Review Article: Thermal Balance and the Role of Clothing on Thermal Comfort in Hot and Humid Climate

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Abstract

In the recent year, human thermal comfort has been claimed to be an adaptive behaviour and controllable environment. Clothing is a controllable personal environment and it should play an important part in built environmental designs. The present study conducted an analysis that was divided into three sections. The first section examined the human thermal comfort evaluation on thermal balance equation. The second section described each term of thermal balance equation. The third section reviewed the role of clothing in parts of heat transfer. This review recommend that clothes property such as evaporative heat transfer resistance of clothing should be included into the thermal balance for thermal comfort estimation.

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Introduction

From past to present, humans wear clothing in daily life to stay alive in the environment. Clothing acts as a shelter for human body. Humans need clothes to keep body temperature to be stable and this relates to comfort feeling. Clothing also helps the thermoregulation systems which automatically control body temperature within the narrow limit. If the thermoregulation is unable to control the body temperature within the narrow limit, humans are possible to feel discomfort, sick or die. So clothes plays a crucial role in humans' living to control the body temperature within comfort range. In the other word, clothing controls heat transfer between human body and the thermal environment. Wearing an appropriate clothing in any weather results into human-clothing-environment thermal balance system and this is thermal comfort condition. In terms of thermal comfort, the two most important parameters are concerned with the transferring of heat and sweat away from the body which can be measured in terms of thermal insulation and evaporative resistance.

Thermoregulatory system of human.

A human has a nearly constant internal temperature around 37 °C. It can be maintained constant only if there is a balance between the internal heat generation in the core body and the heat loss to the environment. In warm-blooded mammals, including man, the heat balance is controlled mainly by the hypothalamus, which is the part of the brain that acts like a thermostat.

The result of thermoregulatory action in this thermal comfort condition is sweating. Sweating does not happen all time. It was produced only when the body is unable to transfer heat immediately with typical method. The typical methods include heat loss due to the differences of temperature and water vapour pressure such as conduction, convection, radiation and moisture diffusion.

Thermal Balance Concept

Exposing in the environment, human body exchanges heat with its surrounding by sensible and latent heat. Sensible heat transfer is driven by human body and environment temperature difference. It can takes place by conduction, convection and radiation. Latent heat transfer occurs by a change of state from liquid to gas (evaporation) such as moisture diffusion through skin and evaporation of sweat.

When environmental temperatures are close to body temperatures. The sensible heat loss from human body is decreased because of the less temperature difference between the body and the environment. The body is unable to transfer the heat by the temperature difference (sensible heat loss) in sufficient rate, consequently, the high air temperature raises the higher body temperature. According to the physiology limitation of human body temperature and thermoregulatory mechanism, human body produces sweat to accelerate the heat transfer from the body to the environment. The sweat is secreted to exhaust the exceed heat. The latent heat loss from sweat evaporation (or water vapour) is the majority heat transfer method in high air temperature; therefore, latent heat loss is particularly important. (Parsons, 2014). Clothing must assist the body's thermal control function under changing physical loads in such a way that heat generation and heat loss is balance in thermal balance (Umbach, 1993).

Human produces heat continuously inside his body during all activities because of metabolic process. With greater physical exertion, and thus a greater level of heat generation. Heat transfer through clothing is insufficient to compensate for the thermal balance. In this case the body begins to sweat to cool down the body temperature by sweat evaporation on the skin. (Umbach, 1993)

The heat balance equation for the human body can be represent in many forms. However, all equations have the same underlying concept and involve three types of term: those for heat generation in the body, heat transfer and heat storage. The metabolic rate of the body (*M*) provides energy to enable the body to do mechanical work (*W*), and the remainder is released as heat (*M*-*W*). Heat transfer can be by conduction (*K*), convection (*C*), radiation (*R*) and evaporation (*E*). When combined together, all of the rates of heat production and loss provide a rate of heat storage (*S*). All terms are in watt per square meter unit (W/m^2). The conceptual thermal balance equation is

$$M - W = E + R + C + K + S \quad (1)$$

For a body to be in thermal balance, the heat storage should be equal to zero (S=0). If S>0, (net heat gain), the body temperature will be higher. On the other way, if S<0, (net heat loss), the heat storage will be negative and the body temperature will be lower.

That is, for heat balance (S=0)

$$M - W - E - R - C - K = 0 \quad (2)$$

Where $M - W$ is always positive, and E, R, C and K are rates of heat loss from the body (positive value is heat loss, negative value is heat gain).

In agreement with ASHRAE standard 55 (1966), thermal comfort is 'that condition of mind which expresses satisfaction with the thermal environment'. It will be less possible to satisfy everybody in one thermal condition at the same time. The achievable environment satisfy majority of people. One must then aim at creating optimal thermal comfort for the group such as a condition in which the highest possible percentage of the group is in thermal comfort. (Fanger, 1970)

The objective to create thermal comfort environment is to make human feel comfortable with the thermal environment. According to Fanger (1970), six most important parameters influencing the condition of thermal comfort are:

activity level (heat production in the body),
thermal insulation of clothing,
air temperature,
mean radiant temperature,
water vapour pressure,
air velocity in ambient air.

Part 1.Thermal Models

Thermal models integrate the fundamental of heat transfer, thermal balance, thermal physiology and thermoregulation along with anthropometry and anatomy into a mathematical representation of the human body and its thermoregulatory systems. These can include skin temperature, internal body temperature, sweat loss and more. They can also be used in research to investigate fundamental mechanisms of thermoregulation, heat transfer and their relationship to human responses. However, physiological response to thermal conditions is complex and there are wide variations between individuals. Moreover, knowledge is incomplete. Models of humans in thermal environments will therefore be imperfect. (Parsons, 2014)

Thermal Model with Thermal insulation of clothing

Clothing materials and clothing ensembles, its dry thermal insulation properties is a majority important parameter in thermal model. It has been extensively investigated. A simple thermal model is a heated body with a layer of insulation for human body to maintain balance heat flows to the skin, with clothing temperature, and the ambient environment.

Fanger assumed all sweat is evaporated, eliminating clothing permeation efficiency as a factor in the equation. This assumption is valid for normal indoor clothing worn in typical indoor environment with low or moderate activity levels. At higher activity level (M>3 met), where a significant amount of sweating occurs even at optimum comfort conditions, this assumption may limit accuracy. The reduced equation is slightly different from the heat transfer equations of ASHRAE (2013).

In Fanger's thermal model, thermal insulation I_{cl} was defined. It effects the temperature of clothing and sensible heat transfer. The values of I_{cl} was chosen from a table of clothing combinations. Fanger (1970) provides thermal balance model with the purpose of the thermoregulatory system of the body. The model provided a relationship of heat production and heat loss in terms of heat storage (S), metabolic heat production (H), heat loss by water vapour diffusion through the skin (E_d), heat loss by sweat (E_{sw}), latent respiration heat loss (E_{res}) dry respiration heat loss (C_{res}), radiative heat loss from the skin (R), convective heat loss from the skin (C) and conduction heat loss from skin through clothing (K). All terms are in watt per square meter unit (W/m^2). The following equation was proposed by Fanger:

$$S = H - E_d - E_{sw} - E_{res} - C_{res} - R - C = K \quad (3)$$

Fanger (1970) defines three conditions for a person to be in thermal comfort: 1) The body is in thermal balance which heat storage, S, equals to zero (W/m^2) as the following equation:

$$0 = H - E_d - E_{sw} - E_{res} - C_{res} - R - C \quad (4)$$

2) The sweat rate is within comfort limits ($E_{rsw,\,req}$, W/m^2) that depends on metabolic rate (M, W/m^2) and mechanical works (W, W/m^2) as the following equation:

$$E_{rsw,\,req} = 0.42\ (M\text{-}W\text{-}58.15) \quad (5)$$

3) The mean skin temperature is within comfort limits ($t_{sk,\,req}$, °C). This depends on metabolic rate (M, W/m^2) and mechanical works (W, W/m^2) as the following equation:

$$t_{sk,\,req} = 35.7\text{-}0.0275\ (M\text{-}W) \quad (6)$$

Thermal balance is a necessary but not sufficient condition for comfort. The body can be in thermal balance but uncomfortably hot due to sweating or uncomfortably cold due to vasoconstriction and low skin temperatures. Skin temperatures and sweat rates required for comfort, $t_{sk, req}$ (°C) and $E_{rsw, req}$ (W/m²) and depended upon activity levels (Rohles & Nevins, 1971).

For sedentary activity, Fanger (1970) and McNall et al. (1967) provide data for four activity levels from 1396 subjects exposed for 3 hours in Kansas State University uniform. They had rated their thermal sensation in that environment on the following scale on Table 1:

PMV rating	-3	-2	-1	0	+1	+2	+3
Thermal sensation	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

Table 1. Thermal sensation and rating scales (ASHRAE, 1966) (Fanger, 1970) (ISO 7730, 2005)

Fanger (1970) divides thermal sensation rating scale into 7 rating scales. Neutral is zero, cold is -3 and hot is +3. This provided an equation of the Predicted Mean Vote (PMV) of a large group of subjects. The value of PMV rating from -3 to +3 is therefore obtained from Equation 7.

$$PMV = (0.303e^{-0.036M} + 0.028)(H - E_d - E_{sw} - C_{res} - E_{res} - R - C) \quad (7)$$

There are three main groups in Equation 5. These are 1) Heat generation from human body (H), 2) Heat transfer from respiration (C_{res} and E_{res}) and 3) Heat transfer from skin (E_d, E_{sw}, R and C) Since clothes are closed to skin, then the role of clothes on thermal balance is in the terms in group 3). The explanation of each term in Equation 7 are shown in Equation 8-22.

Part 2. Description of Terms in Thermal Balance Model

1) Heat generation from human body ($H = M – W$, W/m²)

Metabolism (M, W/m²)
The energy released by the oxidation process in the human body (Metabolic rate, M) per body surface area which is equivalent to the amount of energy the body needs to function. The value of some metabolic rates may vary from resting as shown Table 2:

Activity	Metabolic Rate	
	met	W/m²
Reclining	0.8	45
Seated, quiet	1.0	60
Writing	1.0	60
Typing	1.1	65
House cleaning	2.0-3.4	115-200
Seated, heavy limb movement	2.2	130
Exercise	3.0-4.0	175-235

Table 2. Metabolic rate (ANSI/ ASHRAE Standard 55, 2013)

Mechanical work (W, W/m²)
The external work (W/m²) which is necessary to overcome the resistance from the load and the other part is the internal heat production, which is necessary for the body to perform external work equal to W. This part of energy is used to pump more blood around and increase the respiration.

2) Heat Loss from Respiration

Latent respiration Heat Loss (E_{res}, W/m²)
While breathing human body gets heat losses because there are the differences in water vapour pressure of inhale (p_a, Pa) and exhale air.

$$E_{res} = 1.72 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) \quad (8)$$

where, p_a is partial water vapour pressure in ambient air (Pa).

For normal indoor activities (seated/ standing) and ambient temperatures around 20 °C the heat losses by respiration are small, less than 2-5 W/m², and may often be neglected. (Olsen, 1982)

Sensible Respiration Heat Loss (C_{res}, W/m²)
Heat loss by the temperature difference of inhale and exhale air

$$C_{res} = 0.0014 \cdot M(34 - t_a) \tag{9}$$

The temperature of the exhale air is assumed to be 34 °C. This loss is normally insignificant.

3) Heat transfer from skin

There are two types of heat transfer from human skin 1) Evaporative heat transfer from skin through moisture diffusion (E_d) and through skin sweating (E_{sw}) and 2) Radiation (R) and Convection from skin (C)

Evaporative Heat Transfer (E_d and E_{sw} , W/m^2)

Heat loss by evaporation is partly from water vapour diffusion through the skin (E_d) and from the skin through sweating. But the heat loss by water vapour diffusion through skin takes place all the time and is not controlled by the thermoregulatory system. When evaporation takes place the water uses heat from the skin. The evaporative heat loss from moisture diffusion through skin (W/m^2) is

$$E_d = 3.05 \cdot 10^{-3} (p_{sk} - p_a) \tag{10}$$

where p_{sk} is the saturated water vapour pressure at the skin surface (kPa) is a function of the skin temperature (t_{sk} ,°C)

$$p_{sk} = 256 \cdot t_{sk} - 3373 \tag{11}$$

The sweat is producing when there are more exceed heat than the body can transfer heat in the general way by thermoregulation system. The sweat evaporation heat loss from the skin surface (E_{sw}, W/m^2) is equal to the sweat rate in comfort limitation ($E_{rsw,req}$) in Equation 5 (Fanger, 1970) by

$$E_{sw} = E_{rsw,req} \tag{12}$$

Convective Heat Transfer (C, W/m^2)

The heat loss by convection from the outer surface of the clothed body can be expressed by

$$C = f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \tag{13}$$

Where, f_{cl} is the ratio of the surface area of the clothed body to the surface area of the nude body (dimensionless). I_{cl} is thermal insulation of clothing (clo) For Fanger's PMV equation (Fanger, 1970):

$$f_{cl} = \begin{cases} 1.00 + 0.2 I_{cl} : I_{cl} < 0.5\ clo \\ 1.05 + 0.1 I_{cl} : I_{cl} > 0.5\ clo \end{cases} \tag{14}$$

Fanger (1970) uses a rule for the determination of convective heat transfer in the transition zone, to calculate h_c for both free and forced convection. The magnitude of h_c depends on pattern of convection process. The Equation 15 is the combination of Nielsen and Pedersen (1952) (free convection) and Winslow, Gagge, and Herrington (1939) (forced convection).

$$h_c = \begin{cases} 2.38(t_{cl} - t_a)^{0.25} : 2.38(t_{cl} - t_a)^{0.25} > 12.1\sqrt{v_{ar}} \\ 12.1\sqrt{v_{ar}} \quad : 2.38(t_{cl} - t_a)^{0.25} < 12.1\sqrt{v_{ar}} \end{cases} \tag{15}$$

h_c is the convective heat transfer coefficient (W/m^2·K). t_{cl} and t_a are the mean clothing surface and mean air temperature, respectively (°C). v_{ar} is the relative air velocity (m/s).

According to Equation 15, low air velocity (or still air) the heat transfer takes place by free convection, so h_c is a function of the temperature difference between clothing and ambient air (t_{cl} - t_a). Nielsen and Pedersen (1952) have made a comprehensive investigation using subjects and a manikin, both in seated and standing positions. This free convection for h_c, applicable both for standing and seated positions was found to give excellent agreement between the subject and manikin tests.

In the other way, for higher air velocity the heat transfer takes place by forced convection and h_c is a function of the air velocity instead. Winslow, Gagge, and Herrington (1939) have investigated the convective heat transfer coefficient for subjects in a semi-reclining position with the velocity downward (v_{ar} < 2.6 m/s).

For most practical cases, the air velocity in Equation 15 in free convection is for v_{ar} < 0.10 m/s and forced convection v_{ar} > 0.10 m/s. The h_c in Equation 15 are only applicable at normal barometric pressure at sea level. The effect of low and high air pressures, which can be of interest. (Fanger, 1970)

Radiative Heat transfer (R, W/m^2)

Radiant heat exchange takes place between the human body and its surroundings, from the outer surface of the clothed body. The heat loss by radiation can be expressed in Equation 16. t_r is the mean radiant temperature (°C).

$$R = h_r \cdot f_{cl} \cdot (t_{cl} - t_r) \tag{16}$$

where, h_r is the radiative heat transfer coefficient (W/m^2·K),

h_r is nearly constant for typical indoor temperatures (10 - 30 °C) (Olsen, 1982) (ASHRAE, 2013) and a value of 4.7 W/ (m^2•°K) suffices for most calculations (ASHRAE, 2013). The radiative heat transfer coefficient is calculated by Equation 17.

$$h_r = 4\sigma\varepsilon \cdot \left(\frac{t_{cl} + t_r}{2} + 273\right)^3 \cdot \frac{A_r}{A_{du}} \tag{17}$$

where, σ is the Stefan-Boltzman constant, ($5.67 \cdot 10^{-8}$ W/ $m^2 \cdot K^4$). ε is the emissivity of the clothed body surface (dimensionless), the emissivity is normally close to unity (around 0.95). A_r / A_{du} is the effective surface area participating in the radiative heat transfer (dimensionless). The ratio of A_r / A_{du} is 0.70 for a sitting person and 0.73 for a standing person (Fanger, 1967) (ASHRAE, 2013).

A_{Du} is the DuBois body surface area (m^2),W_b is the body weight (kg) and H_b is the body height (m).
The human body surface area (A_{Du}) is determined by the Dubois and Dubois equation (DuBois & DuBois, 1916) in Equation 18.

$$A_{Du} = 0.202 \cdot W_b^{0.425} \cdot H_b^{0.725} \tag{18}$$

When substituted the constants from Equation 17 and 18 to Equation 16, the heat exchange by radiation may be written by

$$R = 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (t_r + 273)^4] \tag{19}$$

Heat conduction through the clothing (K, W/m^2)
According to Equation 3, thermal balance equation is often used. However, when dealing with a person with clothing it is preferable to write the heat balance equation as heat storage equals to zero. The relation of heat transfer from internal heat to human skin (and respiration) to clothing and the environment are divided by the Equation 20. The net internal heat is ($M – W$) with evaporation on skin ($E_d – E_{sw}$) and respiration (E_{res} - C_{res}). This equals to the conduction from skin through clothing (K) and this conduction heat will transfer out of the cloth surface to the environment by radiation and convection ($R+C$) (Fanger, 1970) (Olsen, 1982).

$$M - W - E_d – E_{sw} - E_{res} – C_{res} = K = R + C \tag{20}$$

The heat exchange from skin through the clothing is given by (Fanger, 1970) (Olsen, 1982)

$$K = \frac{(t_{sk} - t_{cl})}{0.155 \cdot I_{cl}} \tag{21}$$

I_{cl} is thermal insulation of the clothing (clo).
where,

$$t_{cl} = t_{sk} - 0.155 \cdot I_{cl} \cdot (R + C) \tag{22}$$

According to Equation 20 and 21, the conduction heat transfer (K) is calculated from the temperature difference of the skin surface (t_{sk}, °C) and the outer surface of clothing (t_{cl} , °C) divided by thermal resistance of clothing (I_{cl}). In addition, the temperature of the outer surface of clothing (t_{cl} , °C) is calculated by the skin temperature with the thermal resistance effect of clothing (I_{cl}) and sensible heat transfer ($R+C$).

From thermal balance equation of Fanger (1970), it is noticeable that the proposed Equation 5 and 10 (E_d and E_{sw} Term) did not include evaporative heat transfer from human skin through clothes. The evaporative terms in Equation 10-12 concerns about the difference between the vapour pressure on skin and that in the environment. Therefore the evaporation and diffusion of sweat and vapour through clothes has been missing. Therefore, it is interesting to include related properties of clothes into the equation of thermal balance.

Part 3. Role of Clothing in Parts of Heat Transfer

Clothing Insulation and Permeation Efficiency
1) Intrinsic clothing insulation (R_{cl}, $m^2 \cdot K/W$): Thermal resistance of a uniform layer of insulation covering entire body that has same effect on sensible heat flow as actual clothing.

Intrinsic clothing insulation is a property of the clothing itself and represents the resistance to heat transfer between the skin and the clothing surface. Rate of heat transfer through the clothing is by conduction, which depends on surface area, temperature gradient between skin and clothing surface and the thermal conductivity of the clothing. Intrinsic clothing insulation is the reciprocal of clothing conductivity.

Clothing insulation value may be expressed in clo units. To avoid confusion, the symbol I_{cl} is used with the clo unit instead of the symbol R_{cl}. One clo is equivalent to 0.155 ($m^2 \cdot K/W$). The relationship between the two is (ASHRAE, 2013)

$$R_{cl} = 0.155 \cdot I_{cl} \tag{23}$$

2) Evaporative heat transfer resistance of clothing (R_{ecl}, m^2 kPa/W): It is an impedance to transport of water vapour of uniform layer of insulation covering entire body that has same effect on evaporative heat flow as actual clothing.

The vapour pressure difference between skin and environment provide the driving potential for heat loss. Moisture or sweat on the skin evaporates at the skin surface and is transported through the clothing to the environment.

In thermal comfort model, thermal insulation is a basic parameter which are required to input in the equation. And the evaporative resistance of clothing (R_{et}) is calculated on the intrinsic clothing insulation (I_{cl}) and permeation properties to water vapour (i_m). The total water vapour resistance, R_{et}, may be estimated on the thermal insulation of that ensemble, I_T or I_{cl} by means of the permeability index, i_m, and the Lewis relation (LR = 16.5 K/kPa) (ASHRAE, 2013)

The international comfort standards such as ASHRAE standards and the International Standards Organization (ISO) are almost exclusively based on theoretical analysis of human heat exchange performed in mid-latitude climatic regions in North America and northern Europe (Ogbonna & Harris, 2008) (ISO 7730, 2005). They were based primarily on mathematical models developed by Fanger on the basis of studies from special climate-controlled chamber experiments (ANSI/ASHRAE Standard 55, 2013).

The difference between Fanger's thermal model and ASHRAE Standard on clothing variables is the conclusion of the evaporative resistance effect. In ASHRAE Thermal comfort Tool for calculation of SET in ASHRAE Standard 55 provided both thermal and evaporative resistance of clothing. Thermal resistance of clothing (R_{cl}) effects to sensible heat transfer. Evaporative resistance of clothing ($R_{e,cl}$, m^2 ·kPa/W) effects to evaporative heat transfer (E_{sk}). The evaporative resistant is a function of thermal resistance divided by Lewis Relation (LR) and intrinsic clothing insulation (I_{cl}, clo) as

$$R_{e,cl} = \frac{R_{cl}}{LR * I_{cl}} \tag{24}$$

The evaporative heat transfer (E_{sk}) (W/m^2) is in the following form (ASHRAE, 2013)

$$E_{sk} = \frac{w_s\left(p_{sk,s} - p_a\right)}{\left(R_{e,cl} + \dfrac{1}{f_{cl}h_e}\right)} \tag{25}$$

Where, w_s is the skin wetness factor: the fraction of wet skin (dimensionless)

$P_{sk,s}$ is the water vapour pressure at the skin, normally assumed to be saturated water vapour at skin temperature, t_{sk} (kPa)
P_a is the water vapour pressure in the ambient air (kPa)
$R_{e,cl}$ is the clothing intrinsic evaporative resistance (analogous to R_{cl}) (m^2 ·kPa/W)
f_{cl} is the clothing area factor: the fraction of surface area of the clothed body and the surface area of the nude body. (A_{cl}/A_D) (dimensionless)
h_e is the evaporative heat transfer coefficient (analogous to h_c) (W/ m^2 ·kPa)

According to the heat loss on evaporation of skin (E_{sk}) on Equation 24, the clothing is the evaporative resistance variable (R_{et} and R_{ecl}). It decreases the evaporative heat loss by division of the water vapour pressure difference from skin (p_{sk}) and ambient air (p_a) with the skin wetness factor (w).

Skin wetness (w) is the ratio of the actual evaporative heat loss to the maximum possible evaporative heat loss (E_{max}) with the same conditions and a completely wetted skin (w=1). The value of skin wetness is important in determining evaporative heat loss. Maximum evaporative potential (E_{max}) occurs when the skin surface is completely wetted or w = 1.0.

The Equation 24 and 25 are also involved in the UC Berkeley Thermophysiological Comfort model (BTCM) (Fu et al., 2014). In this model, the heat balance in clothed body are divided in to two nodes, human skin node and clothing node. Heat storage in clothing node are considered to increase clothing temperature. The effect of air movement on clothing thermal insulation are taking into account with correction factors obtained from experiments on electrical manikin. This model is developed forty-four years after Fanger's model under a similar theoretical basis, the heat balance model. With modern technology, the new model integrates details in analysis.

Clothing effects of heat transfer from skin

For the thermal comfort estimation on thermal balance method, the clothing properties are thermal insulation and vapour permeability. It has the effects to heat transfer from human skin to the environment:

1) convective and radiative heat transfer (C+R); clothing can reduce the convective and radiative heat transfer by its thermal insulation.

2) evaporative heat transfer (E_{sk}); clothing contains a mass of fibre (such as cellulose or polymer). It can reduce or delay the water vapour diffusion and evaporation of sweat. This property relates to moisture permeability.

Both properties of clothing are major parameters in thermal comfort.

These are some study on clothing with heat transfer. Mecheels and Umbach (1977) pointed out that the thermal properties of a clothing system are determined by its resistance to heat transfer and its resistance to moisture transfer. They also explained that through these two values of resistances, the minimum and the maximum ambient temperature could be determined. The difference between the maximum and minimum ambient temperatures is called the psychometric range of clothing. These parameters depends on clothing design and the wearing type, textile materials and air velocity.

The couple heat and moisture transfer in textile fabric has been widely recognized as being very important for understanding the dynamic thermal comfort of clothing during wear. (Farnworth, 1986) (Li, 1986) (Li & Luo, 2000) (Li, Zhu & Yeung, 2002) (Wehner, 1987). These are the models based on personal thermal comfort estimation. However, Fanger's method apply with estimation thermal comfort in for a large group of people. Presently, there are no thermal comfort estimation coupled with clothing effect for a large group of people.

Clothing Requirements for Hot and Humid Climate

One of the major purposes of clothing is to maintain a uniform body temperature under different thermal environments and to prevent the accumulation of sweat on the skin by allowing perspiration to flow to the outside environment when increasing the activity level. The heat transfer between human body and surrounding is significantly affected by the dynamic response of the clothing system and the way the clothing layers interpose the flow of heat and moisture from the skin to the surrounding (Rengasamy, 2011). In general situation (moderate climate with medium level of activity) the body temperature is maintained by the exchange of heat through water vapour diffusion on skin, with heat transfer by conduction, convection and radiation. When the core temperature rises immediately, the body produce sweat by thermoregulation control system. The sweat increases with the level of activity and the environmental temperature.

The maintenance of thermal comfort under different thermal environment and activity levels requires different clothing properties. In sedentary activity with moderate thermal environment (mid-latitude climatic regions in North America and northern Europe (Ogbonna & Harris, 2008) (Djongyang, Tchinda & Njomo, 2010) with casual wear, diffusion of moisture on skin is producing continuously with thermal comfort feeling (Fanger, 1970). In hot and humid climate, human body mainly maintains its temperature by evaporation of sweat. To be comfort in this condition, the proper clothing with less thermal insulation and less evaporative resistance to provide the maximize evaporation of sweat is required.

Conclusions

Clothing is one of the most important environment for human thermal comfort. Humans wear clothing to keep their body temperature in stable, not immediately change due to the environment. According to the narrow range limit of human body temperature, if the body temperature change immediately the human can be sick, heat stroke or die. (Parsons, 2014). This relates to the heat transfer rate between human internal heat and the thermal environment . This force is driven by the difference of temperature and the water vapour pressure between human and the environment. Keeping human in comfort (or not sick) is to keep the heat transfer rate into balance (heat storage, S =0). Human body losses heat by evaporation of moisture (and sweat) and radiation and conduction. While clothing is the barrier of this latent and sensible heat transfer.

To built the thermal comfort condition the evaporative resistant of clothing and thermal insulation are important factors. When its properties interfere the heat transfer from the skin to the environment. It controls heat and mass transportation of human body and the environment. Inclusion of property of clothes in heat and vapour mass transportation into the heat balance equation can improve the prediction of thermal sensation where sweat and humidity are high.

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