A SIMPLIFIED THERMAL MODEL FOR A CLOTHED HUMAN OPERATOR WITH THERMOREGULATION

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***Abstract*:** This paper presents a simplified yet comprehensive mathematical model to predict steady state temperature distribution for various regions of male clothed human operators who are healthy, passive/active and lean/obese under the influence of different environmental conditions using thermoregulatory control concept. The present model is able to predict the core temperature, (T_c) close to 37 °C for a healthy, passive/active and lean/obese operator at normal ambient temperatures. It is observed that due to increase in body fat, *BF* the skin temperature, (T_s) of the operator decreases by a small amount. However, the effect of *age* of the operator on T_s is found to be insignificant. The present model has been validated against the experimental data available in the literature.

Keywords: *Human operator, thermal model, thermoregulation, steady state.*

1. INTRODUCTION

Heat energy is generated within the body due to (i) chemical processing of the food stuff (basal metabolism), (ii) muscular activity (increased tone and shivering), and (iii) hormones (thyroxine and epinephrine). Heat loss from human body can occur by various mechanisms. This includes conductive heat transfer, convective heat transfer, evaporative heat transfer and radiative heat transfer. The metabolic heat generated inside the body is transferred by means of conduction to the skin surface. There can be forced convection (fluid motion caused by a superimposed pressure gradient) and also free convection (motion caused by density differences within the fluid). Evaporative heat transfer, or simply evaporation, represents energy transfer as a function of the evaporation of water vapour from the skin surface. This energy transport is a heat loss term that is proportional to the amount of water that evaporates. Evaporative heat transfer differs mainly from the conductive, convective, and radiative heat transfer in that it is the only mechanism by which heat loss can occur when the ambient temperature is greater than the core body temperature. Radiative heat transfer occurs between the body and surrounding object so that it requires no intermediate material phase to be located between the radiating surfaces. Heat loss from the human body through these mechanisms generally results because the ambient (external) temperature is usually lower than the core body (internal) temperature. It should be noted that the body may also gain heat by any or all of the above mechanisms, except evaporation, when the thermal gradient is reversed and the body is a cooler object. However, the human body can theoretically gain heat also by latent process, namely when the partial pressure of ambient air is greater than the partial pressure of water vapour at skin temperature. According to Bridger [1], the core temperatures over 39.5 °C are disabling and over 42 °C, are fatal. The lower acceptable limit is 35.5 °C and 33 °C marks the onset of cardiac disturbances. Further drop in core temperature is extremely dangerous, and temperatures as low as 25 °C are fatal. The temperatures of the peripheral body tissues, particularly the skin, can safely vary over a much wider range. However, according to Kroemer *et al.* [2] a higher skin temperature will result in heat rashes and heat cramps. As the skin temperature is lowered from 20° to 15 °C, manual dexterity begins to diminish. Tactile sensitivity is severely diminished as the skin temperature falls below 8 °C. If the temperature approaches freezing, ice crystals develop in the cells and destroy them, a condition known as frostbite. From a thermal point of view, the body can be considered to have a warm core where much of its heat is produced. This core is surrounded by a shell of cooler, insulating tissues, particularly subcutaneous fat. It is believed that hypothalamus is involved in the central control of core temperature.

Thermal models for the human body as well as animals and reptiles have been developed by researchers in the past. Fanger [3] developed a model in which a one-dimensional approximation of the human body and of the heat and mass exchange with the environment were used. Bakken [4] proposed a two-dimensional operative-temperature model for thermal energy management by animals to study the thermal load on the surface of an animal. Smith [5] and Fu [6] used a 3000-node finite element model to simulate the human body. In many models, the body is divided into several segments and each segment is considered to have several tissue layers and each layer is connected to a central blood pool. The heat transfer equations are then written for each layer and subsequently solved using computers to predict temperature of the layers (see [7, 8]). Yokoyama *et al.* [9] considered the heat transported by the blood flow through different layers in their model. Yigit [10] developed a computer model that estimates the resistance to dry and evaporative heat transfer from fabric resistance data using thermoregulatory control mechanisms. Gardner and Martin [11] proposed a thermal model to predict skin temperature of normal subjects and burned patients using thermoregulatory control mechanisms.

Most of the thermal models developed so far are quite complex and difficult for human factors engineers/ergonomists to understand. However, Phillips [12] suggested a simplified methodology to develop thermal models for human operator heat transfer using thermoregulatory control mechanisms. The basic purpose of thermoregulatory control is to keep deep body (core) temperature at a predetermined "set point" (≈ 37 °C). However, during periods of intense physical exercise the body readjusts its "set point" and the core temperature is allowed to increase and can often exceed 40°C. The regulation of the core temperature is accomplished by a thermostatic controlled centre located in the hypothalamus (at the base of the brain)[12]. There is a set point for temperature control (T_{sp}) so that the core temperature (T_c) is regulated by the negative feed back mechanism.

The human being has both warm and cold receptors (located throughout the body) that monitor regional body temperatures and transmit this information to the temperature control centre (the hypothalamus). At the skin surface, these warm and cold receptors monitor the ambient (environmental) temperature. Warm and cold receptors located in the hypothalamus directly monitor the core blood temperature [12]. For the purpose of thermoregulatory control mechanisms of the passive human operator, Phillips [12] introduced a passive proportional heat rate term given by:

$$\dot{Q}_p = -K_p(T_{sp} - T_c) \tag{1}$$

Where, K_p is the passive heat rate constant (W/m^2 °C) and is negative

T_{sp} is the hypothalamic set point temperature (°C)

T_c is the core temperature (°C)

The passive proportional heat rate ($\dot{Q}_p$) has been taken negative because it becomes negative when the core temperature (T_c) is higher than the set point temperature (T_{sp}) indicating the transfer of heat from the human body to the atmosphere which is essential to bring down the core temperature (T_c). It is to be noted that a passive human operator is an individual in a resting state. In the simplest case the core temperature is equal to the set point temperature indicating no need for thermoregulation. However, the proportional heat rate term may be either positive resulting in a proportional heat gain or negative indicating a proportional heat rate loss depending on the sign of temperature difference (ΔT) between (T_{sp}) and (T_c). The proportional heat rate gain is a quantitative representation of the following mechanisms:

Peripheral vasoconstriction, which significantly decreases the forced convection of heat transfer between the core body region and the skin region. Since the fat layer beneath the skin's surface is a good insulator, skin surface temperature is also lowered effectively reducing the thermal gradient for external heat transfer.

There is an increase in muscular tone, which is manifested as shivering. This represents an extra conversion rate of stored chemical energy in the muscle region that is ultimately dissipated as an internal heat.

Certain hormones are released (thyroxin and epinephrine), which increase the basal metabolic rate in the core body region. This also results in an extra stored chemical energy conversion rate that is ultimately dissipated as internal heat within the core body region.

Similarly the proportional heat rate loss represents the following mechanisms:

Stimulate peripheral vasodilation in the skin region. This effectively increases forced convection between the core region and the skin region. The result is an increase in the internal heat transfer toward the periphery of the body. A second result of peripheral vasodilation is to increase the skin surface temperature in order to enhance a thermal gradient that favors external heat transfer to the environment.

Stimulate perspiration at the skin surface for evaporative heat transfer. This may be the only mechanism for body heat loss when the surface skin temperature (T_s) can not be increased above the environmental temperature.

Decrease any extra metabolic rate so that the human operator experiences only basal metabolic rate$(\dot{M})$. This is an indirect effect associated with the sensation of fatigue (from elevated body temperature) combined with dehydration (the loss of water and salt due to evaporative heat transfer), which will result in the human operator becoming as quiescent as possible.

The active human operator will perform work upon the environment which will require an extra metabolic energy rate $(\Delta \dot{M})$ occur in the muscle region. For an active human operator when performing only "internal" work (i.e. purely "static" work or purely "velocity" work) Phillips [12] introduced an active proportional heat rate term given by:

$$\dot{Q}_A = -K_A(T_{sp} - T_c) \qquad (2)$$

Where, K_A is the active heat rate constant (W/m^2 °C)

The reason for taking negative $\dot{Q}_A$ is same as that of$\dot{Q}_p$. It may be noted that K_p and K_A may not be necessarily the same. However, in the absence of a known value of K_A, we will consider it equal to K_p in the present analysis.

When the core temperature (T_c) is either less than or greater than hypothalamic set point temperature (T_{sp}) then the physical definition and physiological interpretation of the resultant thermoregulatory system is analogous to that of a passive human operator. This approach of modelling heat transfer from human body is reasonably simple and avoids considerations of countercurrent and concurrent heat exchanges between flowing blood and tissues. The thermoregulatory mechanism discussed above will be used in the present analysis to develop a simplified yet comprehensive thermal model for the male clothed human operator heat transfer under steady state conditions in order to predict the temperature of various regions for different environmental conditions.

2. MATHEMATICAL DEVELOPMENT OF A MODEL FOR A CLOTHED HUMAN OPERATOR

As discussed earlier, a simplified thermal model to predict steady state temperature of different regions of a clothed human operator is developed in the following section using thermoregulation control mechanism as explained by Phillips [12]. It may be pointed out that Phillips [12] has discussed how a particular region of a human body either loses or gains heat through one mode of heat transfer. In the present work, a comprehensive formulation taking into account all possible modes of heat transfer for different regions of a clothed human operator is presented.

The human body consists of the core region, muscle region, and skin region. Skin region consists of a subcutaneous fat layer (adjacent to the muscle layer), the dermal layer (overlying the subcutaneous fat), and finally the epidermal layer (which includes the skin itself). Fig. 1 illustrates the simplified model to describe the steady state temperature distribution through these regions and various cloth regions for clothed human operators. An air gap existing between the skin surface and the inner cloth as well as between the inner cloth and the outer cloth is also considered. It may be pointed out that the prediction of steady state temperature is valid for a range of about 5°C above or below the comfortable ambient temperature.

The heat generated in the body is dissipated to the environment through the skin and the lungs by convection and radiation as sensible heat and by evaporation as latent heat. Latent heat represents the heat of vaporisation of water as it evaporates in the lungs and on the skin by absorbing body heat, and it is released as the moisture condenses on cold surfaces. During respiration, the inhaled air enters at ambient conditions and exhaled air leaves nearly saturated at a temperature close to the deep body (core) temperature. Therefore, the body loses both sensible heat by convection and latent heat by evaporation from the lungs. The rate of air intake to the lungs is directly proportional to the metabolic rate ($\dot{M}$).

It is to be noted that metabolic heat (M) is produced in the core region while the muscle heat (ΔM) is produced in the muscle region when muscle is active. Out of the total heat produced, some heat will be lost through respiration (QRS) and also through evaporation ($Q_{ev.}$). For a healthy operator, the proportional heat due to effective thermoregulation (QTR) is responsible for the core temperature regulation. These aspects have been incorporated in the present formulation for a healthy clothed male operator. The heat transfer equations that followed for different regions are based on the following assumptions:

- All thermal properties are constant.
- Conduction is one dimensional.
- Steady state conditions prevail.
- Uniform convection coefficient at outer surface.
- For radiation all surfaces are diffused and gray.
- Metabolic heat and muscle heat are uniform.
- Air in the gap is quiescent.
- Ambient air is quiescent.

Heat transfer in the core region is due to conduction and the governing equation is given by:

$$M + QTR - QRS = \frac{k_c A(T_c - T_{cm})}{\Delta x_c} \tag{3}$$

which can be put in the following form:

$$M + QTR - QRS = \frac{T_c - T_{cm}}{\frac{\Delta x_c}{k_c A}} \tag{4}$$

where A is given as [12]:

$$A = 0.1m^{0.67} \tag{5}$$

and QTR can also be calculated as [12]:

$$QTR = -K_p A(T_{sp} - T_c) \tag{6}$$

It is to be noted that, QTR will be either positive or negative depending upon whether T_c is less than or greater than T_{sp} respectively. The values of K_p and T_{sp} are -29.075 W/m^2 °C, and 37 °C respectively as recommended by Phillips [12].

The rate of total heat loss from the lungs through respiration can be expressed approximately as [13]:

$$QRS = 0.0014M(34 - T_a) + 0.0173M(5.87 - P_{va}) \tag{7}$$

Similarly, the heat transfer in the muscle region including the muscle heat generation per unit volume (ΔM) is given by [14]:

$$M + QTR - QRS = \frac{T_{cm} - T_{ms}}{\frac{\Delta x_m}{k_m A}} - \frac{\Delta M V_m}{2.0} \tag{8}$$

Also the heat transfer in the skin region is given by:

$$M + \Delta M V_m + QTR - QRS = \frac{k_s A(T_{ms} - T_s)}{\Delta x_s} \tag{9}$$

which can be written as:

$$M + \Delta M V_m + QTR - QRS = \frac{T_{ms} - T_s}{\frac{\Delta x_s}{k_s A}} \tag{10}$$

Note that the thickness of the skin region (Δx_S) varies with the variation in the body fat (*BF*) which may be calculated from the following equations as suggested by [15]:

$$\Delta x_s = 0.5SF \tag{11}$$

where

$$BF = \left[\frac{4.95}{D_{body}} - 4.50\right]100 \tag{12}$$

and

$$D_{body} = 1.112 - 10^{-6}(434.99SF + 0.55SF^2 - 288.26age) \tag{13}$$

The above equations have been used in an inverse way to retrieve SF from given BF and subsequently to get the value of Δx_S.

The heat transfer in the air gap between the skin surface and the inner cloth is due to the combined effect of conduction, radiation and evaporation from the covered portion of the body. The uncovered portion of the body is subjected to convective, radiative and evaporative heat transfer to the ambient. However, the evaporative heat transfer from the covered as well as uncovered portion of the body is taken together in the analysis. The governing equation under the above conditions is given below:

$$M + \Delta MV_m - Q_{ev.}A_{ev.} + QTR - QRS = \frac{k_{ai}A_{ccond.}(T_s - T_{1i})}{\Delta x_{si}} + \frac{\sigma A_{crad.}(T_s^4 - T_{1i}^4)}{\frac{1}{\varepsilon_s} + \frac{1}{\varepsilon_{ic}} - 1} + hA_{uconv.}(T_s - T_a) + \sigma A_{urad.}\varepsilon_s(T_s^4 - T_a^4) \tag{14}$$

After simplification, we have:

$$M + \Delta MV_m - Q_{ev.}A_{ev.} + QTR - QRS = \frac{T_s - T_{1i}}{\dfrac{1}{\dfrac{k_{ai}A_{ccond.}}{\Delta x_{si}} + \dfrac{\sigma A_{crad.}(T_s^2 + T_{1i}^2)(T_s + T_{1i})}{\frac{1}{\varepsilon_s} + \frac{1}{\varepsilon_{ic}} - 1}}} + \frac{T_s - T_a}{\dfrac{1}{hA_{uconv.} + \sigma\varepsilon_s A_{urad.}(T_s^2 + T_a^2)(T_s + T_a)}} \tag{15}$$

The second term on the right hand side of equation (15) represents the convective and radiative heat transfer from the uncovered portion of the human operator.

The evaporative heat flux ($Q_{ev.}$) in equation (15) may be given by [12]:

$$Q_{ev.} = h_v(p_s - p_a) \tag{16}$$

where

$$h_v = 0.029(T_s - T_a) \tag{17}$$

$$p_a = RH(p_s)_{at\,T_a} \tag{18}$$

The heat transfer in the inner cloth is due to conduction and the heat transfer equation is given by:

$$\begin{aligned} M + \Delta MV_m - Q_{ev.}A_{ev.} + QTR - QRS = {} & \frac{k_{ic}A_{ccond.}(T_{1i} - T_{10})}{\Delta x_{ic}} + hA_{uconv.}(T_s - T_a) \\ & + \sigma A_{urad.}\varepsilon_s(T_s^4 - T_a^4) \end{aligned} \tag{19}$$

It can be simplified in the form

$$M + \Delta MV_m - Q_{ev.}A_{ev.} + QTR - QRS = \frac{T_{1i} - T_{1o}}{\dfrac{1}{\dfrac{k_{ic}A_{ccond.}}{\Delta x_{ic}}}} + \frac{T_s - T_a}{\dfrac{1}{hA_{uconv.} + \sigma\varepsilon_s A_{urad.}(T_s^2 + T_a^2)(T_s + T_a)}} \tag{20}$$

Another air gap between the inner cloth and the outer cloth is also considered in the model. Thus, the heat transfer in this air gap is similar to what is discussed earlier for the air gap between the skin and the inner cloth. The equation for heat transfer for this air gap is given by:

$$\begin{aligned} & M + \Delta MV_m - Q_{ev.}A_{ev.} + QTR - QRS = \\ & \frac{k_{ao}A_{ccond.}(T_{1o} - T_{2i})}{\Delta x_{ioc}} + \frac{\sigma A_{crad.} \times (T_{1o}^{\ 4} - T_{2i}^{\ 4})}{\dfrac{1}{\varepsilon_{ic}} + \dfrac{1}{\varepsilon_{oc}} - 1} + hA_{uconv.}(T_s - T_a) + \sigma A_{urad.}\varepsilon_s(T_s^4 - T_a^4) \end{aligned} \tag{21}$$

Upon simplification, we have:

$$\begin{aligned} & M + \Delta MV_m - Q_{ev.}A_{ev.} + QTR - QRS \\ & = \frac{T_{1o} - T_{2i}}{\dfrac{1}{\dfrac{k_{ao}A_{ccond.}}{\Delta x_{ioc}} + \dfrac{\sigma A_{crad.}(T_{1o}^{\ 2} + T_{2i}^{\ 2})(T_{1o} + T_{2i})}{\dfrac{1}{\varepsilon_{ic}} + \dfrac{1}{\varepsilon_{oc}} - 1}}} + \frac{T_s - T_a}{\dfrac{1}{hA_{uconv.} + \sigma\varepsilon_s A_{urad.}(T_s^2 + T_a^2)(T_s + T_a)}} \end{aligned} \tag{22}$$

The heat transfer in the outer cloth is only due to conduction and the governing equation of the heat transfer is given below:

$$M + \Delta MV_m - Q_{ev.}A_{ev.} + QTR - QRS = \frac{k_{oc}A_{ccond.}(T_{2i} - T_{20})}{\Delta x_{oc}} + hA_{uconv.}(T_s - T_a) + \sigma A_{urad.}\varepsilon_s(T_s^4 - T_a^4) \qquad (23)$$

which can be put in the form:

$$M + \Delta MV_m - Q_{ev.}A_{ev.} + QTR - QRS = \frac{T_{2i} - T_{2o}}{\dfrac{1}{\dfrac{k_{oc}A_{ccond.}}{\Delta x_{oc}}}} + \frac{T_s - T_a}{\dfrac{1}{hA_{uconv.} + \sigma\varepsilon_s A_{urad.}(T_s^2 + T_a^2)(T_s + T_a)}} \qquad (24)$$

The heat transfer from outer cloth to the ambient air is due to the combined effect of convection and radiation and the governing equation in this case is given by:

$$M + \Delta MV_m - Q_{ev.}A_{ev.} + QTR - QRS = hA_{cconv.}(T_{2o} - T_a) + \sigma\varepsilon_{oc}A_{crad.}(T_{2o}^4 - T_a^4) + hA_{uconv.}(T_s - T_a) + \sigma A_{urad.}\varepsilon_s(T_s^4 - T_a^4) \qquad (25)$$

Upon simplification, the following equation is obtained:

$$M + \Delta MV_m - Q_{ev.}A_{ev.} + QTR - QRS = \frac{T_{2o} - T_a}{\dfrac{1}{hA_{cconv.} + \sigma\varepsilon_{oc} \times A_{crad.}(T_{2o}^2 + T_a^2)(T_{2o} + T_a)}} + \frac{T_s - T_a}{\dfrac{1}{hA_{uconv.} + \sigma\varepsilon_s A_{urad.}(T_s^2 + T_a^2)(T_s + T_a)}} \qquad (26)$$

3. RESULTS AND DISCUSSION

The results of the core temperature (T_C) and the skin surface temperature (T_S) for various combinations are presented for the following operator conditions:

- Lean.
- Obese.
- Passive.
- Active.
- Healthy (thermoregulation is effective).

3.1 COMPARISON OF PREDICTED RESULTS WITH MEASURED DATA

In order to investigate how body fat affects skin temperatures, Nishumura *et al.* [16] measured skin temperature for two groups of people with different body fat, 10.7% (lean group) and 19.4% (obese group). The three environmental temperatures were 22 °C, 28 °C and 34 °C. Zhang *et al.* [17] also obtained skin temperatures of the above mentioned groups of people for the same environmental temperatures from their simulation model. Our proposed model has also predicted skin temperatures of the same groups of people for the same environmental temperatures and for the data listed in Table 1. The comparison of the skin temperature for the average of the entire body for lean group is presented in Fig. 2 and for obese group in Fig. 3. It can be seen from Fig. 2 that the predicted skin temperatures of lean people at environmental temperatures of 22 °C, 28 °C and 34 °C are very close to the measured ones. It should be mentioned that at environmental temperatures of 22 °C and 28 °C, only 5% of the body area was considered for evaporative heat transfer as suggested by Phillips [12] whereas at a relatively higher environmental temperature i.e. 34 °C, 20% of the body area was considered. This was done since the environmental temperatures of 22 °C and 28 °C are reasonably comfortable temperatures while the environmental temperature of 34 °C is a bit higher temperature at which more body area should be allowed for the evaporation of the sweat. It may be mentioned that the above calculations, where 5% of the body area was considered for calculating evaporative heat loss, were repeated by reducing the area by half as well as by increasing the area two times. It was found that the skin temperature varied by ± 0.5 °C for the same operating conditions. This indicated that the exact estimate of wetted skin area does not affect substantially the skin temperatures. Similar trend was also observed for higher ambient temperature range considered in the analysis.

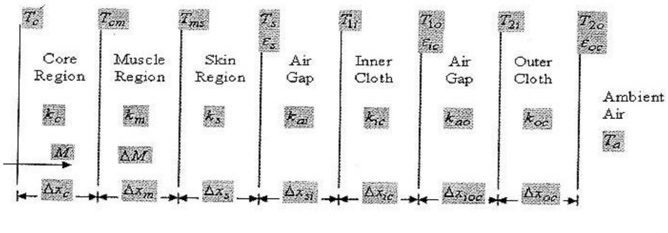

Fig. 1: A simplified model showing different regions for a clothed operator.

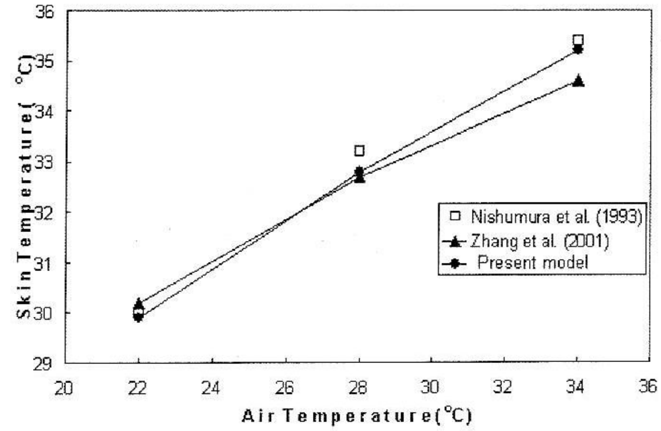

Fig. 2: Comparison of lean subjects' skin temperatures.

Figure 3 also shows that the predicted skin temperatures of obese people at each environmental temperature are very close to the measured values. So, the present model is therefore, in good agreement with the available data in the literature.

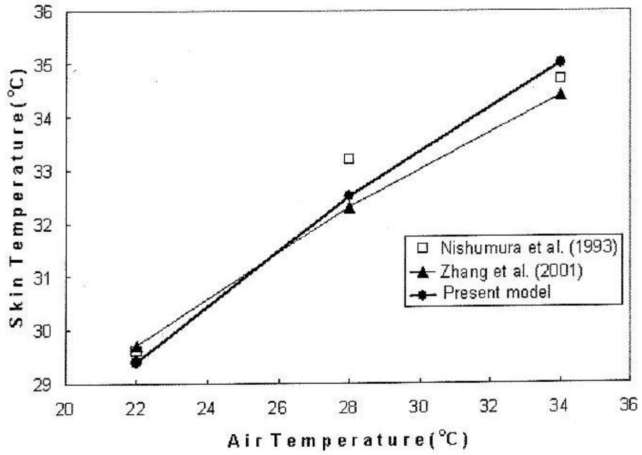

Fig. 3: Comparison of obese subjects' skin temperatures.

3.2 CLOTHED HEALTHY HUMAN OPERATOR

3.2.1. Predicted Temperatures for Different Combinations of Human Operator Conditions

The core as well as skin temperatures have been obtained after solving system of equations given earlier. Table 1 shows the details of the geometrical and thermal properties used in the illustrative problem. Most of the data shown in Table 1 were taken from Phillips [12] and a few data such as thicknesses of cloth and air gap regions were suitably assumed. It is assumed that 90% of the body area is covered with the cloth while remaining 10% is uncovered. The area for evaporative heat transfer is very small and is taken to be only 5% of the body area as discussed earlier for lower temperature range. Similarly, only 10% of the body area is assumed to be involved in the muscle activity. Further, the heat generated in the muscle region due to muscle activity is taken to be 30% of the metabolic heat as recommended by Phillips [12] for sedentary activity.

Table 1: Numerical values of the parameters used in the model.

Parameter	Value	Parameter	Value
Δx_c	0.04 m	ε_{oc}	0.9
Δx_m	0.02 m	m	65.0 kg
Δx_{si}	0.001 m	A	1.639 m^2
Δx_{ic}	0.001 m	V_m	0.003 m^3
Δx_{ioc}	0.004 m	$A_{ccond.}$	1.475 m^2
Δx_{oc}	0.002 m	$A_{cconv.}$	1.475 m^2
k_c	0.494 W/m °C	$A_{crad.}$	1.475 m^2
k_m	0.494 W/m °C	$A_{uconv.}$	0.1639 m^2
k_s	0.494 W/m °C	$A_{urad.}$	0.1639 m^2
k_{ai}	0.026 W/m °C	$A_{ev.}$	0.082 m^2
k_{ic}	0.06 W/m °C	M	70.53 W
k_{ao}	0.026 W/m °C	ΔM	6454.85 W/m^3
k_{oc}	0.06 W/m °C	σ	5.67×10^{-8} $W/m^2\,K^4$
ε_s	0.87	RH	0.8
ε_{ic}	0.9	h	1.369 W/m^2 K
T_{sp}	37.0 °C		
K_p	-29.075 W/m^2 °C		

Table 2 shows the values of the core temperature (T_c) and the skin surface temperature (T_s) of a healthy and passive/active 40 year old clothed male operator of with 10% of body fat, *BF* for ambient temperatures of 21°C, 31°C and 0 °C calculated for the data listed in Table 1. The value of relative humidity (RH) is equal to 0.8 has been taken in the analysis. From Table 2 it can be seen that at an ambient temperature of 21°C, for a normal operator who is healthy and passive, the core temperature (T_c) is 37.17°C and the skin temperature (T_s) is 29.49 °C. When the ambient temperature is increased to 31°C, a rise of 10 °C, the temperature T_c increases by 0.73 °C only whereas T_s increases by almost 5 °C (as expected). On the other hand when the ambient temperature is reduced to 0°C then T_c reduces by 1.34 °C (35.83 °C) and T_s reduces by 9.17 °C (20.32 °C) as compared to those obtained at an ambient temperature of 21 °C. Thus, we observe that the change in the ambient temperature will affect T_s significantly whereas its effect on T_c is less. This may be due to the thermoregulation being effective in this case.

Also, for healthy and active operator where the muscle heat (ΔM) due to muscle activity comes into account is considered. At an ambient temperature of 21 °C, the temperature T_c is 37.49 °C and T_s is 30.32 °C. By comparing with the passive and healthy operator, T_c has increased by 0.32°C only whereas T_s has increased by 0.83 °C. Similarly, when the ambient temperature is increased to 31 °C, T_c increases by 0.73 °C whereas T_S increases by 4.88 °C against an ambient temperature of 21 °C. Furthermore, when the ambient temperature is reduced to 0 °C then T_c reduces to 36.16 °C (a reduction of 1.33 °C) whereas T_s reduces by 9.12 °C as compared to the results obtained at an ambient temperature of 21 °C. It may be noted that the change in the two temperatures due to the change in the ambient temperature for a healthy and active operator is slightly higher than that of a healthy and passive operator.

For temperatures T_{cm}, T_{ms}, T_s, T_{1i}, T_{1o}, T_{2i}, and T_{2O}, there is a continuous drop in these temperatures. All these results follow a trend, as expected. The above behaviour is represented in Fig. 4 by two typical curves as shown for active and passive, healthy operators at an ambient temperature of 21 °C. It can be seen from the figure that for active operator these temperatures are higher than those of passive operator. This is due to the additional heat generated in the muscle region for the active operator.

Table 2: Core temperature and skin temperature in degree Celsius for a clothed healthy male operator.

Ambient temperature (°C)	**Passive operator**		**Active operator**	
	Core temperature (°C)	**Skin temperature (°C)**	**Core temperature (°C)**	**Skin temperature (°C)**
21.0	37.17	29.49	37.49	30.32
31.0	37.90	34.39	38.22	35.20
0.0	35.83	20.32	36.16	21.20

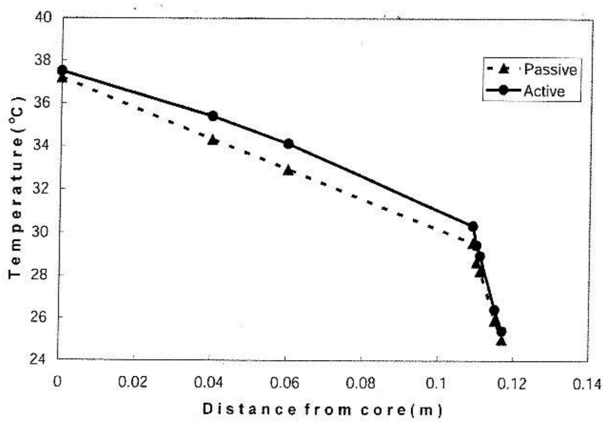

Fig. 4: Predicted temperature variations for active and passive healthy clothed operator at an ambient temperature of 21°C ($BF = 10\%$; $age = 40$ Years).

3.2.2. The Effect of Body Fat on Skin Temperature

The skin temperatures of healthy and passive clothed human operators for different ages (10 and 70 years respectively) and different values of body fat (i.e. 10, 20, 30, and 40%) at fixed ambient temperature of 31 °C using the data listed in Table 1 are obtained and presented in Fig. 5. It can be observed from this figure that the skin temperatures of a 10 years old operator vary in the range between 34.5 °C to 33.8 °C while those of a 70 years old operator vary in the range between 34.3 °C to 33.7 °C due to variation in the body fat from 10 to 40%. This shows that the skin temperatures of the operators decrease by a small amount as the body fat increases. This happens because of the reason that the thermal resistance to heat flow increases with increase in body fat. Also, for the given body fat, the skin temperature of a young operator is only slightly higher than that of the old operator.

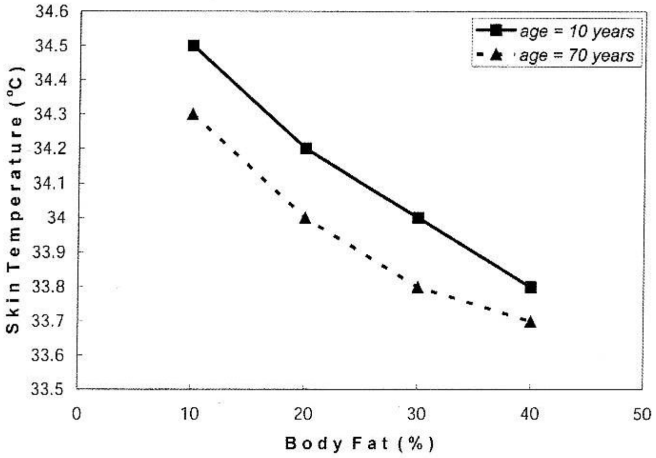

Fig. 5: Variation in the skin temperature due to variation in the body fat.

4. CONCLUSIONS

The model presented in this paper is comprehensive, flexible and yet simple enough that can easily be used to predict steady state temperatures of different body regions as well as clothed regions for healthy, active/passive and lean/obese clothed male operator for different environmental conditions. On the basis of the results obtained the following can be concluded:

- The predictions agree well with the available results in the literature.
- The predicted core temperature T_c is very close to 37 °C for passive/active, healthy clothed operator at all ambient temperatures considered in the analysis.
- The model predicts a small reduction in the skin temperature caused by increase in body fat.
- For a given body fat, skin temperature of a young operator is slightly higher than that of an old operator.
- The predicted temperatures for an active clothed operator are higher than those of a passive operator.

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NOMENCLATURE

A	Area of the body	m^2
$A_{ccond.}$	Covered area of the body for conduction	m^2
$A_{cconv.}$	Covered area of the body for convection	m^2
$A_{crad.}$	Covered area of the body for radiation	m^2
$A_{ev.}$	Area of the body for evaporative heat transfer	m^2
$A_{uconv.}$	Uncovered area of the body for convection	m^2
$A_{urad.}$	Uncovered area of the body for radiation	m^2
BF	Body fat	%
D_{body}	Average density of the body tissue	kg/l
h	Free convective heat transfer coefficient	W/m^2 °C
h_v	Evaporative heat transfer coefficient	W/m^2 °C
k_{ai}	Thermal conductivity of the air gap between skin and inner cloth	W/m °C
k_{ao}	Thermal conductivity of the air gap between inner cloth and outer cloth	W/m°C
k_c	Thermal conductivity of the core region	W/m °C
k_{ic}	Thermal conductivity of the inner cloth	W/m °C
k_m	Thermal conductivity of the muscle region	W/m °C
k_{oc}	Thermal conductivity of the outer cloth	W/m °C
K_p	Negative passive/active heat rate constant	W/m^2 °C
k_s	Thermal conductivity of the skin region	W/m °C
m	Mass of the body	kg
p_a	Partial pressure of the water vapour in the ambient air	Pa
p_s	Vapour pressure of the water at skin surface temperature	Pa
P_{va}	Vapour pressure of ambient air	kPa
$Q_{ev.}$	Evaporative heat flux	W/m^2
$\dot{Q}_A$	Active proportional heat rate	W/m^2
$\dot{Q}_p$	Passive proportional heat rate	W/m^2
QRS	Respiratory heat Loss	W
QTR	Proportional heat due to thermoregulation	W
RH	Relative humidity	%
SF	Skin fold thickness	m
T_a	Ambient temperature	°C
T_c	Body core temperature °C	
T_{cm}	Temperature between core and muscle	°C

T_{ms}	Muscle temperature	^{o}C
T_s	Skin surface temperature	^{o}C
T_{sp}	Hypothalamic set point temperature	^{o}C
T_{1i}	Temperature of the inner layer of the inner cloth	^{o}C
T_{1o}	Temperature of the outer layer of the inner cloth	^{o}C
T_{2i}	Temperature of the inner layer of the outer cloth	^{o}C
T_{2o}	Temperature of the outer layer of the outer cloth	^{o}C
V_m	Muscle volume	m^3
Δx_c	Thickness of the core region	m
Δx_{ic}	Thickness of the inner cloth	m
Δx_{ioc}	Thickness of the air gap between inner cloth and outer cloth	m
Δx_m	Thickness of the muscle region	m
M	Metabolic heat	W
ΔM	Muscle heat generated per unit volume in the muscle region due to activity	W/m^3
$\dot{M}$	Basal metabolic heat rate	W/m^2
Δx_{oc}	Thickness of the outer cloth	m
Δx_s	Thickness of the skin region	m
Δx_{si}	Thickness of the air gap between skin and inner cloth	m
ε_{ic}	Emissivity of the inner cloth	-
ε_{oc}	Emissivity of the outer cloth	
ε_s	Emissivity of the skin surface	
σ	Stefen Boltzman constant	W/m^2 K^4