QUANTITATIVE ANALYSIS OF HEAT TRANSFER ON HUMAN OPERATOR USING THERMAL MODELS

by

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This project is particularly dedicated to my beloved Father Mr.Maniyan, Mother Mrs. Elamah and Wife Subashini

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

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 body tissue (kg/l)
h	Free convective heat transfer co-efficient (W/m^2 °C)
h_v	Evaporative heat transfer co-efficient (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)
M	Metabolic heat (W)
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)
QRS	Respiratory heat Loss (W)
QTR	Proportional heat (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 (°C)
T_s	Skin surface temperature (°C)
T_{sp}	Hypothalamic set point temperature (°C)
T_{1i}	Temperature of the inner layer of the inner cloth (°C)
T_{1o}	Temperature of the outer layer of the inner cloth (°C)
T_{2i}	Temperature of the inner layer of the outer cloth (°C)
T_{2o}	Temperature of the outer layer of the outer cloth (°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)
ΔM	Muscle heat generated per unit volume in the muscle region due to activity (W/m^3)

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)
C_p	Specific Heat (J/kg-K)
Q'	Heat transfer from skin to ambient (W)
R_{a1}	Total thermal resistance due to conduction and radiation in the air gap between skin and inner cloth (K/W)
R_{a2}	Total thermal resistance due to conduction and radiation in the air gap between inner and outer cloth (K/W)
R_{amb}	Total thermal resistance due to convection and radiation from outer cloth to ambient (K/W)
R_c	Thermal resistance due to conduction in the core region (K/W)
R_{ea}	Total thermal resistance due to convection and radiation from uncovered portion of the body to ambient (K/W)
R_{ic}	Thermal resistance due to conduction in the inner cloth region (K/W)
R_m	Thermal resistance due to conduction in the muscle region (K/W)
R_{oc}	Thermal resistance due to conduction in the outer cloth region (K/W)
R_s	Thermal resistance due to conduction in the skin region (K/W)
T_{an}	New Ambient temperature (°C or K)
ΔT	Change in ambient temperature (°C or K)
Δt	Time step (s)

$\frac{dT_c}{dt}$	Change in core temperature with time (°C or K/s)
F_{mvc}	Maximal EMG amplitude at the maximal voluntary contraction
F_{mvc-35}	Maximal EMG amplitude at the maximal voluntary contraction at 35^{0}C
F_T	Target force
B	Root mean square of amplitude of the EMG
B_{mvc}	Maximal amplitude at the maximal voluntary contraction force that can be exerted with a brief isometric (less than 3s) contraction
F_δ	Brief force impulse
f_c	Center frequency of EMG power spectrum
f_{mvcc}	Brief maximal isometric contraction in the unfatigued muscle
$\frac{f_{ci}}{f_{cmvc}}$	Fractional center frequency
EMG	Electromyogram

ANALISIS KUANTITATIF PEMINDAHAN HABA KE ATAS OPERATOR MANUSIA DENGAN MENGGUNAKAN MODEL-MODEL TERMA

ABSTRAK

Satu percubaan untuk menghasilkan jangkaan masa untuk mencapai tahap kelesuan operator manusia berdasarkan beban kerja telah dilakukan dalam tesis ini. Beban kerja pula bergantung kepada keadaan operator dan juga keadaan persekitaran yang boleh dipertonjolkan dalam suhu otot. Model matematik yang mudah dan komprehensif untuk pemindahan haba dalam badan manusia telah dihasilkan bagi keadaan keseimbangan dan juga keadaan transien. Pemindahan haba jenis konduksi, perolakan, radiasi and pengewapan telah diambil kira dalam penghasilan model ini. Model-model ini telah dipastikan kesahihannya dengan menggunakan hasil kerja yang sedia ada. Kajian parametrik juga telah dilakukan untuk keadaan operator dan keadaan persekitaran. Suhu otot untuk pengiraan jangkaan masa untuk keadaan lesu diperoleh daripada model matematik ini.

Tiga kajian kes yang menunjukkan jenis operasi yang berlainan telah diperoleh daripada sebuah syarikat multinasional. Jangkaan masa untuk keadaan lesu telah diperoleh dengan menggunakan model matematik dan dibandingkan dengan masa sebenar yang diperoleh daripada sesi temubual dengan operator. Diperhatikan bahawa kedua-dua nilai masa ini adalah lebih kurang sama, sebagai contohnya dalam kajian kes 1, masa untuk keadaan lesu yang dijangka adalah 0.56 minit dan masa sebenar adalah 0.6 minit. Ini menunjukkan bahawa masa yang diperoleh dengan menggunakan model matematik adalah adalah lebih kurang sama dengan masa sebenar. Keputusan yang sama telah diperoleh untuk kajian kes 2 iaitu masa yang dijangka adalah 0.15 minit berbanding dengan masa sebenar 0.18 minit. Untuk kajian kes 3 masa yang dijangka adalah 0.26 minit dibandingkan dengan masa sebenar 0.22 minit.

Oleh kerana keputusan menunjukkan bahawa masa yang dijangka merapati masa sebenar, analisis sebegini boleh diperkembangkan untuk operasi-operasi yang melesukan dalam industri.

QUANTITATIVE ANALYSIS OF HEAT TRANSFER ON HUMAN OPERATOR USING THERMAL MODELS

ABSTRACT

An effort has been made in this thesis to estimate the time for fatigue of a human operator based on the workload. Workload in turn depends on the condition of the operator and environmental conditions, which is reflected in the muscle temperature. Simple yet comprehensive mathematical models for heat transfer in human body were developed for both steady as well as transient states. Conduction, convection, radiation, and evaporation modes of heat transfer were considered in the models. The models were also validated against the results available in the literature. Parametric studies involving the condition of the operator and the environment were also carried out. From the mathematical model muscle temperature required for the estimation of the time for fatigue of the operator was determined.

Three case studies from a multinational company were considered which involve different types of task. The time for fatigue has been estimated for the three cases by mathematical calculation and compared with the actual time for fatigue of the operator, which is obtained from by interviewing the operators. It is observed that for these case studies the estimated value and also the actual value are in close agreement, e.g. case study 1 estimated value of time to fatigue is 0.56 minute and actual time to fatigue is 0.6 minute which shows that the calculated value is in close agreement with the actual value. Similarly for case study 2 the calculated value is 0.15 minute in compared to the actual value of 0.18 minute. The same result was also obtained for case study 3 whereby the actual result is 0.22 minute versus the predicted value of 0.26 minute.

As the predicted value and the actual time are in close agreement it has been proposed that the same type of analysis can be expanded to other fatiguing tasks across the industry.

CHAPTER 1

INTRODUCTION

Philips (2000) has defined human factors engineering as "The discipline of engineering which is concerned with the analysis, design, and development of human-technological systems with emphasis primarily on the human" provides room for quantitative analysis using the standard methods of engineering analysis.

Current methods depend more on experimental findings and do not provide mathematical models for quantitative analysis to determine fatigue point of an active human operator. One of the most important objectives of an industry, be it a manufacturing or service industry, is to optimize its productivity. Productivity optimization tool like Time and Motion study is vastly and frequently used for work simplification where the existing method of doing work is simplified and improved by eliminating unnecessary motions of the operators. Thus the assigned job can be completed in less time with less fatigue and consequently with increased productivity. Environmental condition such as heat can affect the operators performance, hence the productivity of the company. External heat or heat source from environment disturbs thermoregulation of the body and it will lead to high fever and even fatality.

It is believed that productivity can further be improved if the operator works in comfortable environmental conditions and with sufficient rest. Extreme environmental conditions and insufficient rest may cause discomfort to the operators and they may feel internal stresses, fatigue, and sickness. This will hamper the productivity of the operator. With this, the main task of an ergonomist is to quantify the relationship between time to fatigue and the environmental condition for performing both static and dynamic work. In this research the problem of developing the quantitative model/approach for this purpose has been addressed.

1.1 OBJECTIVE OF THE THESIS

This thesis is done based on the below listed objectives

1. Develop a simplified thermal model to predict steady state temperature of clothed and unclothed human operator
2. Develop a generalized transient behaviour of clothed and unclothed human operator due to sudden change in the environmental condition
3. Perform a quantitative workload analysis based case studies
4. Provide suggestions to industrial problems based on the models developed

1.2 OVERVIEW OF THE THESIS

Detailed contents of the research put forth in the form of present thesis are organized into five chapters. While the current chapter (Chapter 1) deals with the introduction of the thesis, the next chapter (Chapter 2) presents an overview of the previous researches carried out in the field of human heat transfer as well as human workload analysis. Chapter 3 presents the methodology for developing the mathematical models for human heat transfer and for calculating static workload as well as time required to get fatigued. The next chapter, (Chapter 4), forms the core of the thesis. In this chapter the results obtained from the proposed models are first validated against those available in the literature and then many other results, in terms of parametric studies are presented and discussed. In addition, the application of heat transfer models is also demonstrated through case studies. Chapter 5 presents major conclusions of the work as well as a few recommendations for future work.

CHAPTER 2

LITERATURE SURVEY

The purpose of the present review is to put forth some major features of the previously conducted researches in the area of human heat transfer and human workload analysis.

2.1 THERMAL MODEL OF HUMAN BODY

Thermal models for the human body as well as animals and reptiles have been developed by the researchers in the past. Fanger (1982) developed a relatively simple model in which he used only a one-dimensional approximation of the human body and of the heat and mass exchange with the environment. Bakken (1981) proposed a two-dimensional operative-temperature model for thermal energy management by animals. Smith (1991) and Fu (1995) 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 (O'Connor, 1999; Dzialowski and O'Connor, 2001). Yokoyama et al. (1997) considered the heat transported by the blood flow through different layers in their model. Yigit (1998) 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 (1994) 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. Thus there is a need for a simplified, yet comprehensive thermal model for human operator heat transfer including thermoregulation. Of late, Phillips (2000) has 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" ($\approx 37°$ C). However, during periods of intense physical exercise the body readjusts it's "set point" and the core temperature is allowed to increase and can often exceed 40°C. According to Phillips (2000) regulation of core temperature is accomplished by a thermostatic controlled centre located in the hypothalamus (at the base of the brain). There is a set point for temperature control (T_{sp}) so that the core temperature (T_c) is regulated by a negative feed back mechanism.

Apart from the research done on developing thermal models for the human body under steady state conditions, there were many researches carried out as well to develop transient thermal model for human body. Lotens (1993), Jones and Ogawa (1992) developed the transient model of heat and moisture transport through the clothing using simple thermal model of the body where as Smith (1991) and Fu (1995) have only considered the transient heat transfer through clothing. Recently, Phillips (2000) 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. Thus a thermal model to demonstrate transient behaviour has been developed for the core as well as the skin temperatures of both clothed and unclothed human operators when they go from one ambient condition to the other.

2.2 HUMAN WORKLOAD ANALYSIS

Apart from the heat transfer in human body, there have been researches carried out in the past on the subject of workload analysis. Stokes, Rich and Foord (2006) have devised a methodology to optimise the staffing in a process industry. This paper describes work to determine the optimum staffing using human engineering tools such as task analysis, function allocation, workload analysis, and human reliability analysis. Ma and Kaber (2006) have presented findings on a research to understand presence, workload and performance effects of synthetic environment design factors. This research examined a range of synthetic environment design features (viewpoint, auditory cue type and visual background) suspected to influence presence, and evaluated differences in presence, workload and task performance caused by manipulations of the factors and task difficulty in a virtual-reality-based basketball free-throw task. Philips and Repperger (2003) have proposed a physiological state model for human ergonomic workload. This model provides an alternative to measure and quantify the actual workload value for a mixed static and dynamic work. Kontogiannis (2003) proposed a Petri Net-based approach for ergonomic task analysis and modeling, which emphasizes on adaptation to system changes. The proposed technique has been developed to reflect aspects of task representation, control and decision making, and usability. Laring et. al. (2002) have developed a model to study an ergonomic complement to a modern MTM system called SAM that gives the production engineer a first insight into the future ergonomic quality of a planned production. Keller (2002) has developed a methodology for modeling of human performance using multiple resource theory within a discrete-event simulation, which can be used to assess the workload on operators. Jung and Jung (2001) proposed a model for overall workload assessment technique for various tasks and analysis. This model was developed to asses overall workload by introducing linguistic variable sets and applying the analytic hierarchy process to estimate the external workload imposed on human operator man-machine systems. Mitchell (1996) has also proposed various models for the design of human interaction with complex dynamic systems which describe similarities between human-machine systems models and a variety of other recent approaches to understanding and aiding human interaction in real-world systems. Corlett et.al (1987) have proposed a method to assess workload from the measurement of stature. They have described that the variation in height of the body could provide a reliable means of assessing the effects on the spine of both physical work and rest-pauses. The above models did not describe a methodology to quantify the task or the workload that has been done.

From the literature it appears that very little attempts have been made to develop a mathematical model to perform quantitative workload analysis. Thus, there is a need to develop a methodology to perform quantitative workload analysis by considering heat transfer in human body and workload performed in order to obtain the optimum productivity out of human operator. In this thesis an attempt is made to develop a comprehensive model for static workload analysis by integrating human body heat transfer and workload analysis models.

CHAPTER 3

MATERIALS AND METHODS

3.1 HUMAN OPERATOR HEAT TRANSFER

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. 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. Evaporative heat transfer may differ due to either free convection or forced convection. 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. According to Bridger (1995), the core temperatures over 39.5°C are disabling and over 42°C, they are usually 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. (2001) 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.

3.2 BIOMECHANICS

In order to perform human operator heat transfer analysis forces involved in the particular task need to be assessed. This assessment can be accomplished using biomechanics principles.

Biomechanics is the study of mechanics with particular interest to biological systems. Biostatic mechanic on the other hand defined as the science of the structure of living organisms in relation to the forces with which they interact. Biostatics mechanics focuses upon the musculoskeletal system for the purposes of human factors engineering evaluation and application. This system is characterized by five elements. These elements are proximal segment, distal segment, joint, agonist, and antagonist. If one thinks that of the navel as the center of the body with the arms stretched straight out to the side and the legs in a standing position spread somewhat apart, then the proximal segment is that anatomical structure nearest the navel and the distal segment is its adjoining structure, but farther from the navel. Joint can be defined by junction of the proximal with distal segment. Agonist muscle is an internal force generator that crosses the joint. One end is usually connected to the proximal segment and the other end (the insertion) is usually connected to the distal segment. This muscle is referred to as the agonist when it is the prime mover of the anatomical system. Agonist muscle is an internal force generator that also crosses the joint and usually has its origin at the proximal segment and its insertion at the distal segment. An antagonist muscle develops an opposing force with respect to its agonist partner.

3.3 STATIC WORKLOAD ANALYSIS

Workload can be defined as the reaction of human body when performing external work. When the external work is physical work, the bodily reactions consist of physiological adjustments and adaptations required for the performance of that physical work, Philips (2000). Generally work can be classified into two types which are static work and dynamic work. Static work occurs when no external work is accomplished in the environment. Dynamic work is performed when the external work is accomplished in the environment. There are two main factors that decide human strength and endurance when performing static work. These factors are muscle length and muscle temperature. Based on this an analytical basis for the quantitative assessment of human physical workload for the physiological adjustments and adaptations can be measured and quantified. Various factors affect physical workload such as:

1. Physical condition of an individual
2. Rate of performing external work
3. Environmental condition

3.4 MATHEMATICAL DEVELOPMENT OF STEADY STATE HUMAN HEAT TRANSFER MODEL

A simplified thermal model to predict steady state temperature of different regions of clothed and unclothed human operator will be developed in the following section. The different regions of human body, the mode of heat transfer considered in the analysis along with the necessary assumptions are clearly discussed.

3.4.1 Thermoregulatory Physiology

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. For the purpose of thermoregulatory control mechanisms of passive human operator, Philips (2000) introduced a passive proportional heat rate term given by:

$$-K_p * (T_{sp} - T_c) \tag{3.1}$$

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

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

T_c is the core temperature (°C)

It is to be noted that a passive human operator is an individual in a resting state. No muscle metabolic energy is being generated, nor is any external work being performed. It is apparent from inspection of Equation 3.1 that $K_p * (T_{sp} - T_c)$ is a heat rate that is proportional to the difference between the set point temperature and core temperature. In the simplest case the core temperature is equal to the set point temperature;

Equation 3.1 will reduce to zero indicating no need for thermoregulation. The passive heat rate constant (K_p) is intrinsically a negative heat rate. However, the proportional heat rate term may be either positive or negative depending on the sign of ΔT. This is of both physiological significance and thermoregulatory control significance. In the situation when the core temperature (T_c) is lower than the hypothalamic set point temperature (T_{sp}), the passive proportional heat rate term becomes a positive (input) heat rate and consequently a proportional heat rate gain. The obvious effect of this negative feedback would be to increase the core temperature (T_c) toward the hypothalamic set point temperature (T_{sp}).

The physiological interpretation of this thermoregulatory control is as follows. When the core temperature (T_c) is less than the hypothalamic set point temperature (T_{sp}), cold receptors are stimulated and neural impulses to the posterior hypothalamus initiate reflex adaptive mechanisms that result in an overall heat gain by the system. This is accomplished by a combination of increasing heat production by the human body as well as decreasing heat loss. Specifically, the positive (input) passive proportional heat rate is a quantitative representation of the following mechanisms:

1. 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.
2. 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 internal heat.
3. 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.

On the other hand for the case in which the core temperature (T_c) is higher than the hypothalamic set point temperature (T_{sp}), the temperature differential (ΔT) is then a negative value and when multiplied by a negative value of the passive heat rate constant (K_p) results in a negative (output) value for the passive proportional heat rate and consequently a proportional heat rate loss. The physiological interpretation of this thermoregulatory system for the passive human operator is as follows. When the core temperature (T_c) is greater than the hypothalamic set point temperature (T_{sp}) warm receptors are stimulated. Consequently, nerve impulses to the anterior hypothalamus initiate adaptive reflex mechanisms which result in an overall human operator heat loss. This overall heat loss is a combination of both decreased heat production and also increased heat dissipation. Specifically, the negative (output) passive proportional heat rate represents the following mechanisms:

1. 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 skin surface temperature in order to enhance a thermal gradient that favours external heat transfer to the environment.
2. 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) cannot be increased above the environmental temperature.
3. 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 (2000) introduced an active proportional heat rate term given by:

$$-K_A * (T_{sp} - T_c) \qquad (3.2)$$

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

It may be noted that K_p and K_A may not be necessarily same.

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 modeling heat transfer from human body is reasonably simple and avoids considerations of countercurrent and concurrent heat exchanges between flowing blood and tissues. It has been here followed the same procedure to develop a thermal model for the male human operator (clothed and unclothed) heat transfer under steady state conditions in order to predict temperature of various body regions under the impact of different environmental conditions.

3.4.2 Clothed Human Operator

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). Figure 3.1 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 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.

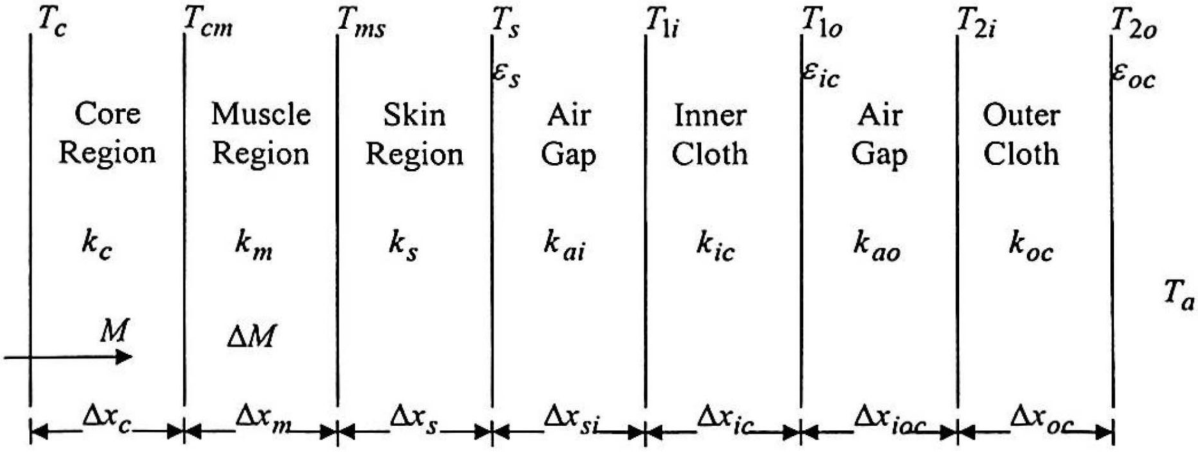

Figure 3.1: A simplified model showing different regions for a clothed operator.

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 ($\dot{M}$).

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 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 the proportional heat (QTR) due to effective thermoregulation is responsible for regulating the core temperature. According to Phillips (2000) thermoregulation is impaired with infirmity (poor hydration and/or nutrition), with debility and disease, and with chemical agents (certain prescription drugs, some over-the-counter drugs, specific street drugs, and alcohol). Simultaneous combinations of these factors result in significant impairment (deregulation) of the thermoregulation system. Henceforth a human operator with impaired thermoregulation system is considered as sick operator and therefore, contribution of (QTR) is zero for such an operator. 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) Steady state conditions prevail.
(iv) Uniform convection coefficient at outer surface.
(v) For radiation all surfaces are diffuse and gray.
(vi) Metabolic heat and muscle heat are uniform.

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

$$M + QTR - QRS = \frac{k_c * A * (T_c - T_{cm})}{\Delta x_c} \tag{3.3}$$

Rearranging, following equation is obtained:

$$M + QTR - QRS = \frac{T_c - T_{cm}}{\dfrac{\Delta x_c}{k_c * A}} \tag{3.4}$$

The area of the body, A is given by the following equation (Phillips, 2000):

$$A = 0.1 * m^{0.67} \tag{3.5}$$

The value of QTR can be calculated from the following equation (Phillips, 2000):

$$QTR = -K_p * A * (T_{sp} - T_c) \tag{3.6}$$

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 (2000).

The rate of total heat loss from the lungs through respiration can be expressed approximately as (Cengel, 2003):

$$QRS = 0.0014 * M * (34 - T_a) + 0.0173 * M * (5.87 - P_{va}) \tag{3.7}$$

Similarly, heat transfer in the muscle region is also due to conduction. The basic differential equation for heat transfer in the muscle region, including heat generation, ΔM, is given by (Kreith and Bohn, 1997):

$$\frac{d^2T}{dx^2} + \frac{\Delta M}{k_m} = 0 \tag{3.8}$$

Integrating the above equation and substituting the boundary conditions (T_{cm} and T_{ms}), the final equation for the heat transfer in this region is given by:

$$M + QTR - QRS = \frac{T_{cm} - T_{ms}}{\frac{\Delta x_m}{k_m * A}} - \frac{\Delta M * V_m}{2.0} \tag{3.9}$$

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

$$M + \Delta M * V_m + QTR - QRS = \frac{k_s * A * (T_{ms} - T_s)}{\Delta x_s} \tag{3.10}$$

Rearranging, following equation is obtained:

$$M + \Delta M * V_m + QTR - QRS = \frac{T_{ms} - T_s}{\frac{\Delta x_s}{k_s * A}} \tag{3.11}$$

It is to be noted that thickness of the skin region (Δx_s) varies with variation in the body fat (*BF*). Thickness of the skin region is calculated from the following equations suggested by Havenith (1997):

$$\Delta x_s = 0.5 * SF \tag{3.12}$$

$$BF = \left[\frac{4.95}{D_{body}} - 4.50 \right] * 100 \tag{3.13}$$

$$D_{body} = 1.112 - 10^{-6} * (434.99 * SF + 0.55 * SF^2 - 288.26 * age) \tag{3.14}$$

The above equations have been used in an inverse way to retrieve *SF* from *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 and radiation from the covered portion of the body. The uncovered portion of the body is subjected to convective and radiative heat transfer to the ambient. At the same time there is also evaporative heat loss from the skin surface to the ambient. The governing equation under the above conditions is given below:

$$M + \Delta M * V_m - Q_{ev.} * A_{ev.} + QTR - QRS = \frac{k_{ai} * A_{ccond.} * (T_s - T_{1i})}{\Delta x_{si}} + \frac{\sigma * A_{crad.} * (T_s{}^4 - T_{1i}{}^4)}{\frac{1}{\varepsilon_s} + \frac{1}{\varepsilon_{ic}} - 1}$$
$$+ h * A_{uconv.} * (T_s - T_a) + \sigma * A_{urad.} * \varepsilon_s * (T_s{}^4 - T_a{}^4) \tag{3.15}$$

After simplification, following equation is obtained:

$$M+\Delta M*V_m-Q_{ev.}*A_{ev.}+QTR-QRS=\frac{T_s-T_{1i}}{\dfrac{1}{\dfrac{k_{ai}*A_{ccond}}{\Delta x_{si}}+\dfrac{\sigma*A_{crad}*(T_s^2+T_{1i}^2)*(T_s+T_{1i})}{\dfrac{1}{\varepsilon_s}+\dfrac{1}{\varepsilon_{ic}}-1}}}+\frac{T_s-T_a}{\dfrac{1}{h*A_{uconv}+\sigma*\varepsilon_s*A_{urad}*(T_s^2+T_a^2)*(T_s+T_a)}} \tag{3.16}$$

It is to be noted that the second term on the right hand side (R.H.S.) of the above equation represents the convective and radiative heat transfer from the uncovered portion of the human operator.

In the above equation, $Q_{ev.}$ represents the evaporative heat flux, and is given by (Phillips, 2000):

$$Q_{ev.}=h_v*(p_s-p_a) \tag{3.17}$$

Where $h_v=3.84*(T_s-T_a)$ (3.18)

$$p_s=0.049*T_s^2-0.954*T_s+15.6\text{, and} \tag{3.19}$$

$$p_a=RH*p_s \tag{3.20}$$

Heat transfer in the inner cloth is due to conduction and the governing equation is given below:

$$M+\Delta M*V_m-Q_{ev.}*A_{ev.}+QTR-QRS$$
$$=\frac{k_{ic}*A_{ccond.}*(T_{1i}-T_{10})}{\Delta x_{ic}}+h*A_{uconv.}*(T_s-T_a)+\sigma*A_{urad.}*\varepsilon_s*(T_s^4-T_a^4) \tag{3.21}$$

After simplification, following equation is obtained:

$$M+\Delta M*V_m-Q_{ev.}*A_{ev.}+QTR-QRS$$
$$=\frac{T_{1i}-T_{1o}}{\dfrac{1}{\dfrac{k_{ic}*A_{ccond.}}{\Delta x_{ic}}}}+\frac{T_s-T_a}{\dfrac{1}{h*A_{uconv.}+\sigma*\varepsilon_s*A_{urad.}*(T_s^2+T_a^2)*(T_s+T_a)}} \tag{3.22}$$

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 due to the combined effect of conduction and radiation for which the equation is given below:

$$\begin{aligned} & M+\Delta M*V_m-Q_{ev.}*A_{ev.}+QTR-QRS \\ & =\frac{k_{ao}*A_{ccond}*(T_{1o}-T_{2i})}{\Delta x_{ioc}}+\frac{\sigma*A_{crad}*(T_{1o}^4-T_{2i}^4)}{\frac{1}{\varepsilon_{ic}}+\frac{1}{\varepsilon_{oc}}-1}+h*A_{uconv}*(T_s-T_a) \\ & +\sigma*A_{urad}*\varepsilon_s*(T_s^4-T_a^4) \end{aligned} \tag{3.23}$$

Upon simplification, following equation is obtained:

$$\begin{aligned} & M+\Delta M*V_m-Q_{ev.}*A_{ev.}+QTR-QRS \\ & =\frac{T_{1o}-T_{2i}}{\cfrac{1}{\cfrac{k_{ao}*A_{ccond}}{\Delta x_{ioc}}+\cfrac{\sigma*A_{crad}*(T_{1o}^2+T_{2i}^2)*(T_{1o}+T_{2i})}{\frac{1}{\varepsilon_{ic}}+\frac{1}{\varepsilon_{oc}}-1}}} \\ & +\frac{T_s-T_a}{\cfrac{1}{h*A_{uconv}+\sigma*\varepsilon_s*A_{urad}*(T_s^2+T_a^2)*(T_s+T_a)}} \end{aligned} \tag{3.24}$$

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

$$\begin{aligned} & M+\Delta M*V_m-Q_{ev.}*A_{ev.}+QTR-QRS \\ & =\frac{k_{oc}*A_{ccond.}*(T_{2i}-T_{20})}{\Delta x_{oc}}+h*A_{uconv.}*(T_s-T_a) \\ & +\sigma*A_{urad.}*\varepsilon_s*(T_s^4-T_a^4) \end{aligned} \tag{3.25}$$

After simplification, following equation is obtained:

$$M + \Delta M * V_m - Q_{ev.} * A_{ev.} + QTR - QRS = \frac{T_{2i} - T_{2o}}{\frac{1}{\frac{k_{oc} * A_{ccond.}}{\Delta x_{oc}}}} + \frac{T_s - T_a}{\frac{1}{h * A_{uconv.} + \sigma * \varepsilon_s * A_{urad.} * (T_s^2 + T_a^2) * (T_s + T_a)}} \tag{3.26}$$

Heat transfer from outer cloth to the ambient air is due to the combined effect of convection and radiation for which the governing equation is given below:

$$\begin{aligned} &M + \Delta M * V_m - Q_{ev.} * A_{ev.} + QTR - QRS \\ &= h * A_{cconv} * (T_{2o} - T_a) + \sigma * \varepsilon_{oc} * A_{crad} * (T_{2o}^4 - T_a^4) + h * A_{uconv} * (T_s - T_a) \\ &+ \sigma * A_{urad} * \varepsilon_s * (T_s^4 - T_a^4) \end{aligned} \tag{3.27}$$

Upon simplification, following equation is obtained:

$$M + \Delta M * V_m - Q_{ev.} * A_{ev.} + QTR - QRS = \frac{T_{2o} - T_a}{\frac{1}{h * A_{cconv} + \sigma * \varepsilon_{oc} * A_{crad} * (T_{2o}^2 + T_a^2) * (T_{2o} + T_a)}} + \frac{T_s - T_a}{\frac{1}{h * A_{uconv} + \sigma * \varepsilon_s * A_{urad} * (T_s^2 + T_a^2) * (T_s + T_a)}} \tag{3.28}$$

3.4.3 Unclothed Human Operator

The model to describe the steady state temperature distribution through various regions for an unclothed human operator is shown in Figure 3.2, where same symbols as expressed in Figure 3.1 are preserved.

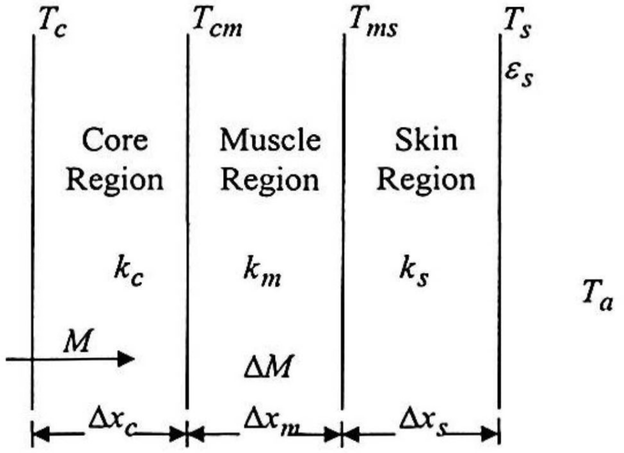

Figure 3.2: A simplified model showing different regions for an unclothed operator.

In such a case, the heat transfer in the core region, muscle region, and skin region remains 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. Thus, the governing equation for the heat transfer from skin surface to the ambient air, under this condition, is given by:

$$M + \Delta M * V_m - Q_{ev.} * A_{ev.} + QTR - QRS =$$
$$h * A_{uconv.} * (T_s - T_a) + \sigma * \varepsilon_s * A_{urad.} * (T_s^4 - T_a^4) \qquad (3.29)$$

After simplification, following equation is obtained:

$$M + \Delta M * V_m - Q_{ev.} * A_{ev.} + QTR - QRS = \frac{T_s - T_a}{\dfrac{1}{h * A_{uconv.} + \sigma * \varepsilon_s * A_{urad.} * (T_s{}^2 + T_a{}^2) * (T_s + T_a)}} \tag{3.30}$$

3.5 MATHEMATICAL DEVELOPMENT OF TRANSIENT HUMAN HEAT TRANSFER 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 condition. The different regions of human body, the mode of heat transfer considered in the analysis along with the necessary assumptions are clearly discussed.

3.5.1 Clothed human operator

The human body consists of the core region, muscle region, and skin region. Figure 3.1 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.

When an operator goes from one ambient condition 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:

$$m*C_p*\frac{dT_c}{dt}=M+\Delta M*V_m+QTR-QRS-Q_{ev.}*A_{ev.}-Q' \quad (3.31)$$

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 Equation 3.6.

The value of T_{sp} is taken to be 37^{0}C and the area of the body, *A* is given by the Equation 3.5.

The rate of total heat loss from the lungs through respiration, QRS can be expressed approximately as Equation 3.7.

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:

$$\begin{aligned}Q'=h*A_{uconv.}*(T_s-T_a-\Delta T)+\sigma*A_{urad.}*\varepsilon_s*[(T_s{}^4-(T_a+\Delta T)^4]+\\ h*A_{cconv.}*(T_{2o}-T_a-\Delta T)+\sigma*A_{crad.}*\varepsilon_{oc}*[T_{2o}{}^4-(T_a+\Delta T)^4]\end{aligned} \quad (3.32)$$

In Equation 3.31, $Q_{ev.}$ represents the evaporative heat flux, and is given by, Equation 3.17

Rearranging Equation 3.31, we get

$$\frac{dT_c}{dt}=\frac{1}{m*C_p}*(M+\Delta M*V_m+QTR-QRS-Q_{ev.}*A_{ev.})-\frac{1}{m*C_p}(Q') \quad (3.33)$$

Equation 3.33 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:

$$T_c(t+\Delta t)=T_c(t)+\Delta t*\frac{dT_c}{dt} \quad (3.34)$$

It should be noted that the solution of Equation 3.33 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 3.1 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 3.1, 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:

$$\begin{aligned} T_c - T_a = {} & (M + QTR - QRS) * R_{1c} + \Delta M * V_m * R_{2c} - Q_{ev.} * A_{ev.} * R_{3c} - \\ & (T_s - T_a) * R_{3c} / R_{ea} \end{aligned} \tag{3.35}$$

Where, $R_{1c} = R_c + R_m + R_s + R_{a1} + R_{ic} + R_{a2} + R_{oc} + R_{amb}$ (3.36)

$$R_{2c} = 0.5 * R_m + R_s + R_{a1} + R_{ic} + R_{a2} + R_{oc} + R_{amb} \tag{3.37}$$

$$R_{3c} = R_{a1} + R_{ic} + R_{a2} + R_{oc} + R_{amb} \tag{3.38}$$

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:

$$R_c = \frac{\Delta x_c}{k_c * A} \tag{3.39}$$

$$R_m = \frac{\Delta x_m}{k_m * A} \tag{3.40}$$

$$R_s = \frac{\Delta x_s}{k_s * A} \tag{3.41}$$

$$R_{a1} = \frac{1}{\dfrac{k_{ai} * A_{ccond.}}{\Delta x_{si}} + \dfrac{\sigma * A_{crad.} * (T_s^{\,2} + T_{1i}^{\,2}) * (T_s + T_{1i})}{\dfrac{1}{\varepsilon_s} + \dfrac{1}{\varepsilon_{ic}} - 1}} \tag{3.42}$$

$$R_{ic} = \frac{\Delta x_{ic}}{k_{ic} * A_{ccond.}} \tag{3.43}$$

$$R_{a2} = \frac{1}{\dfrac{k_{ao} * A_{ccond.}}{\Delta x_{ioc}} + \dfrac{\sigma * A_{crad.} * (T_{1o}^{2} + T_{2i}^{2}) * (T_{1o} + T_{2i})}{\dfrac{1}{\varepsilon_{ic}} + \dfrac{1}{\varepsilon_{oc}} - 1}} \tag{3.44}$$

$$R_{oc} = \frac{\Delta x_{oc}}{k_{oc} * A_{ccond.}} \tag{3.45}$$

$$R_{amb} = \frac{1}{h * A_{cconv.} + \sigma * \varepsilon_{oc} * A_{crad.} * (T_{2o}^{2} + T_{a}^{2}) * (T_{2o} + T_{a})} \tag{3.46}$$

$$R_{ea} = \frac{1}{h * A_{uconv.} + \sigma * \varepsilon_{s} * A_{urad.} * (T_{s}^{2} + T_{a}^{2}) * (T_{s} + T_{a})} \tag{3.47}$$

Similarly for calculating T_s following equations are required:

$$T_s - T_a = \frac{(M + \Delta M * V_m + QTR - QRS - Q_{ev.} * A_{ev.}) * R_c'}{1 + \dfrac{R_c'}{R_{ea}}} \tag{3.48}$$

Where, $R_c' = R_{a1} + R_{ic} + R_{a2} + R_{oc} + R_{amb}$ (3.49)

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

$$T_{2o} - T_a = (M + \Delta M * V_m + QTR - QRS - Q_{ev.} * A_{ev.}) * R_{amb} - \frac{(T_s - T_a) * R_{amb}}{R_{ea}} \tag{3.50}$$

3.5.2 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:

$$Q' = h * A_{uconv.} * (T_s - T_a - \Delta T) + \sigma * A_{urad.} * \varepsilon_s * [(T_s^{4} - (T_a + \Delta T)^{4}] \tag{3.51}$$