature and the hour of the day.

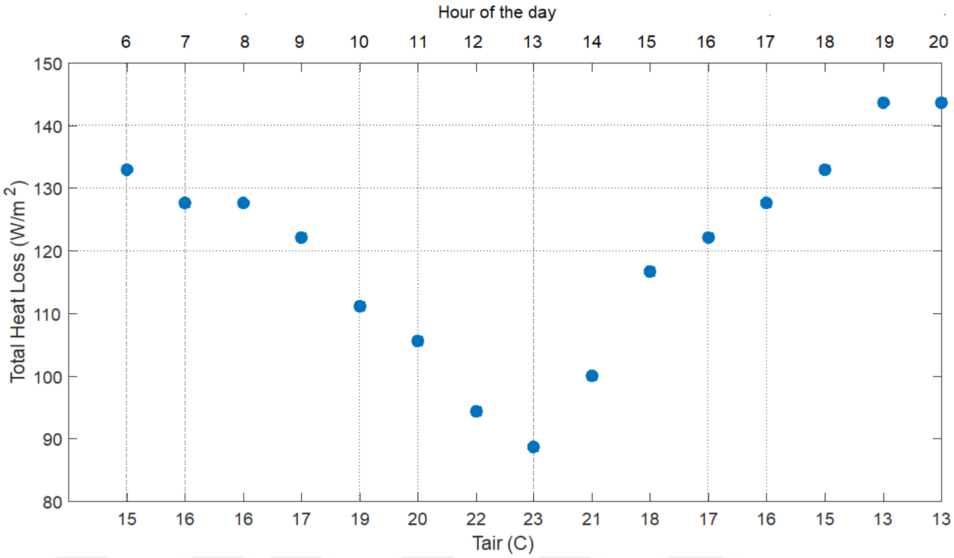


Figure 4.23: Change of total heat loss from skin through clothing with respect to change of air temperature and the hour of the day.

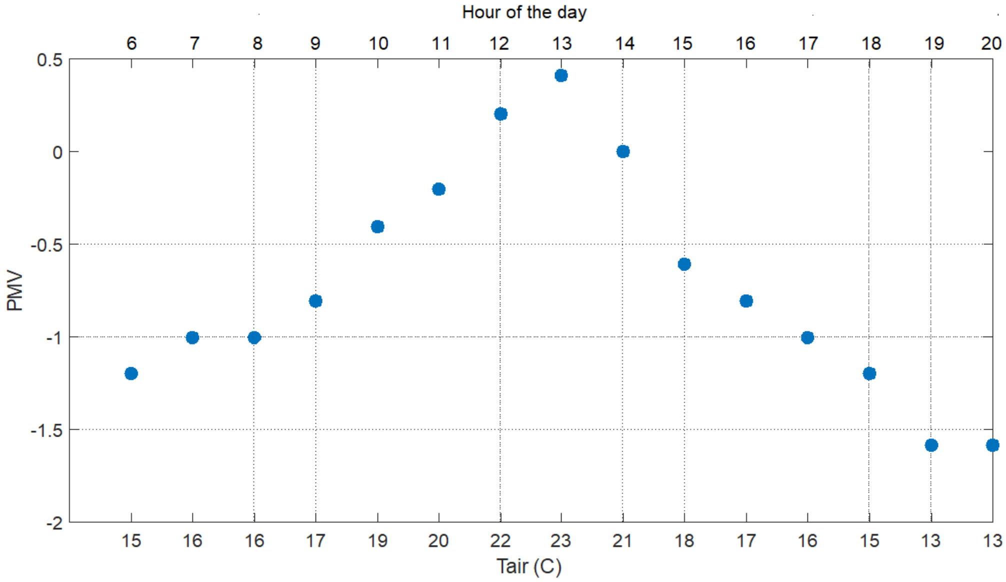


Figure 4.24: Change of PMV with respect to change of air temperature and the hour of the day.

As seen in Figure 4.20, dry heat loss from human skin is higher when the air temperature is lower. It has the lowest value $(52\,W/m^2)$ at 13:00 when the T_{air} is 23℃. In Figure 4.21, 4.22 and 4.23 evaporative heat transfer from skin to environment through clothing, respiration and total heat loss are displayed as a function of external temperature corresponding to the hour of the day. As expected, the higher the air temperature, the lower the heat loss from skin to the environment. In Figure 4.24, at time 13:00 Predicted Mean Vote is about $+0.5$ meaning that the person feels slightly warm. Highest heat loss is at 19:00 and 20:00 where the person feels coolest entire day.

4.9 CASE 7: Thermal Resistance of Clothing and Comfort on a Day in Istanbul

In this case, objective is to observe whether a person can feel comfortable with same clothing entire day in Istanbul or not. Throughout the day, hourly temperature values of Istanbul on 21 October 2019 are taken for calculations. Every hour according to changing temperature, relative humidity and wind velocity, PMV is calculated for a person with clothing that is 0.6 *clo* and activity level. So that, according to the changed whether conditions, the change of comfort feeling of a subject who has the same clothing from the beginning of the day is observed.

Another question we need to ask is about changing weather conditions and how the clothing should be changed to keep the state of comfort.

In Figure 4.25 hours are on the upper x-axis and temperatures representing each hour are on the lower x-axis. A person starts his/her day with a clothing that has a thermal resistance 0.093 m^2kPa/W. Clothing thermal resistance values that are required for comfort, are found by equalizing PMV to 0 at each hour for corresponding temperature as in the Figure 4.25.

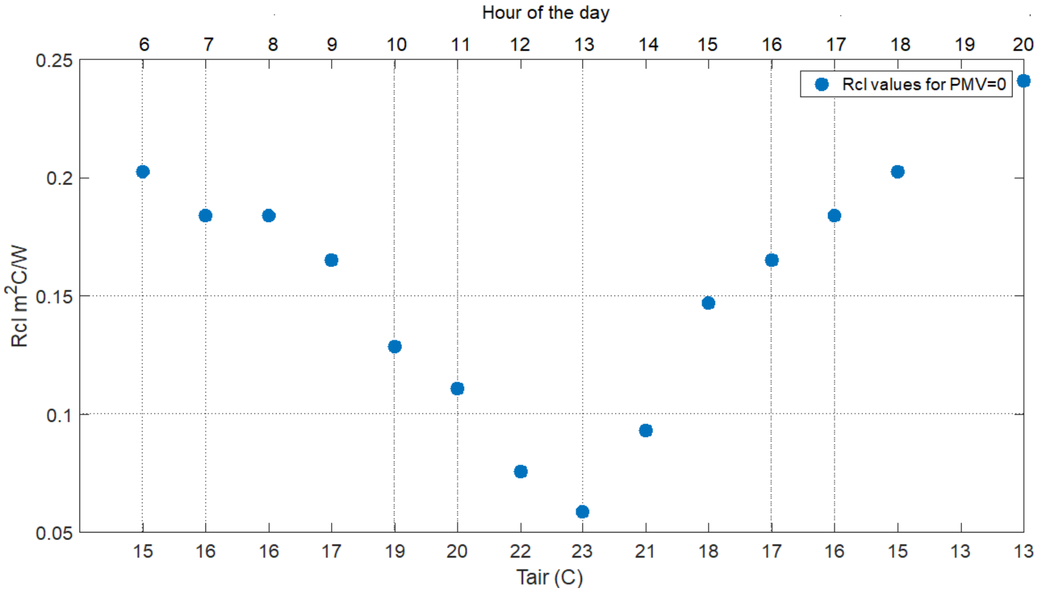


Figure 4.25: Required R_{cl} values for comfort with respect to change in air temperature.

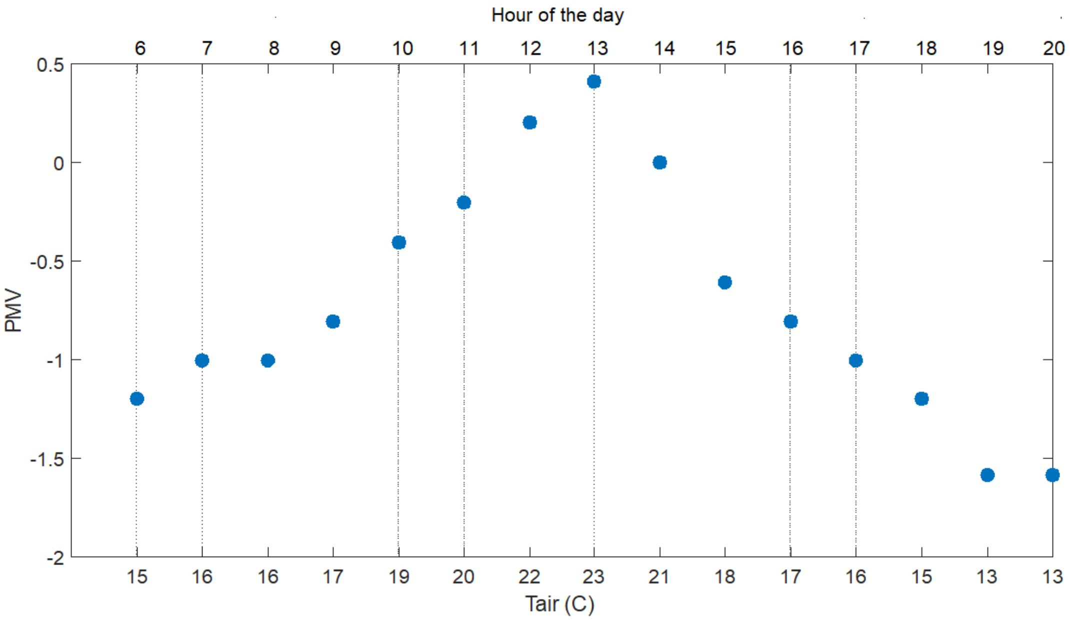


Figure 4.26: Change of the comfort feeling according to air temperature with a clothing of 0.6 *clo*.

In Figure 4.26, PMV values are calculated using same clothing which is 0.6 *clo*, each hour for corresponding temperature. When the air temperature is 16 ℃ PMV is -1 meaning that the person feels slightly cool. The person feels slightly warm at 13:00. when the air temperature is 23 ℃ and feels most comfortable at 14:00. with $T_{air} = 21$℃.

4.10 CASE 8: Strategy for a Typical Scenario in Ankara

In this case study, the objective is to propose solutions to a person for reaching feeling of comfort by examining the change of thermal comfort feeling during the day if he/she has the same clothes all day in different environments. A scenario is tested for this purpose; an algorithm is wanted to be developed, that answers to the questions such as “Is the person comfortable?” or “What should he/she wear to feel comfortable in any environment?”. This algorithm then produces simple answers very quickly which makes the information usable in an IOT applications. To see its applicability, a typical scenario that may be possible in Ankara is considered.

It is assumed that a typical person in Ankara wakes up at 6 a.m. and wears underwear with short sleeves and legs, trousers, long sleeves shirt, jacket, socks and thin soaled shoes, this corresponds to Overall $I_{cl} = 1.10$ which is based on the calculation of summation of each thermal resistance value of each clothing in *clo*. She goes out at 7:00.

Table 4.2. Hours and the corresponding temperatures from different environments that is used in this case.

Hour xx:00	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Temperature °C:	6	7	9	11	24	24	19	20	20	21	19	18	16	15	13	13

How does a person feel in terms of thermal comfort throughout the day can be seen mathematically in the Figure 4.27. In the lower x-axis the temperature values can be seen, in the upper x-axis hours of the day and in the y-axis calculated Predicted Mean Vote values correspond to each temperature value can be seen.

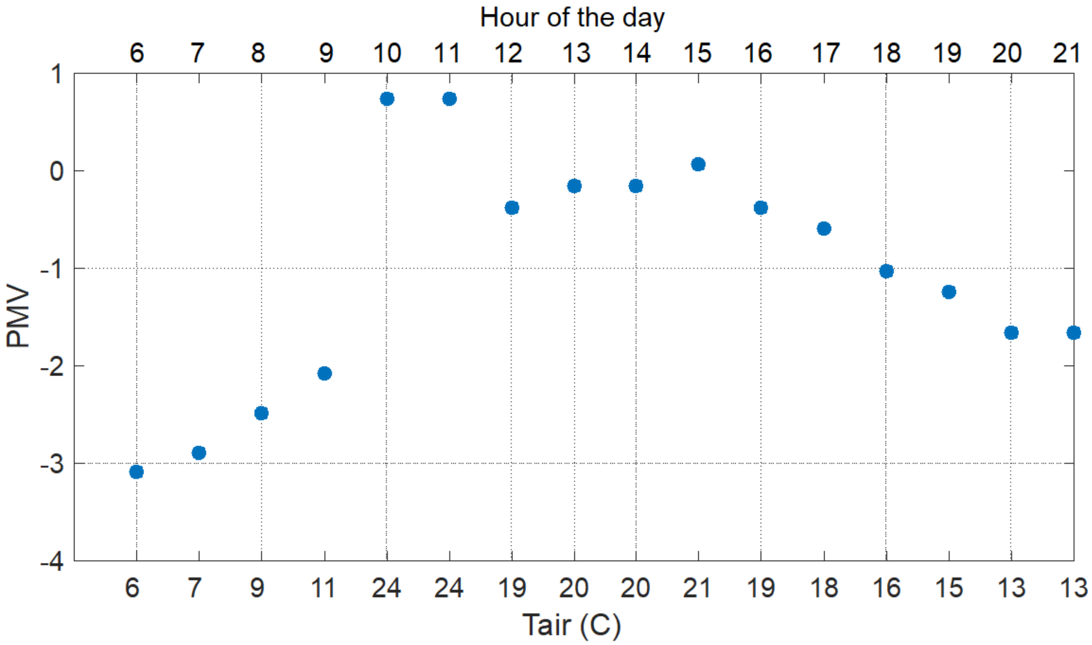


Figure 4.27: Hourly Predicted Mean Votes versus air temperature values with a clothing of 1.1 *clo*

Between 10:00 and 12:00 she is assumed to be at a meeting or sitting in an office where the temperature of the room is 24℃ and air conditioning does not work. The calculated PMV is 0.8 and she feels slightly warm with her clothing because she wears clothing with 1.10 *clo* yet in that office environment she should be wearing clothing of 0.5 *clo* to be able to feel comfortable as one can see from the Figure 4.29. Therefore, she should take off her jacket, which reduces her overall clothing resistance level to 0.7 *clo* and therefore she feels very close to neutral state. In Figure 4.28 this corresponds to path A.

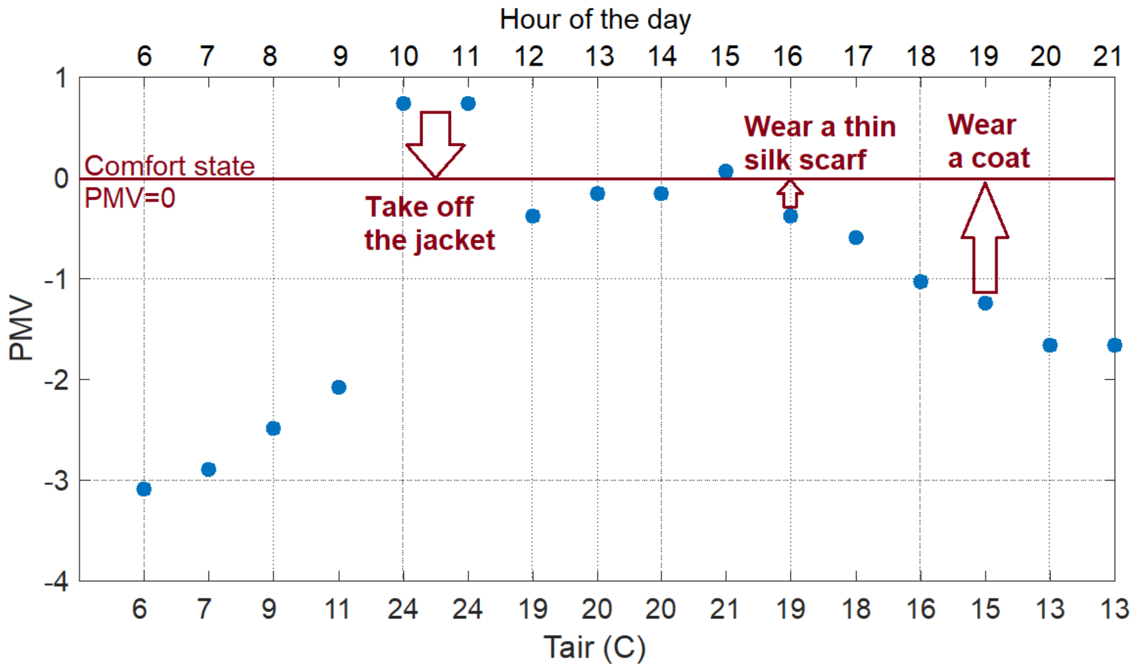


Figure 4.28: A) This path corresponds to change of clothing from 1.10 *clo* to 0.5 *clo* since he/she is in the office and should take his/her jacket to feel neutral. B) This path corresponds to wearing a thin silk scarf when he/she is out. C) This path corresponds to a change of clothing from 1.1 *clo* to 2 *clo* by wearing a coat to reach a comfortable state when the air temperature drops down to 15℃, therefore he/she should wear a coat.

After the meeting she goes out for a lunch break and the outside air temperature is 19 ℃. If she would not wear her jacket she would feel cold but with her jacket she feels close to neutral ($PMV = -0.2$) because as it can be seen from the Figure 4.27, she should be wearing 1.3 *clo* to feel exactly comfortable at 12:00 but, she already wears 1.1 *clo* and she only needs a very thin ($1mm$) silk scarf to reach that state.

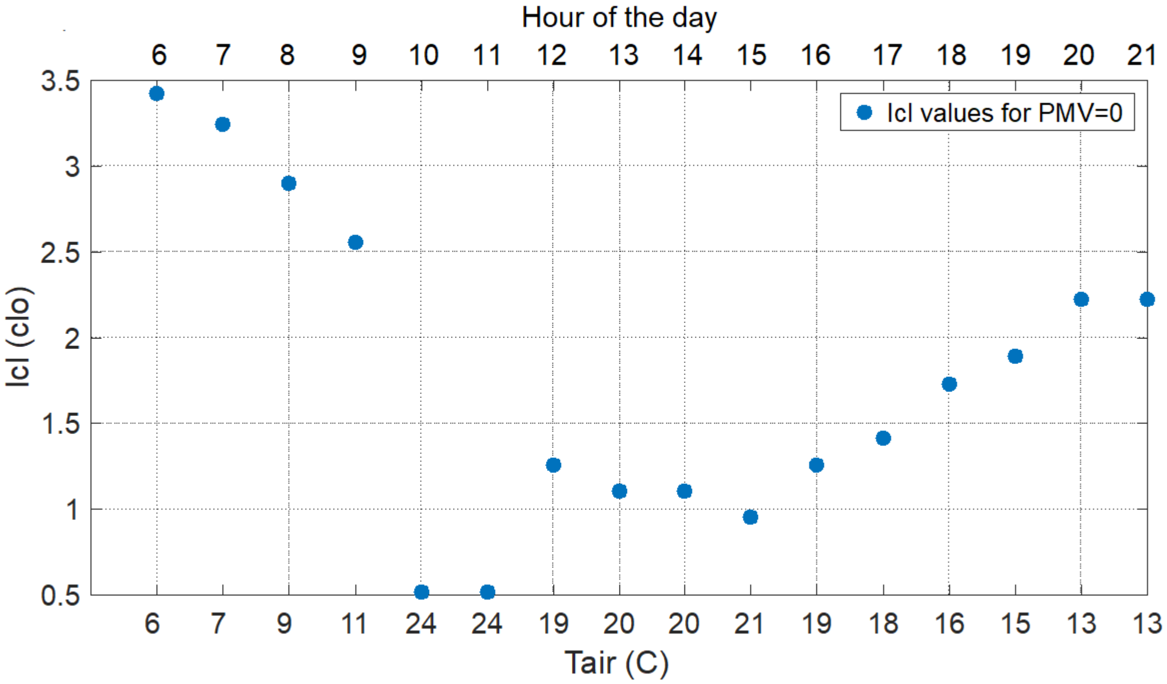


Figure 4.29: I_{clo} values needed to feel comfortable for each hour and each temperature.

She goes back to her office and stays between hours 13:00 and 15:00. This time the room air is at temperature of 20°C because she opened the air conditioning. At this situation she feels neutral. When clocks show 16:00 she leaves the office and goes out to meet her friends. In the first hour she doesn't feel discomfort but after 17:00. the temperature of outdoor air decreases to 16°C at 17:00 and 13°C at 20:00 She starts feeling slightly cool first and then feels cold when the temperature drops down to 13°C. Now she should have a coat for wearing on her jacket corresponding to path C in the Figure 4.28. Therefore, the algorithm needs to inform her about this situation in the morning before she leaves home and she can be rescued from feeling cold.

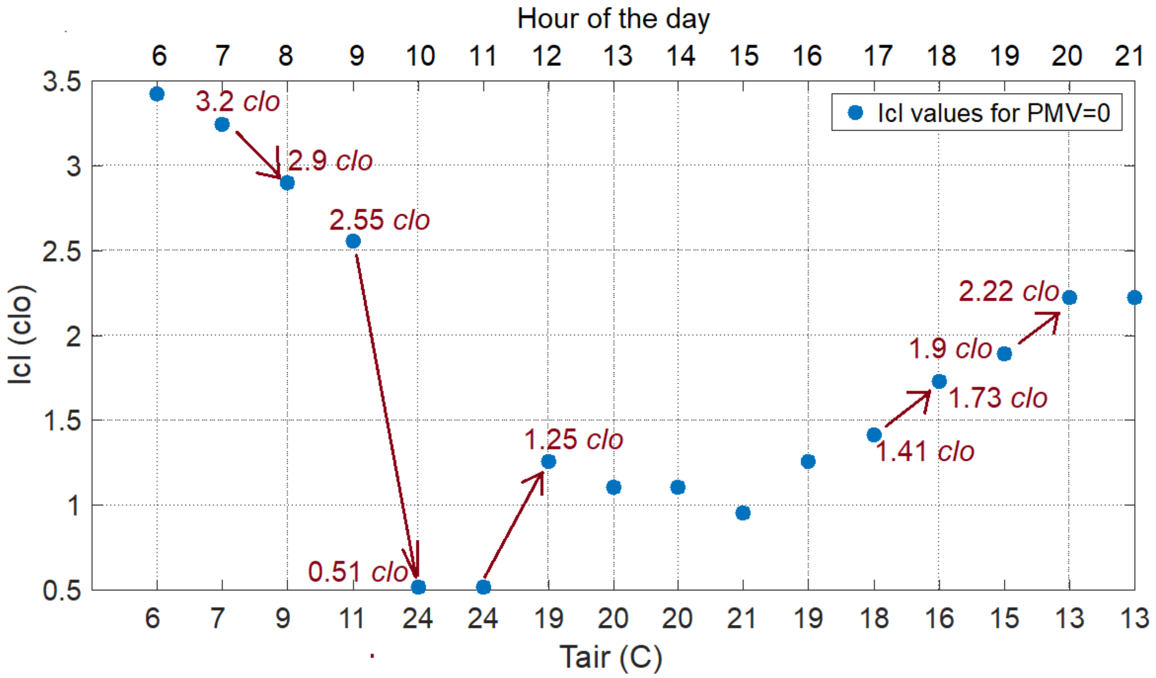


Figure 4.30: The change of required clothing insulation value (I_{cl}) for comfort with respect to air temperature are displayed for some hours. Directions of changes are shown by arrows. From 7 a.m. to 8 a.m. the required clothing insulation value decreases from 3.2 *clo* to 2.9 *clo* which is due to 2 °C increase of the air temperature.

Obviously a person cannot stay in a neutral comfortable state through an entire day, because in real life no one stays in the same location and environmental conditions changes as the place is changed. Therefore, this study is important as it shows an algorithm given a person a scenario shows her numerically how she would feel in terms of thermal comfort.

Last but not least, this algorithm developed in this study is important by being an algorithm letting someone know how to change his/her clothes to reach thermal comfort. In Figure 4.29, I_{clo}, total clothing resistance values needed to feel comfortable are given for each hour and each temperature. By looking this figure, suggestions can be made on how one should make a change in his/her clothing to reach thermal comfort.

4.11 CASE 9: Should You Take Your Cashmere Sweater with You?

In this case study a typical day of a business man is considered. The objective is to see for if he has to take his %100 cashmere sweater with him when he starts a typical day in Istanbul. On the day of 21 November 2019, he leaves the house at 9:15 a.m. and turns back at 8 p.m. In the morning he wears underwear with short sleeves and legs, trousers, shirt, jacket, socks and shoes. Summing up all clothing resistances, he wears $I_{cl} = 1.0$ and the hourly temperature values of environments he is present for 21 November in Istanbul, as given in the Table 4.3.

Between 9:15 a.m. and 9.45 a.m. he walks to a coffee shop where the temperature is 24℃ and stays here till 11 a.m.

At 11 a.m. he moves to his office where temperature is kept stable at 21℃ by air conditioning system.

At 1 p.m. he goes out for a lunch and turns back at 2 p.m.

He stays in the office between 2 p.m. and 5 p.m.

Around 5 p.m. he leaves the office to meet his friends. He sits in a garden of a restaurant for 2 hours.

After 7 p.m. he walks to home which is 20 minutes away.

According to the scenario above, the change of comfort feeling and required clothing insulation levels for comfort are displayed in Figures 4.31 and 4.32.

Table 4.3. Hours and the corresponding temperatures from different environments that is used in this case.

Hour xx:00	9.30 10 11 12 13 14 15 16 17 18 19
Temperature °C:	11 24 21 21 18 21 21 21 17 16 15

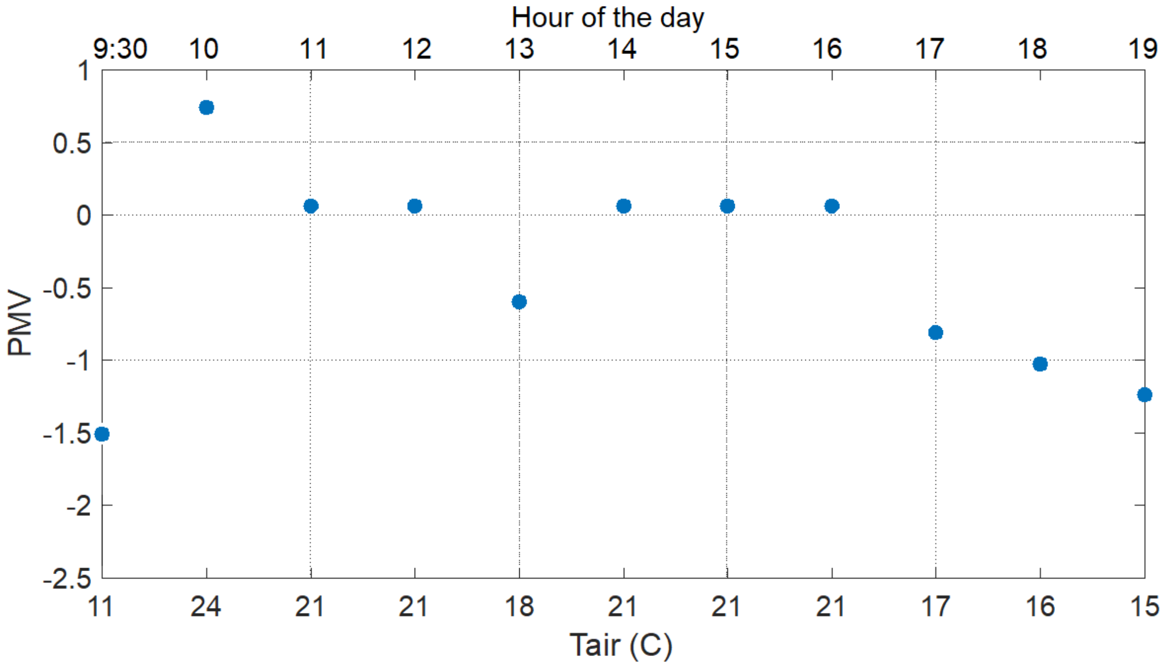


Figure 4.31: Predicted Mean Vote with respect to air temperature and hour.

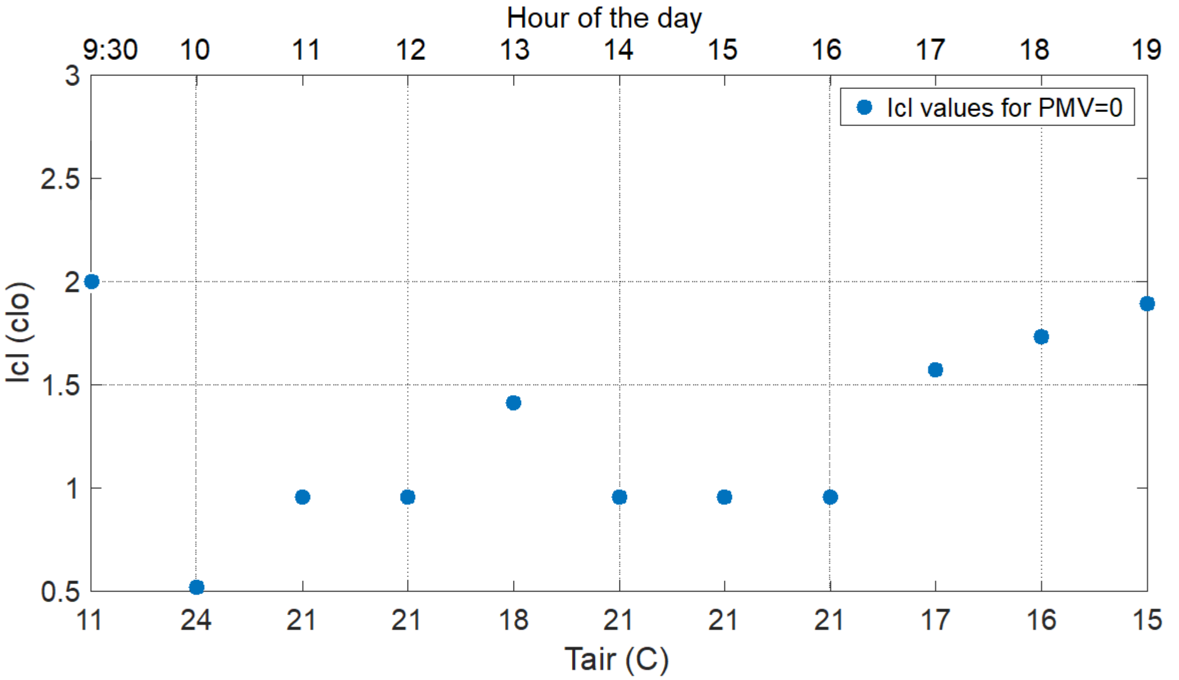


Figure 4.32: I_{cl}, intrinsic clothing resistance values required to feel comfortable with respect to time and hour.

In Figure 4.33 and 4.34 paths represents the need of change of clothing due to feeling of discomfort. At 9:30 a.m. he has been walking for 15 minutes and his metabolic rate is $120\ W/m^2$, therefore his body warmer than standing still and feels less cold. $PMV = -1.5$ meaning that he feels slightly cool. The required $I_{cl} = 2\ clo$ for him to feel neutral as it can be seen from the Figure 4.34. Path A represents that he needs to wear additional 1 *clo* level of clothing which corresponds to:

$$R_{cl} = I_{cl} \times 0.155\,\frac{m^2℃}{W} = 1.6 \times 0.155 = 0.248\ \frac{m^2℃}{W} \qquad \textbf{(4.10)}$$

$$R_{cl} = \frac{thickness}{k} \qquad \textbf{(4.11)}$$

where R_{cl} is the heat resistance of clothing and k is the conductivity value. %100 cashmere has a conductivity 0.12 W/mK, and 8 mm thick cashmere sweater is 0.43 clo. Therefore, in the morning he should take his sweater and a coat (0.6 clo) with him.

Now, let's consider a different scenario now, at 10 a.m. he is sitting in the coffee shop and his metabolic rate is 58 W/m^2. The temperature in the coffee shop is 24 ℃. Path B represents that he should take off his jacket which is 0.4 clo to get rid of the slightly warm feeling.

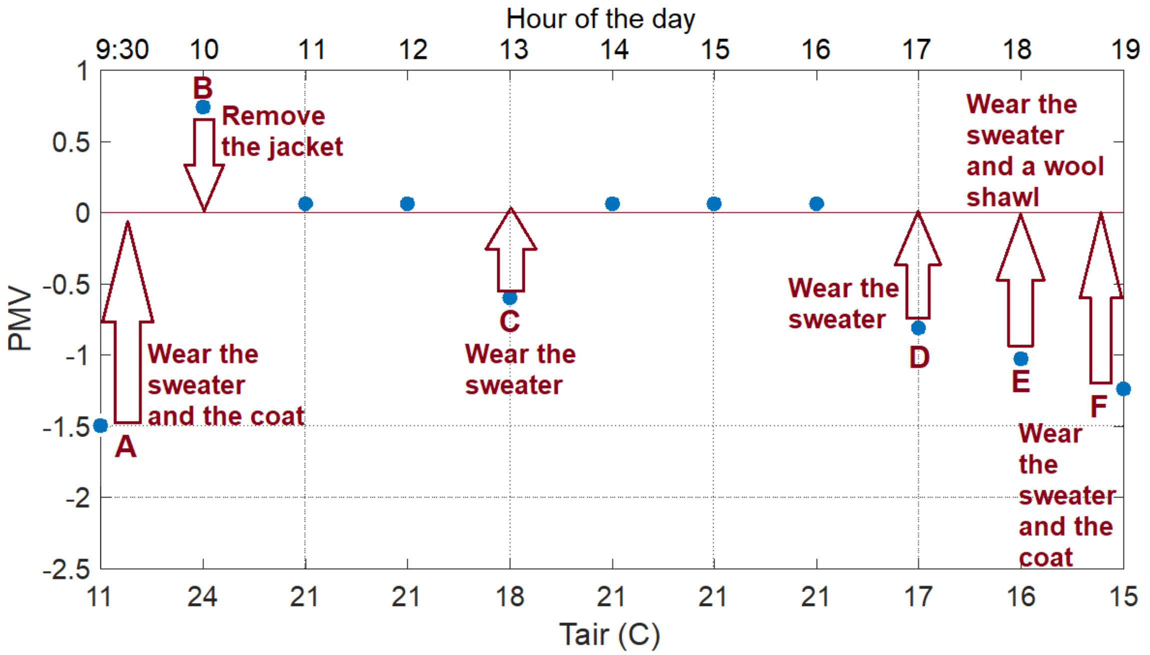


Figure 4.33: Paths shown by arrows directing from the points, where an action should be taken to reach a comfortable state, represent how far the person is from feeling neutral, at

each temperature and hour. Shawl is assumed to be wool, and the sweater is assumed to be cashmere.

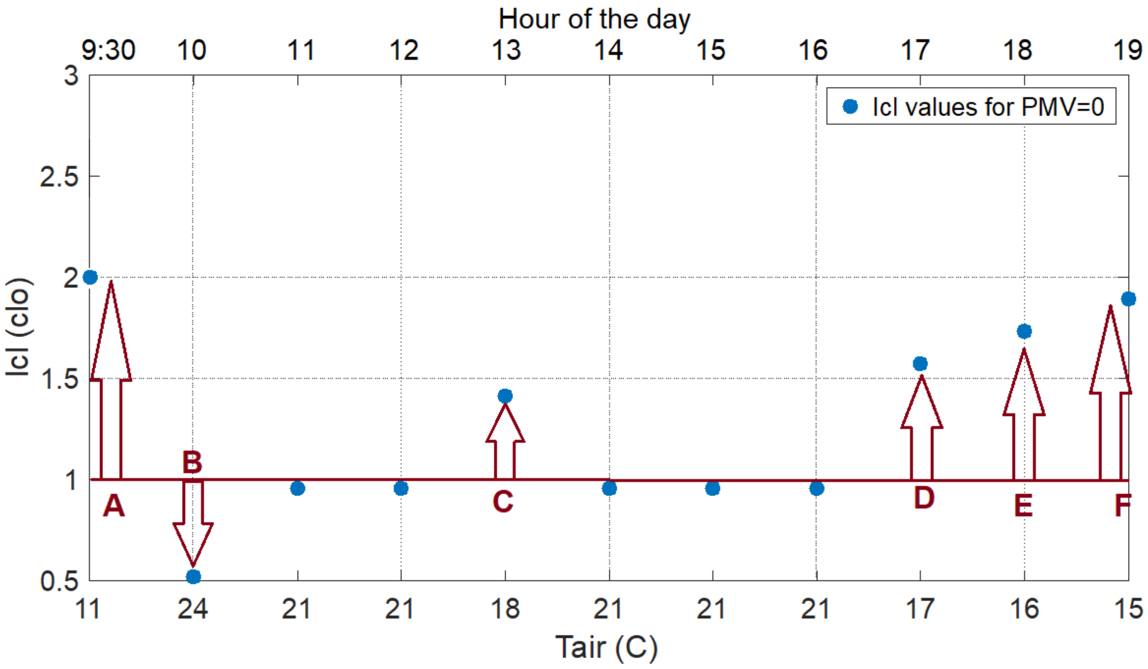


Figure 4.34: How much change is needed in clothing resistance to reach a comfortable state at each temperature and hour. $I_{cl} = 1.0\ clo$ represecondnts the insulation value of clothing that the person wears. Each path shows the *clo* value of clothing that the person should wear to feel comfortable. He should wear additional clothing which is 1 *clo* for path A; 0.4 *clo* for path C; 0.5 *clo* for path D; 0.8 *clo* for the path E; and 0.9 *clo* for path F. He should remove clothing that is 0.5 *clo* for path B.

In Figure 4.34, path C shows a need of additional 0.4 *clo* clothing which can be achieved by wearing the cashmere sweater where he is out for a lunch at 13:00. From 17:00 to 19:00 he is sitting in a garden of a restaurant. The temperature of the weather is 17℃ and drops 1℃ per hour. Initially he feels slightly cool with $PMV = -0.7$ and after one hour at 18:00 $PMV = -1$ and at 19:00 $PMV = -1.5$ meaning that he is between slightly cool and cold; yet each hour his feeling of cold increases. In this manner, path D represents that he should need an extra 0.5 clo clothing and again wearing his cashmere sweater will make him feel comfortable. For path E, the sweater will not be enough and additional 0.3 clo is needed and a thick wool shawl can make him reach a comfortable state. Path F shows I_{cl} should be 1.9 clo for neutral feeling. This can be achieved by wearing the sweater (0.4 clo) and a coat (0.6 clo).

4.12 The Importance of Case Studies

In this Chapter, all cases considered are chosen to mimic real life. First five cases are performed as parametric studies to observe how well the algorithm developed in this thesis matches with the data in literature and also, to observe effects of environment and thermophysiological clothing parameters on thermal comfort. The parametric study is significant on developing thermally comfortable clothing. In Case 5, blending ratios of different fabrics are compared in terms of providing comfort in a specific environment. In Case 6, heat losses of the body are examined with respect to variable air temperature and the comparison between dry and evaporative heat loss is made. In Case 7, Case 8 and Case 9, real life scenarios are investigated and change of thermal comfort feelings of different people in various environments are investigated. According to outputs of the algorithm, how each person should change his/her clothing to reach a comfort state, is shown numerically and suggestions for actions to be taken, are made.

Humans, by nature, always try to protect personal comfort. Most of the time, people try to achieve comfort by interfering in heating and cooling systems of buildings which usually results in consuming energy very inefficiently. Therefore, to minimize the over consumption of energy, human needs should be carefully considered. Clothes have a remarkable effect on human thermal comfort. So why not to use them more intelligently. Connecting clothes to the smart phones, that is used in every aspect of life every day, would be the next step of IOT applications. Modifying the clothes that a person wear, can decrease the desire of changing air conditioning in buildings, which may also decrease the energy usage in buildings in return.

CHAPTER V

CONCLUSIONS AND FUTURE DIRECTIONS

5.1 Conclusions

In this thesis heat transfer from human skin to the environment through clothing is examined in detailed to investigate the effect of garment on human thermophysiological comfort. A comprehensive literature search is provided. Thermal comfort models are examined and a simplified thermal comfort model is proposed in this thesis. The model is developed based on heat and mass transfer principles and thermal comfort model developed by Fanger (Fanger, 1970). The objective is to provide a theoretical model which is easy to calculate but gives best possible results. This study is performed numerically, therefore, some simplifications had to be done. The codes are simulated in MATLAB. Fanger's Predicted Mean Vote model is used to quantify comfort feeling. Different cases that are focusing on clothing thermal resistance, evaporative resistance and PMV, are modelled and solved. The main question answered in this study is how a person should dress to feel comfortable in an any environment.

Majority of the thermal comfort models in literature are based on the experimental results. This study uses the available data from the literature and provide an effective numerical model to obtain quick results where people are unable to make measurements through experiments. The results in this study agree well with the experimental data with a tolerable error.

This thesis, also provides a parametric study of a clothing. The results indicate that the most influential parameters of a garment on heat transfer is thermal and evaporative resistance values. More specifically, conductivity and thickness of a garment are two parameters that decide on thermal resistance. Furthermore, conductivity is a material property, so that from which materials the fabric is made of, what is the volume ratios of these materials and what is the porosity of the fabric are crucial questions that decide on the conductivity of fabric.

5.2 The Impact of the Study

In this thesis, an algorithm is developed to explore feeling of thermal comfort of different people. As it can be seen from the cases and results, the algorithm produces accaptable results that match well with literature and also reasonable for real life cases.

However, to make thermal comfort controllable and understandable for normal people, the algorithm needs to be modified in real time by integrating it to smart gadgets used in daily life. Through the simplified algorithm developed in this study, people may become able to control their thermophysiological wear comfort for instance by using a smart phone. An application in a phone can tell the person how to wear or what not to wear to feel comfartable in an any environmental condition.

Another way of using the algorithm can be smart buildings. If the person does not feel comfortable with his/her clothings but there is no chance to change them, the building can be informed and modify itself by changing air conditioning to make him/her feel comfortable.

This study is also provides a scientific parametric study for clothing thermal comfort. It can be used to decide required values of parameters when designing a thermally comfortabe clothing. It is also a very quick and easy but fair way of designing composite fabrics by producing resultant thermal parameters.

5.3 Future Works

Clothing thermal comfort is a very complex area and need so many improvements. In this thesis simplified but effective model of heat transfer from human skin to the environment through clothing is proposed. From the thermodynamics point of view, being able to keep human body at the comfort state is what the people in the 21st century is looking for. In order to provide better clothing, thermo-physiological properties of fabrics should be improved. As a future work, different thermal properties of clothing will be focused on. Also, some experiments can be done in the future to improve the numeric solutions.

This algorithm is developed to be able to use clothes in a cleverer way. In the future, this study can be used for phone applications and/or in smart buildings. Today, every information can be gathered from smart phones, they can be answers to many questions. So why not to control our clothes from smart phones. The next step of IOT applications would be connecting clothes to the IOT system of building through internet or local networks. This way, the energy consumption in buildings can be reduced.

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APPENDIX A

In this Appendix, KVR and KVI values which was explained in the Chapter 3, is given in Tables A1 and A2. As in the Chapter 3.8, Qian (2005) proposed the following empirical formulas to predict heat and mass transfer coefficients by wind penetration (h_{dev}) and air ventilation (h_{eev}) for a clothed person walking under windy conditions:

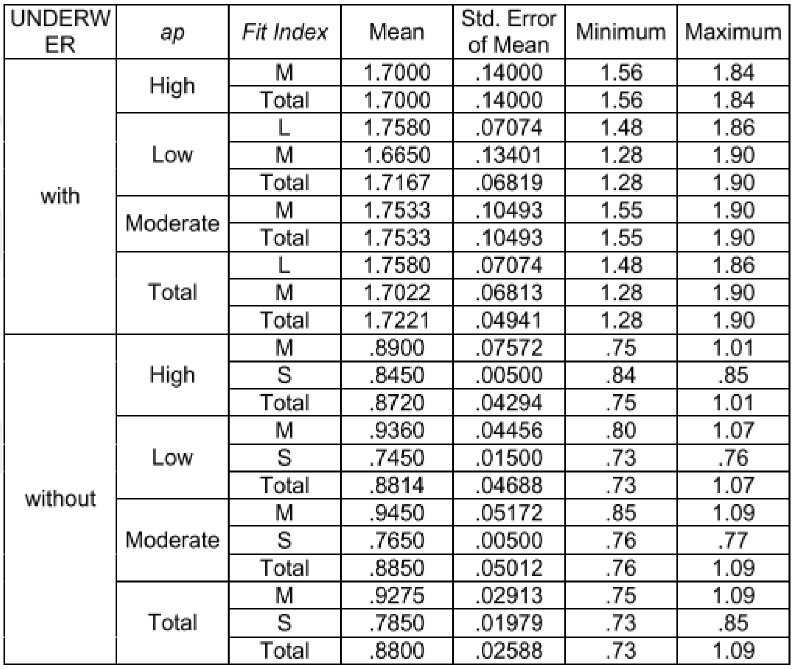
$$h_{dev} = KVI \cdot (V_{wind} + 2 \cdot V_{walk} - v_0) \quad \textbf{(A1)}$$

$$h_{eev} = KVR \cdot (V_{wind} + 2 \cdot V_{walk} - v_0) \quad \textbf{(A2)}$$

$$v_v = V_{wind} + 2 \cdot V_{walk} - v_0 \quad \textbf{(A3)}$$

where KVI and KVR are constants that depend on garment fitting, design and construction of the clothing. KVI and KVR values range from 0.6 to 2.0 and 0.005 to 0.015 respectively. V_{wind} is the velocity of wind blowing towards a person, V_{walk} is the walking speed, v_v is the equivalent wind velocity taking into account the effect of walking speed. v_0 is the air current in the “still air” condition and taken as $O.22\ m/s$ (Qian, 2005). $h_{dev} = h_{eev} = 0$ when there is no air exchange by walking and wind motion, in other words at the still air condition. KVI and KVR values are provided by Qian (2005) in the following tables.

Table A1 : KVI values for each category of clothing ensemble (Qian, 2005)



UNDERWER	*ap*	*Fit Index*	Mean	Std. Error of Mean	Minimum	Maximum
with	High	M	1.7000	.14000	1.56	1.84
		Total	1.7000	.14000	1.56	1.84
	Low	L	1.7580	.07074	1.48	1.86
		M	1.6650	.13401	1.28	1.90
		Total	1.7167	.06819	1.28	1.90
	Moderate	M	1.7533	.10493	1.55	1.90
		Total	1.7533	.10493	1.55	1.90
	Total	L	1.7580	.07074	1.48	1.86
		M	1.7022	.06813	1.28	1.90
		Total	1.7221	.04941	1.28	1.90
without	High	M	.8900	.07572	.75	1.01
		S	.8450	.00500	.84	.85
		Total	.8720	.04294	.75	1.01
	Low	M	.9360	.04456	.80	1.07
		S	.7450	.01500	.73	.76
		Total	.8814	.04688	.73	1.07
	Moderate	M	.9450	.05172	.85	1.09
		S	.7650	.00500	.76	.77
		Total	.8850	.05012	.76	1.09
	Total	M	.9275	.02913	.75	1.09
		S	.7850	.01979	.73	.85
		Total	.8800	.02588	.73	1.09

Table A2 : KVR values for each category of clothing ensemble (Qian, 2005)

UNDERWER	*ap*	*Fit Index*	Mean	Std. Error of Mean	Minimum	Maximum
with	High	M	.012750	.0008500	.0119	.0136
		Total	.012750	.0008500	.0119	.0136
	Low	L	.011220	.0007990	.0086	.0134
		M	.009900	.0005477	.0087	.0111
		Total	.010633	.0005302	.0086	.0134
	Moderate	M	.011233	.0003180	.0107	.0118
		Total	.011233	.0003180	.0107	.0118
	Total	L	.011220	.0007990	.0086	.0134
		M	.010978	.0004827	.0087	.0136
		Total	.011064	.0004042	.0086	.0136
without	High	M	.008833	.0004333	.0081	.0096
		S	.007650	.0001500	.0075	.0078
		Total	.008360	.0003776	.0075	.0096
	Low	M	.007660	.0001887	.0072	.0080
		S	.005350	.0005500	.0048	.0059
		Total	.007000	.0004614	.0048	.0080
	Moderate	M	.008425	.0004308	.0074	.0095
		S	.005800	.0000000	.0058	.0058
		Total	.007550	.0006168	.0058	.0095
	Total	M	.008208	.0002291	.0072	.0096
		S	.006267	.0004688	.0048	.0078
		Total	.007561	.0003057	.0048	.0096