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A GENERALISED TRANSIENT THERMAL MODEL FOR HUMAN BODY

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ABSTRACT

A generalised thermal model for the determination of transient core and skin temperatures for both clothed and unclothed operators has been developed. Healthy/sick and passive/active operators have been considered in the analysis where the effects of sickness and the addition of muscle heat are investigated. The developed model has been validated against the results available in the literature. It is also observed that core and skin temperatures attained by an operator exposed to various environmental conditions for a long time correspond to the steady state temperatures. Though the model is generalized to take into account various aspects of the problem, yet it is comprehensive to be used in practice.

Keywords: *Human operator, Thermal model, Transient and steady state, Healthy and sick, Active and passive.*

1.0 INTRODUCTION

Human's health and productivity are adversely affected by poor environmental conditions in which they work. The core body temperature and the skin surface temperature determine to a greater extent health and comfort conditions of human operators [1]. These temperatures depend upon whether the operator is healthy or sick, passive or active, environment is hot or cold etc. In case of a passive operator, these temperatures are affected by metabolic heat where as for an active operator they are affected by muscle heat also. Heat transfer from the human body can occur by conduction, convection, radiation, and evaporation. There can be forced convection (fluid motion caused by wind) and also free convection (no wind motion). Evaporative heat transfer, or simply evaporation, represents energy transfer as a function of the evaporation of water vapour from the skin surface.

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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 ambient temperature is higher than the body temperature. According to Bridger [2], the core temperatures over 39.5°C are disabling and over 42°C, they are usually fatal. The lower acceptable core temperature limit is 35.5°C. Core temperature of 33°C marks the onset of cardiac disturbances. Further drop in the 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. 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. However, according to Kroemer et al [1] a higher skin temperature will result in heat rashes, and heat cramps. 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 consisting of tissues.

Thermal models for the human body under steady state conditions have been developed by many researchers [3-11]. Lotens [12], Jones and Ogawa [13] developed the transient model of heat and moisture transport through the clothing using simple thermal model of the body where as Smith [14] and Fu [15] have only considered the transient heat transfer through clothing. Recently, Phillips [16] has proposed transient model for estimation of the core temperature when a healthy/sick and active/passive operator goes from one ambient condition to the other. The model considers the initial core body temperature to be equal to 37°C and a fixed value of the difference between core and skin temperatures. The model does not include evaporative heat transfer as well as heat loss through respiration. Keeping in view the limitations of these models, there is a need to develop a general and yet comprehensive model to overcome these limitations and to demonstrate transient behaviour of the core as well as skin temperature of the operator. This paper presents such a thermal model to demonstrate transient behaviour of the core as well as skin temperatures of both clothed and unclothed human operators when they go from one ambient condition to the other.

2.0 MATHEMATICAL DEVELOPMENT OF THE MODEL

A generalised thermal model is developed to evaluate the transient behaviour of the core as well as skin temperatures of the operator due to a sudden change in the environmental temperature. The different regions of human body, the mode of heat transfer considered in the analysis along with the necessary assumptions are clearly discussed.

2.1 Clothed human operator

The human body consists of the core region, muscle region, and skin region. Figure 1 illustrates the simplified model to describe these regions and various cloth regions for clothed human operators. An air gap exists between the skin surface and the inner cloth as well as between the inner cloth and the outer cloth. This aspect is being considered in the present formulation.

The human body has a complex control system, called thermoregulatory system for maintaining the temperature of the deep body tissues (the core temperature) within a narrow range, around 36 to 37° C. Thermoregulation is achieved by balancing the two main factors which determine body temperature - the metabolic heat and the rate of heat loss. 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 vapourisation of water as it evaporates in the lungs and on the skin by absorbing body heat, and latent heat 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 M [17].

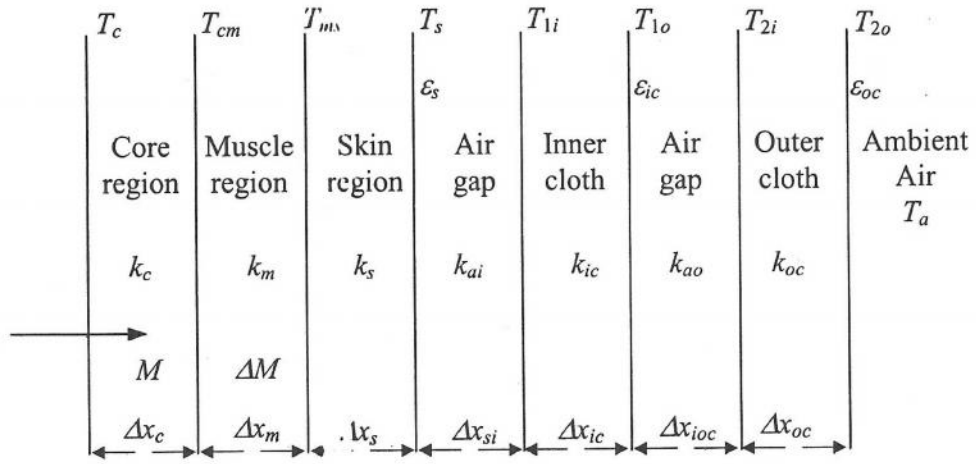


Figure 1 A simplified model showing different regions for a clothed operator.

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 only when muscle is active. Out of total heat produced some heat is lost through respiration (QRS) and also through evaporation ($Q_{ev.}$) from the uncovered portion of the body. For a healthy operator thermoregulation heat, QTR is responsible for maintaining the core temperature, whereas it is absent in a sick operator [16]. These aspects have been incorporated in the present formulation. All the heat transfer equations that follow in the present analysis for different regions are based on the following assumptions appropriate to the modes of heat transfer considered in that region:

(i) All thermal properties are constant.
(ii) Conduction is one dimensional.
(iii) Uniform convection coefficient at outer surface.
(iv) For radiation all surfaces are diffused and gray.
(v) Metabolic heat and muscle heat are uniform.
(vi) Air in the gap is quiescent.
(vii) Ambient air is quiescent.

When an operator goes from one ambient temperature to another then the core body temperature, T_c of the operator changes with time until it attains steady state value. The governing equation for calculating change in core temperature with time (unsteady condition) is given by:

$$mC_p \frac{dT_c}{dt} = M + \Delta MV_m + QTR - QRS - Q_{ev.}A_{ev.} - Q' \tag{1}$$

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 and is calculated from the following equation [16]:

$$QTR = K_p A(T_{sp} - T_c) \tag{2}$$

The value of T_{sp} is taken to be 37°C and the area of the body, A is given by the following equation as recommended by [16]:

$$A = 0.1m^{0.67} \tag{3}$$

The rate of total heat loss from the lungs through respiration, QRS can be expressed approximately as [17]:

$$QRS = 0.0014M(34 - T_a - \Delta T) + 0.0173M(5.87 - P_{va}) \tag{4}$$

Heat transfer from the uncovered portion as well as covered portion of the body to the ambient is assumed to be due to the combined effect of convection and radiation. Total heat transfer (Q') which is the heat transfer from skin through clothing to the ambient, under these conditions is given by:

$$Q' = h.A_{uconv.}(T_s - T_a - \Delta T) + \sigma A_{urad.}\varepsilon_s\,[(T_s{}^4 - (T_a + \Delta T)^4] + \\ h.A_{cconv.}(T_{2o} - T_a - \Delta T) + \sigma A_{crad.}\varepsilon_{oc}[T_{2o}{}^4 - (T_a + \Delta T)^4] \tag{5}$$

In Equation (1), $Q_{ev.}$ represents the evaporative heat flux, and is given by [16]:

$$Q_{ev.} = h_v(p_s - p_a) \tag{6}$$

where,

$$h_v = 3.84(T_s - T_a - \Delta T) \tag{7}$$

$$p_s = 0.049T_s{}^2 - 0.954T_s + 15.6\text{, and} \tag{8}$$

$$p_a = RH \times p_s \tag{9}$$

Rearranging Equation (1), we get

$$\frac{dT_c}{dt} = \frac{1}{mC_p}(M + \Delta MV_m + QTR - QRS - Q_{ev.}A_{ev.}) - \frac{1}{mC_p}(Q') \tag{10}$$

Equation (10) is a first order ordinary differential equation which is to be solved by some numerical method to get the variation of T_c with time t. For this, if T_c at any time, t is known then employing the simple Taylor's series, the value of T_c at time $t + \Delta t$ can be expressed as:

$$T_c(t + \Delta t) = T_c(t) + \Delta t\frac{dT_c}{dt} \tag{11}$$

It should be noted that the solution of Equation (10) requires the values of T_s and T_{2o}. These temperatures can be determined from the transmission of energy from one region to another with reference to Figure 1 starting from the core region. At any instant of time heat transfer in different regions can be expressed by proper equations corresponding to the mode/modes of heat transfer considered in that region. With reference to Figure 1, heat transfer in the core, muscle, skin, inner cloth, and outer cloth regions is considered to be due to conduction where as in the air gaps it is due to the combined effect of conduction and radiation. Heat transfer from uncovered and covered portions of the body to the ambient is due to combined effect of convection and radiation. In order to calculate T_c following equations are used:

$$T_c - T_a = (M + QTR - QRS)R_{1c} + \Delta MV_m R_{2c} - Q_{ev.}A_{ev.}R_{3c} - \\ (T_s - T_a)R_{3c}/R_{ea} \tag{12}$$

where,
$$R_{1c} = R_c + R_m + R_s + R_{a1} + R_{ic} + R_{a2} + R_{oc} + R_{amb} \tag{13}$$

$$R_{2c} = 0.5R_m + R_s + R_{a1} + R_{ic} + R_{a2} + R_{oc} + R_{amb} \tag{14}$$

$$R_{3c} = R_{a1} + R_{ic} + R_{a2} + R_{oc} + R_{amb} \tag{15}$$

The values of R_c, R_m, R_s, R_{a1}, R_{ic}, R_{a2}, R_{oc} and R_{amb} can be found from the following equations:

$$R_c = \frac{\Delta x_c}{k_c A} \tag{16}$$

$$R_m = \frac{\Delta x_m}{k_m A} \tag{17}$$

$$R_s = \frac{\Delta x_s}{k_s A} \tag{18}$$

$$R_{a1} = \frac{1}{\dfrac{k_{ai} A_{ccond.}}{\Delta x_{si}} + \dfrac{\sigma A_{crad.} (T_s^{\ 2} + T_{1i}^{\ 2})(T_s + T_{1i})}{\dfrac{1}{\varepsilon_s} + \dfrac{1}{\varepsilon_{ic}} - 1}} \tag{19}$$

$$R_{ic} = \frac{\Delta x_{ic}}{k_{ic} A_{ccond.}} \tag{20}$$

$$R_{a2} = \frac{1}{\dfrac{k_{ao} A_{ccond.}}{\Delta x_{ioc}} + \dfrac{\sigma A_{crad.} (T_{1o}^{\ 2} + T_{2i}^{\ 2})(T_{1o} + T_{2i})}{\dfrac{1}{\varepsilon_{ic}} + \dfrac{1}{\varepsilon_{oc}} - 1}} \tag{21}$$

$$R_{oc} = \frac{\Delta x_{oc}}{k_{oc} A_{ccond.}} \tag{22}$$

$$R_{amb} = \frac{1}{h A_{cconv.} + \sigma \varepsilon_{oc} A_{crad.} (T_{2o}^{\ 2} + T_a^{\ 2})(T_{2o} + T_a)} \tag{23}$$

$$R_{ea} = \frac{1}{h A_{uconv.} + \sigma \varepsilon_s A_{urad.} (T_s^{\ 2} + T_a^{\ 2}) * (T_s + T_a)} \tag{24}$$

Similarly for calculating T_s following equations are required:

$$T_s - T_a = \frac{(M + \Delta MV_m + QTR - QRS - Q_{ev.}A_{ev.})R_c'}{1 + \frac{R_c'}{R_{ea}}} \tag{25}$$

where, $$R_c' = R_{a1} + R_{ic} + R_{a2} + R_{oc} + R_{amb} \tag{26}$$

For calculating T_{2o} following equation is required:

$$T_{2o} - T_a = (M + \Delta MV_m + QTR - QRS - Q_{ev.}A_{ev.})R_{amb} - \frac{(T_s - T_a)R_{amb}}{R_{ea}} \tag{27}$$

2.2 Unclothed human operator

When an unclothed operator goes from one ambient condition to the other then the core temperature of the operator changes with time and the governing equation to obtain this change is same as that of clothed operator except the equation for Q' which is given by:

$$Q' = hA_{uconv.}(T_s - T_a - \Delta T) + \sigma A_{urad.}\varepsilon_s\ [(T_s^4 - (T_a + \Delta T)^4] \tag{28}$$

The model to describe the temperature distribution at any instant of time through various regions for an unclothed human operator is shown in Figure 2, where same symbols as expressed in Figure 1 are preserved. In such a case, the heat

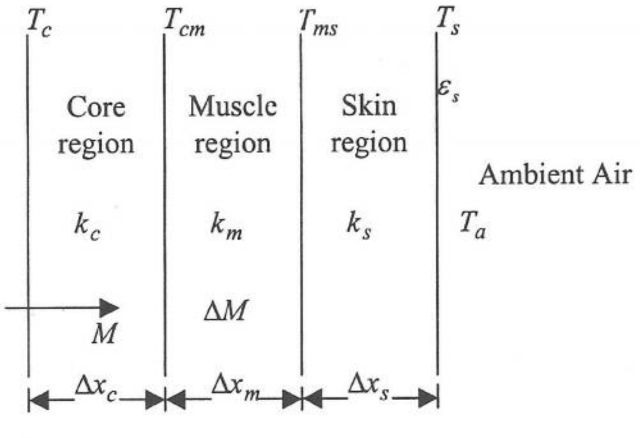


Figure 2 A simplified model showing different regions for an unclothed operator.

transfer in the core region, muscle region, and skin region is due to conduction which is same as expressed earlier for the case of a clothed human operator. However, due to the absence of cloth on the body, heat transfer from skin surface to the ambient air is due to the combined effect of convection and radiation. The evaporative heat loss from the skin surface also takes place. Heat transfer due to respiration and thermoregulation as considered for the clothed operator is also considered for the unclothed operator. In order to calculate T_c following equations are used:

$$T_c - T_a = (M + QTR - QRS)R_{1uc} + \Delta MV_m R_{2uc} \tag{29}$$

where,

$$R_{1uc} = R_c + R_m + R_s + R_{amb} \tag{30}$$

$$R_{2uc} = 0.5R_m + R_s + R_{amb} \tag{31}$$

Similarly T_s can be calculated from the following equation:

$$T_s - T_a = (M + \Delta MV_m + QTR - QRS - Q_{ev.}A_{ev.})R_{amb} \tag{32}$$

3.0 RESULTS AND DISCUSSION

The results that follow present the variation in the core temperature, T_c and the skin surface temperature, T_s with time due to sudden change in ambient temperature for the following combinations of the clothed and unclothed operator conditions:

(i) Healthy (Thermoregulation is effective) and Passive (No muscle heat/operator in resting condition).
(ii) Healthy and Active (With muscle heat/operator in working condition).
(iii) Sick (Thermoregulation is not effective) and Passive.
(iv) Sick and forcibly active.

3.1 Model validation

Phillips [16] has obtained the value of core temperature, T_c for sick and passive as well as healthy and passive clothed operator after 2 and 12 hours respectively when the operator goes from an ambient temperature of 22°C to 12°C for the data listed in Table 1. He has considered convection as the effective mode of heat transfer from the skin surface through the clothing to the external environment (Q_c'). He has assumed 82% of thc body area (A) of the operator to be covered with cloth. He has also assumed the difference between core temperature, T_c and skin temperature, T_s as a constant value equal to 2.8°C. In order to obtain value of T_c he used the data listed in Table 1 to solve the following equation:

$$mC_p \frac{dT_c}{dt} = M + QTR - Q_c' \tag{33}$$

Table 1 Numerical values of the parameters used for validation of the model.

Parameter	Value	Parameters	Value
M	46.52 W m^{-2}	T_s	34.2°C
h_{TOT}	4.652 W m^{-2} K^{-1}	A	1.80 m^2
m	68.0 kg	A_{TOT}	1.48 m^2
C_p	3516.912 J kg^{-1} K^{-1}	T_{sp}	37.0°C
T_c	37.0°C	K_p	29.075 W m^{-2} K^{-1}
T_a	22.0°C	ΔT	-10.0°C
Δx_c	0.04 m	Δx_m	0.02 m
Δx_s	0.01 m	$k_c, k_m,$ and k_s	0.494 W m^{-1} K^{-1}

where, $$Q_c' = h_{TOT} A_{TOT} (T_c - 2.8 - T_a - \Delta T) \tag{34}$$

h_{TOT} is the effective heat transfer constant (W m^{-2} K^{-1})
A_{TOT} is the effective body surface area (m^2)

It is to be noted that for a sick operator QTR is equal to zero. After simplification Phillips [16] presented the solution in the closed form as given by:

$$T_c(t) = \frac{c}{b}(1 - e^{-bt}) + T_c(0)e^{-bt} \tag{35}$$

Where, b and c are constants,
$T_c(t)$ is the core temperature at time 't'
$T_c(0)$ is the core temperature at time '0 (zero)'
t is the time (h)

The values of T_c thus obtained by Phillips [16] for healthy and passive as well as for sick and passive operators after 2 and 12 hours respectively are given in Table 2.

Table 2 Validation of the predicted Core Temperature, T_c in °C

	Time			
	2 Hours		**12 Hours**	
	Present Numerical Scheme	**Phillips (2000)**	**Present Numerical Scheme**	**Phillips (2000)**
Healthy and Passive	36.04	36.05	35.83	35.86
Sick and Passive	35.17	35.13	29.97	29.94

Present analysis uses a numerical scheme based on Taylor's series as explained earlier and given by equation (11). The values of T_c after 2 and 12 hours obtained from the present numerical scheme for the operator data listed in Table 1 and for the same mode of heat transfer as considered by Phillips [16] are also presented in Table 2. It can be seen from Table 2 that the value of T_c obtained from the present numerical scheme is same as that obtained by Phillips [16] who used equation (35). Thus the present numerical scheme to predict the value of T_c at any instant of time is validated against the results of Phillips [16]. It may be noted that Phillips [16] fixed the skin temperature, T_s to be equal to 34.2°C. An attempt is made to relax the above restriction in the present analysis i.e. T_s is not fixed at a constant value of 34.2°C as used by Phillips [16]. The value of T_s has been obtained by subtracting the product of heat flow and conduction resistance from core to skin as shown in Figure 1 from the known value of T_c at any given instant of time. The new value of T_s has been used to calculate the convective heat transfer from the skin surface through clothing to the external environment. The values of T_c after 2 and 12 hours thus obtained from the present analysis for the same operator data listed in Table 1 are presented in Table 3. It can be seen from Table 3 that the values of T_c obtained from the present analysis are close to those of Phillips [16] except for the case of 12 hours with sick person. This difference is due to fixing the skin temperature, T_s at 34.2°C by Phillips [16].

Table 3 Estimation of the Core Temperature, T_c in °C – New Results *

	Time			
	2 Hours		**12 Hours**	
	Present Analysis	**Phillips (2000)**	**Present Analysis**	**Phillips (2000)**
Healthy and Passive	36.55	36.05	36.51	35.86
Sick and Passive	35.86	35.13	32.63	29.94

* The restriction of constant temperature difference between core and skin is relaxed. Skin temperature is not restricted to 34.2 °C.

3.2 Predicted transient behaviour of core and skin temperatures for different combinations of operator conditions

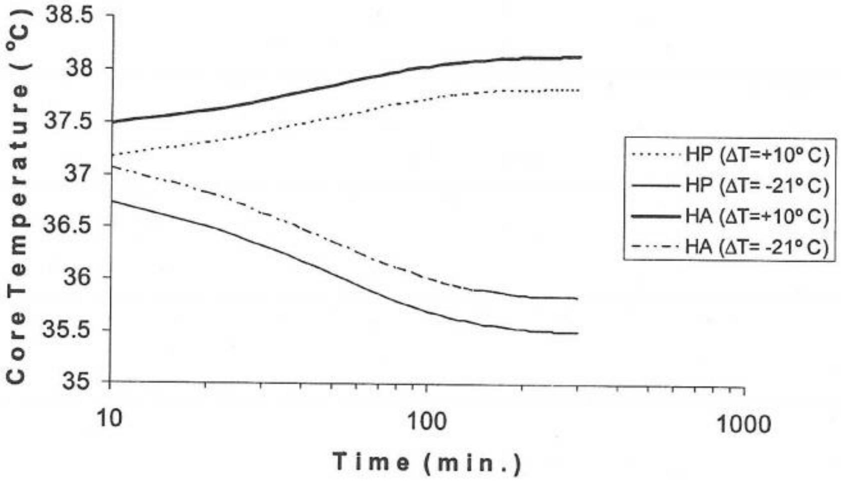
The steady state values of the core as well as skin temperatures (T_c and T_s) at an ambient temperature of 21°C for different combinations of operator conditions as discussed earlier have been obtained after equating the right hand term of

Table 4 Numerical values of the parameters used in the model.

Parameters	Value	Parameters	Value
Δx_c	0.04 m	ε_{oc}	0.9
Δx_m	0.02 m	m	65.0 kg
Δx_s	0.01 m	A	1.639 m^2
Δx_{si}	0.001 m	V_m	0.003 m^3
Δx_{ic}	0.001 m	$A_{ccond.}$	1.475 m^2
Δx_{ioc}	0.004 m	$A_{cconv.}$	1.475 m^2
Δx_{oc}	0.002 m	$A_{crad.}$	1.475 m^2
k_c	0.494 $W\ m^{-1}\ K^{-1}$	$A_{uconv.}$	0.1639 m^2
k_m	0.494 $W\ m^{-1}\ K^{-1}$	$A_{urad.}$	0.1639 m^2
k_s	0.494 $W\ m^{-1}\ K^{-1}$	$A_{ev.}$	0.082 m^2
k_{ai}	0.026 $W\ m^{-1}\ K^{-1}$	M	70.53 W
k_{ic}	0.06 $W\ m^{-1}\ K^{-1}$	ΔM	6454.85 $W\ m^{-3}$
k_{ao}	0.026 $W\ m^{-1}\ K^{-1}$	σ	5.67 x 10^{-8} $W\ m^{-2}\ K^{-4}$
k_{oc}	0.06 $W\ m^{-1}\ K^{-1}$	RH	0.8
ε_s	0.87	h	1.369 $W\ m^{-2}\ K^{-1}$
ε_{ic}	0.9	K_p	29.075 $W\ m^{-2}\ K^{-1}$
T_{sp}	310.0 K		
C_p	3516.912 $J\ kg^{-1}\ K^{-1}$	Δt	60 s

equation (1) to zero. Table 4 shows the details of the geometrical and thermal properties used in the illustrative problem. Many of the values given in the table are taken from Phillips [16]. 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 as recommended by Phillips [16] and is considered to be equal to only 5% of the body area for the clothed operator where as it is full body area for the unclothed operator. Similarly, only 10% of the body area is assumed to be involved in the muscle activity. The muscle volume V_m is obtained by multiplying the active muscle area by the thickness of the muscle region. Further, the muscle heat generated in the muscle region due to activity is taken to be 30% of the metabolic heat as recommended by Phillips [16] for sedentary activity.

Figure 3 shows the variation in T_c with time for a healthy and passive as well as healthy and active clothed operator when the ambient temperature is suddenly changed from 21°C to 31°C as well as from 21°C to 0°C. It may be noted that the time is plotted on the log scale in order to bring out the time for steady state more clearly. It can be seen from Figure 3 that for a normal operator who is healthy, under passive condition, the steady state value of T_c is 37.02°C at an ambient temperature of 21°C. As the operator goes from an ambient temperature of 21°C to an ambient temperature of 31°C, an increase in the ambient temperature of 10°C ($\Delta T = +10$°C) and stays there, the temperature T_c starts

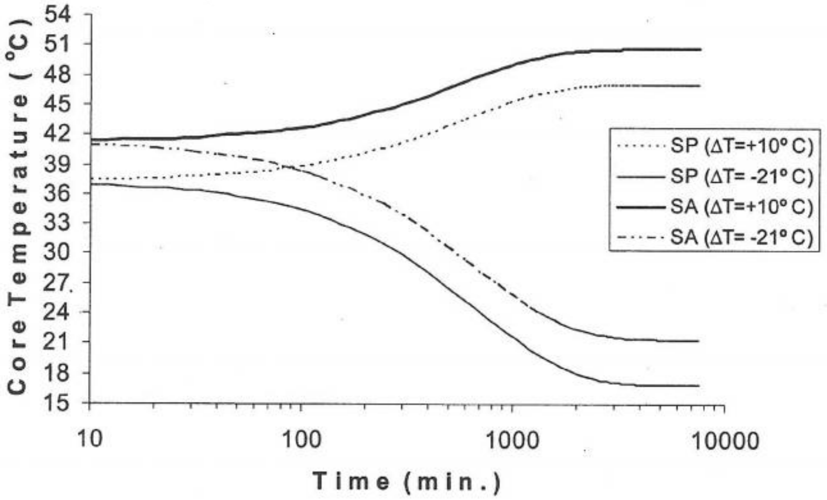


HP: Healthy and Passive; HA: Healthy and Active

Figure 3 Transient behaviour of core temperature (T_c) due to sudden change in ambient temperature for Healthy and Passive as well as Healthy and Active clothed operator increasing with time and attains a steady state value of 37.83°C after 236 minutes. The same temperature is also obtained when the transient term in the present analysis is dropped and calculation is carried out. On the other hand if the operator goes from an ambient temperature of 21°C to an ambient temperature of 0°C, a reduction in the ambient temperature of 21°C ($\Delta T = -21$°C) then the temperature T_c starts decreasing as the time progresses at a faster rate as compared to the rate of increase for the case when $\Delta T = +10$°C and attains a steady state value of 35.52°C after 244 minutes. It can also be seen from Figure 3 that for a healthy and active operator, the steady state value of T_c at an ambient temperature of 21°C is 37.33°C which is slightly higher than that of healthy and passive operator because of additional muscle heat due to activity. As this healthy and active operator goes from an ambient temperature of 21°C to an ambient temperature of 31°C ($\Delta T = +10$°C), the temperature T_c starts increasing with time and attains a steady state value of 38.14°C after 269 minutes which is slightly higher than that for healthy and passive operator for the same change in ambient temperature because of the presence of additional muscle heat. Similarly, as the healthy and active operator goes from an ambient temperature of 21°C to an ambient temperature of 0°C ($\Delta T = -21$°C), the core temperature starts decreasing at a faster rate as compared to the rate of increase for the case when $\Delta T = +10$°C with time and attains a steady state value of 35.83°C after 297 minutes. Once again the steady state value of T_c at an ambient temperature of 0°C is slightly higher than that of healthy and passive operator at the same ambient temperature due to additional muscle heat. It is interesting to note that for a healthy operator since thermoregulation is effective, the steady state value of the core temperature T_c is very close to 37°C at any ambient temperature considered in the present analysis and thus the operator is safe. Similar trends in the variation of T_c with time are observed for healthy and passive as well as healthy and active unclothed operators. It is found that the temperature T_c for a healthy and passive unclothed operator attains a steady state value of 37.21°C after 124 minutes for the case when $\Delta T = +10$°C and 34.09°C after 208 minutes for the case when $\Delta T = -21$°C as can also be seen from Figure 5. Similarly, for a healthy and active unclothed operator, T_c attains steady state value of 37.41°C after 130 minutes for the case when $\Delta T = +10$°C and 34.34°C after 201 minutes for the case when $\Delta T = -21$°C. It is also found that the temperature T_c at any given ambient temperature for unclothed operator is lower than that of clothed operator for the same ambient temperature because of high rate of heat transfer from the unclothed operator.

Figure 4 shows variation in the temperature T_c with time for a sick and passive as well as sick and forcibly active clothed operator. It can be seen from Figure 4 that for a sick and passive clothed operator, the temperature T_c attains a steady state value of 47.10°C after 3798 minutes for the case when $\Delta T = +10$°C and

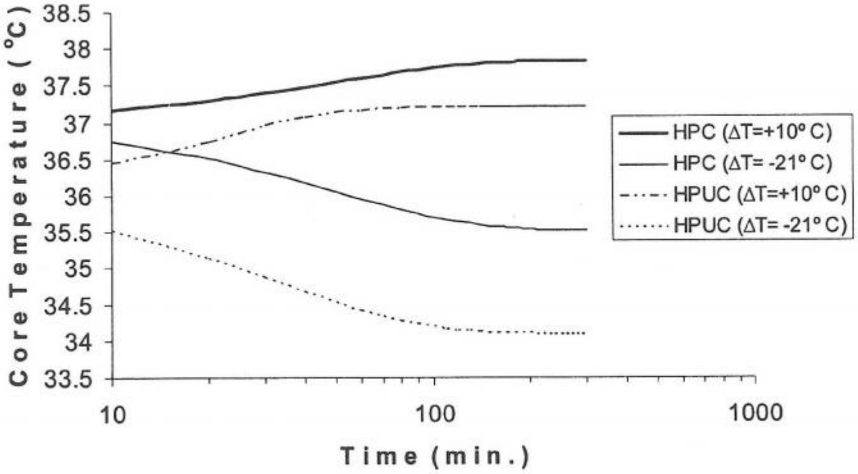
16.90°C after 5163 minutes for the case when $\Delta T = -21°C$. Similarly, if the sick operator is forced to do work then the temperature T_c attains a steady state value of 50.73°C after 3645 minutes for the case when $\Delta T = +10°C$ and 21.36°C after 5083 minutes for the case when $\Delta T = -21°C$. On comparing Figure 3 with Figure 4 it can be observed that for a sick operator the temperature T_c is no where close to 37°C at any ambient temperature except at 21°C because of the failure of thermoregulation and hence, the operator is not safe. It is also observed that for a sick operator the time required for T_c to reach to steady state value is much higher than that for a healthy operator. Similar trends in the variation of T_c with time are observed for sick and passive as well as sick and forcibly active unclothed operator. It is found that the temperature T_c for a sick and passive unclothed operator attains a steady state value of 38.45°C after 1077 minutes for the case when $\Delta T = +10°C$ and 9.47°C after 3022 minutes for the case when $\Delta T = -21°C$. Similarly, for a sick and forcibly active unclothed operator T_c attains a steady state value of 39.92°C after 1207 minutes for the case when $\Delta T = +10°C$ and 12.20°C after 3074 minutes for the case when $\Delta T = -21°C$.



SP: Sick and Passive; SA: Sick and Active

Figure 4 Transient behaviour of core temperature (T_c) due to sudden change in ambient temperature for Sick and Passive as well as Sick and Active clothed operator

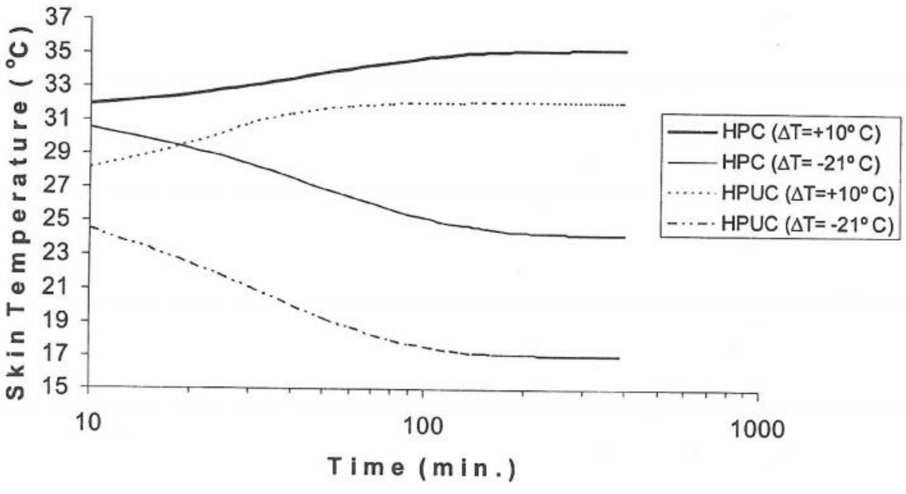
Figure 5 shows variation in T_c with time for a healthy and passive clothed as well as healthy and passive unclothed operator. The main purpose of this figure is to present a comparison of T_c between clothed and unclothed operators. It can be seen from Figure 5 that the steady state value of T_c for any given ambient temperature difference for a clothed operator is higher than that of unclothed operator for the same ambient temperature difference. This is because of the absence of clothing from unclothed operator which leads to higher amount of heat transfer from the body to the external environment.



HPC: Healthy and Passive Clothed; HPUC: Healthy and Passive Unclothed

Figure 5 Transient behaviour of core temperature (T_c) due to sudden change in ambient temperature for Healthy and Passive clothed and unclothed operator

As regards the skin temperature T_s is concerned, similar trends in the variation of T_s with time are observed. The transient behaviour of T_s due to change in ambient temperature is represented by four typical curves shown in Figure 6 for healthy and passive clothed as well as healthy and passive unclothed operators for the cases when $\Delta T = +10^{\circ}$C and $\Delta T = -21^{\circ}$C respectively. It can be seen from Figure 6 that for a clothed operator the steady state value of T_s for any given ambient temperature difference is higher than that of an unclothed operator for the same ambient temperature difference. It can also be seen that for higher ambient temperature difference, T_s is reasonably close to 35°C where as for lower ambient temperature difference it is much below 35°C. Thus, the temperature T_s is significantly affected when the operator goes from a higher



HPC: Healthy and Passive Clothed; HPUC: Healthy and Passive Unclothed

Figure 6 Transient behaviour of skin temperature (T_s) due to sudden change in ambient temperature for Healthy and Passive clothed and unclothed operator.

temperature to a much lower temperature. In all the cases considered it is observed that the temperatures T_c and T_s attained after a long time correspond to the steady state temperature determined independently from the steady state analysis. This confirms the accuracy of the transient analysis carried out for all the cases considered.

4.0 CONCLUSIONS

A simple, comprehensive and flexible thermal model is presented to predict the transient behaviour of the core as well as skin temperatures of both clothed and unclothed operators due to sudden change in the ambient temperature. The results are presented for healthy/sick and active/passive operators for a wide range of ambient temperature difference. The model is validated against the results available for both healthy and sick operators. The model also predicts correctly the steady state core as well as skin temperatures of the operators.

5.0 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)
$A_{ev.}$	Body area for evaporation (m^2)
$A_{uconv.}$	Uncovered area of the body for convection (m^2)
$A_{urad.}$	Uncovered area of the body for radiation (m^2)
C_p	Specific heat ($J\ kg^{-1}\ K^{-1}$)
h	Free convective heat transfer co-efficient ($W\ m^{-2}\ K^{-1}$)
h_v	Evaporative heat transfer co-efficient ($W\ m^{-2}\ K^{-1}$)
k_{ai}	Thermal conductivity of the air gap between skin and inner cloth ($W\ m^{-1}\ K^{-1}$)
k_{ao}	Thermal conductivity of the air gap between inner cloth and outer cloth ($W\ m^{-1}\ K^{-1}$)
k_c	Thermal conductivity of the core ($W\ m^{-1}\ K^{-1}$))
k_{ic}	Thermal conductivity of the inner cloth ($W\ m^{-1}\ K^{-1}$)
k_m	Thermal conductivity of the muscle ($W\ m^{-1}\ K^{-1}$)
k_{oc}	Thermal conductivity of the outer cloth ($W\ m^{-1}\ K^{-1}$)
K_p	Heat rate constant ($W\ m^{-2}\ K^{-1}$)
k_s	Thermal conductivity of the skin ($W\ m^{-1}\ K^{-1}$)
M	Metabolic heat (W)
m	Body mass (kg)
p_a	Partial pressure of water vapour in the ambient air (mm of Hg)
p_s	Vapour pressure of water at skin surface temperature (mm of Hg)
P_{va}	Vapour pressure of ambient air (kPa)

$Q_{ev.}$	Evaporative heat flux (W m^{-2})
Q'	Heat transfer from skin to ambient (W)
QRS	Respiratory heat loss (W)
QTR	Thermoregulation heat (W)
R_{a1}	Total thermal resistance due to conduction and radiation in the air gap between skin and inner cloth (K W^{-1})
R_{a2}	Total thermal resistance due to conduction and radiation in the air gap between inner and outer cloth (K W^{-1})
R_{amb}	Total thermal resistance due to convection and radiation from outer cloth to ambient (K W^{-1})
R_c	Thermal resistance due to conduction in the core region (K W^{-1})
R_{ea}	Total thermal resistance due to convection and radiation from uncovered portion of the body to ambient (K W^{-1})
RH	Relative humidity
R_{ic}	Thermal resistance due to conduction in the inner cloth region (K W^{-1})
R_m	Thermal resistance due to conduction in the muscle region (K W^{-1})
R_{oc}	Thermal resistance due to conduction in the outer cloth region (K W^{-1})
R_s	Thermal resistance due to conduction in the skin region (K W^{-1})
T_a	Ambient temperature (^{o}C or K)
T_{an}	New ambient temperature (^{o}C or K)
T_c	Body core temperature (^{o}C or K)
T_{cm}	Temperature between core and muscle (^{o}C or K)
T_{ms}	Muscle temperature (^{o}C or K)
T_s	Skin surface temperature (^{o}C or K)
T_{sp}	Hypothalamic set point temperature (^{o}C or K)
T_{1i}	Temperature of the inner layer of the inner cloth (^{o}C or K)

T_{1o}	Temperature of the outer layer of the inner cloth (^{o}C or K)
T_{2i}	Temperature of the inner layer of the outer cloth (^{o}C or K)
T_{2o}	Temperature of the outer layer of the outer cloth (^{o}C or K)
V_m	Muscle volume (m^3)
ΔM	Muscle heat generated per unit volume in the muscle region due to activity (W m^{-3})
Δx_c	Core thickness (m)
Δx_{ic}	Inner cloth thickness (m)
Δx_{ioc}	Air gap thickness between inner cloth and outer cloth (m)
Δx_m	Muscle thickness (m)
Δx_{oc}	Outer cloth thickness (m)
Δx_s	Skin thickness (m)
Δx_{si}	Air gap thickness between skin and inner cloth (m)
ΔT	Change in ambient temperature (^{o}C or K)
Δt	Time step (s)
ε_{oc}	Emissivity of the outer cloth
ε_s	Emissivity of the skin surface
σ	Stefen Boltzman constant (W m^{-2} K^{-4})
$\frac{dT_c}{dt}$	Change in core temperature with time (^{o}C or K s^{-1})

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