Old Dominion University Research Foundation

DEPARTMENT OF MECHANICAL ENGINEERING
COLLEGE OF ENGINEERING AND TECHNOLOGY
OLD DOMINION UNIVERSITY
NORFOLK, VA 23529

THERMODYNAMIC MODELING AND ANALYSIS OF HUMAN STRESS RESPONSE

By
S. C. Boregowda, Graduate Research Assistant
and S. N. Tiwari, Principal Investigator
Department of Mechanical Engineering

FINAL REPORT
For the period ending October 21, 1999

Prepared for
NASA Langley Research Center
Attn.: Dr. Alan T. Pope
Technical Officer
Mail Stop 152
Hampton, VA 23681-2199

Under
NASA Cooperative Agreement NCC-1-254
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ABSTRACT

A novel approach based on the second law of thermodynamics is developed to investigate the psychophysiology and quantify human stress level. Two types of stresses (thermal and mental) are examined. A Unified Stress Response Theory (USRT) is developed under the new proposed field of study called Engineering Psychophysiology. The USRT is used to investigate both thermal and mental stresses from a holistic (human body as a whole) and thermodynamic viewpoint. The original concepts and definitions are established as postulates which form the basis for thermodynamic approach to quantify human stress level. An Objective Thermal Stress Index (OTSI) is developed by applying the second law of thermodynamics to the human thermal system to quantify thermal stress or discomfort in the human body. The human thermal model based on finite element method is implemented. It is utilized as a "Computational Environmental Chamber" to conduct series of simulations to examine the human thermal stress responses under different environmental conditions. An innovative hybrid technique is developed to analyze human thermal behavior based on series of human-environment interaction simulations. Continuous

monitoring of thermal stress is demonstrated with the help of OTSI. It is well established that the human thermal system obeys the second law of thermodynamics. Further, the OTSI is validated against the experimental data. Regarding mental stress, an Objective Mental Stress Index (OMSI) is developed by applying the Maxwell relations of thermodynamics to the combined thermal and cardiovascular system in the human body. The OMSI is utilized to demonstrate the technique of monitoring mental stress continuously and is validated with the help of series of experimental studies. Although the OMSI indicates the level of mental stress, it provides a strong thermodynamic and mathematical relationship between activities of thermal and cardiovascular systems of the human body.

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A	area, cm^2
BP	blood pressure, mm of Hg
CO	cardiac output, cm^3/hr
C_p	specific heat or heat capacity, J/g-° C
c	moisture concentration in air, g/cm^3
D_{AB}	mass diffusivity of water in dry air, cm^2/hr
E_{CNV}	convective heat loss from the skin surface, J/sec
E_{RAD}	radiative heat loss from the skin surface, J/sec
E_{EVAP}	evaporative heat loss from the skin surface, J/sec
E_{RES_CNV}	convective heat loss due to respiration, J/sec
E_{RES_EVAP}	evaporative heat loss due to respiration, J/sec
HR	heart rate, beats per minute (bpm)
h	surface heat transfer coefficient, J/hr-° C-Cm^2
h_{fg}	latent heat of vaporization, J/g
h_m	mass transfer coefficient along the respiratory tract, cm/hr
I_{cl}	thermal resistance of clothing ensemble, dimensionless
K	thermal conductivity, J/hr-cm-° C
Le	Lewis number

M	metabolic rate of the entire body, J/hr
M_{shiv}	increase in metabolic rate due to shivering, J/hr
m_{res}	moisture transfer rate between the air in the respiratory tracts and the surrounding tissue, cm^2/hr
m_{sw}	sweat rate of the entire body, J/hr
N	shape functions or number of nodes
OBT	oral body temperature, °C
OMSI	objective mental stress index, beays, mm Hg/min. °C
OTSR	objective thermal stress response, J/sec/K
OTSI	objective thermal stress index, %
P	pressure or vapor pressure, kPa, mm Hg
Q, q	heat transfer rate, J/hr-cm, J/hr-cm^2
q_m	internal heat generation by metabolic reactions per unit volume of tissue, J/hr-cm^2
Rd	thermal resistance, cm^2-°C-hr/J
R_{H20}	gas constant for water vapor, J/g-°C
RH	relative humidity
RQ	respiration quotient
r, θ, z	coordinates along three cylindrical axes
r_0	blood vessel radius, cm
r, R	radius or radial distance from the center of the cylinder
T	temperature, °C
T_{core}	core temperature, °C

T_m	mean radiant temperature, ° C
T_{shiver}	shivering threshold, ° C
T_{skin}	skin temperature, ° C
t	time, hr
U	internal energy, J
V,v	velocity, cm/hr
V	heat loss by respiration or volume, J/hr or cm^3
V_b	volumetric blood flow rate, cm^3/hr
V_{O2}	volumetric oxygen consumption rate cm^3/hr
w	humdity ratio, g H_2O/g dry air
w_b	volumetric blood flow rate in the capillary bed, cm^3/hr
Z, x	coordinate or length along axial direction of 1-D elements

Greek Symbols

α	fraction of the total body mass in the skin node
μ	viscosity
ρ	density, g/cm^3; also reflectivity
σ	Stefan-Boltzman constant, J/hr-cm-° C^4
τ	transmissivity
φ	relative humidity
ΔS	total entropy change in the human body, J/sec/K
Δt	time step size, hr

CHAPTER I

INTRODUCTION

The present chapter provides an introduction to the thermodynamic study of human body. In Sec. 1.1, the motivation behind the research activity is presented. A detailed review of the literature is outlined in Sec. 1.2. Finally, objectives of the study are presented in Sec. 1.3.

1.1 Motivation

During the past several years, various studies have been conducted to examine the stress level in aircrew and other system operators. The Crew Hazardous and Error Management (CHEM) group at NASA Langley Research Center examines various aspects of aerospace flight that involves the development of human response measurement technologies to assess the mental loading, attention, and vigilance capabilities of the crew. Several studies have shown the deleterious effects of stress on human attention and vigilance capabilities thus creating a need for design and development of stress-proof systems for optimal safety and performance.

Stress has long been the subject of psychological and physiological interpretation. In fact, more often than not, the word itself is not well-defined and has been overused, meaning different things to different people. In human factors engineering, stress is considered as a reaction to what is perceived to be a threat to either the individual's security or his/her accomplishment of the assigned task [1]*. Stress may also be a response to a physical condition, like excessive heat or cold, that challenges the body's protective mechanisms. Stressors arise from several sources such as environmental conditions, risk of physical harm, and heavy mental workload or information overload. Thermal stress, for example, is a property of the physical environment which is a result of exposure to extreme hot or cold conditions. Whereas, mental stress can come about as a result of a stressful cognitive task. If the individual is using a machine, then mental stress becomes a property of the machine. In the context of the present study, stress is expressed as a function of the physiological output produced by the individual in response to a stressor. The type of stress experienced by the human being depends on the nature of the stressor. If the stressor is thermal environment, then the resulting physiological changes in an individual indicate a thermal stress. While, the changes in physiological responses to information processing or mental workload will indicate mental stress. The individual is assumed to be interacting with both environment and machine simultaneously.

There is a growing interest in the thermal aspects of the environmental condition and its effects of human thermal stress. With regard to academic interest, it poses some challenging problems that require the expertise of researchers from different fields such as Engineering, Psychology, Physiology, and Medicine. In many cases, one specialist does not know what the other specialist is doing. The need to bridge this gap between the academic disciplines is one of the motivating factors behind the present work.

*The numbers in brackets indicate references; the format used is a combination of the AIAA and ASME Journal format.

Human attention, vigilance, and perceptual capabilities will be at its peak during the state of thermal comfort. Human thermal comfort is a strong function of both psychological and physiological factors. Thermal comfort is influenced by environmental and physical factors such as air temperature, humidity, air movement, physical activity, and clothing. According to ASHRAE standard 55-66 [2], human thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment." However, there is no accurate method to quantitatively determine the effect of thermal environmental condition on comfort feeling in a human being. Therefore, there is a strong need to develop objective measure of thermal stress that would quantitatively provide an indication of thermal comfort in the form of a single summative number.

Due to rapid increase in the degree of automation of human-machine systems, human operators spend less time actively controlling such systems and more time passively monitoring system functioning. As a result of this high level of automation, the manual work is replaced by prolonged static work, which requires usage of only a small group of muscles, often in a fixed position at an intense working rate. This causes mental tension requiring a high degree of accuracy, a stress situation the human being is not ideally equipped to endure or to cope with [2]. According to Rodahl [3], the metabolic events and the organic stress at the cellular level are extremely different in the two situations: manual labor and mental work. Thus, it is established by Hockey [4] that energetical factors play an extremely important role in the regulation of information processing. The information processing is traditionally characterized as non-physical in nature and is called either mental workload or mental effort as mentioned earlier. But there are completely reliable yardsticks against which individual response to stressor may be measured. Several theoretical and experimental studies have demonstrated the relationship between physiological responses and mental workload [5, 6]. However, there is a need to combine these different physiological responses using a closed form deterministic equation based on a fundamental scientific theory to quantify mental stress.

Further, the effects of both thermal and mental stresss have been recognized to cause degradation of human performance. However, currently there is no unified theory that provides a quantitative approach to determine the effects of different forms of stress such as thermal and mental stress on the performance capability of system operators to enhance the safety of human-machine-environment systems.

1.2 Literature Review

Numerous studies have been conducted to investigate the effects of thermal environment and mental workload on human physiological responses. In this section, studies pertaining to thermal stress and mental stress have been reviewed separately for the sake of convenience. The literature review is mainly focused on the studies related to the development of stress indices to quantitatively indicate the level of thermal stress or mental stress

1.2.1 Thermal Stress

A thermal stress index is traditionally defined as one which combines two or more parameters, such as air temperature, mean radiant temperature, humidity, or air velocity into a single variable [7]. Thermal or environmental stress indices may be classified according to how they are developed. Rational indices are based on the theoretical concepts presented earlier. Empirical indices are based on measurements with subjects or on simplified relationships that do not necessarily follow any theory. Indices may also be classified according to their application, generally either heat stress or cold stress. Although many stress indices have been developed, none of them have been found satisfactory [8]. In developing the criteria for a thermal stress index, it is important that the following factors be considered [8]:

1. The index should be quantitative and yield scalar values relating to thermal stress and physiological strain.
2. The index should be calculated from available data concerning the conditions that are present in the thermal environment.
3. The index should be tested and proved applicable through use.
4. All important factors should be in the index.
5. The method should be simple to use and not lead to rigorous calculation or difficult measurements.
6. All factors should be related to physiological strain in a weighted manner.
7. The method should be applicable and feasible for determining regulatory limits or threshold values for exposure to heat or cold stress.

In addition to these seven factors, the index should be a rational one based on fundamental scientific theory [9]. Some of the widely used thermal stress indices are discussed below:

(1) Effective Temperature

There are two indices of effective temperature, both of which were developed under the sponsorship of the American Society of Heating, Refrigerating, and Air-Conditioning (ASHRAE). The original effective temperature (ET) scale was developed in 1920s as an empirical sensory index, combining into a single value the effect of temperature and humidity on thermal sensations, with an adjustment for the effects of air movement [10]. It was developed through a series of experimental studies on human subjects. The test subjects were placed in a climatic chamber in still air, at a given temperature, and with 100% relative humidity. They were required to note their impressions of the temperature and to remember them. Then the relative humidity was reduced and temperature varied until the test subjects felt the same sensation of warmth as before [11]. This original ET scale has been demonstrated to overemphasize the effects of humidity in cool and neutral conditions and to underemphasize its effects in warm conditions. Also, it does not fully account for air movement in hot-humid conditions. Therefore, under the sponsorship of ASHRAE, a new effective temperature (ET^*) scale was developed [7]. It is mathematically defined as follows:

$$ET^* = T_o + wi_m \, LR \, (P_a - 0.5 \, P_{ET^*,s}) \qquad (1.1)$$

where,

T_o = operative temperature, average of the mean radiant and ambient temperatures weighted by their respective heat transfer coefficients,

w = skin wettedness,

i_m = moisture permeability index,

LR = Lewis Ratio = evaporative heat transfer coeff./convective heat transfer coeff,

P_a = ambient partial vapor pressure.

The ET^* is the temperature of an environment at 50% relative humidity (RH) that results in the same total skin heat loss as in the actual environment. The human body is in a state of thermal neutrality with respect to regulatory (sensible) heat loss when the dry bulb temperature is about 77°F (25°C) and RH is 50% [10]. Holding RH constant at

50%, higher or lower air temperatures would alter the evaporative process, thus affecting the levels of skin wettedness at various temperatures. The ET^* scale is essentially based on the resulting levels of wettedness. However, any given level of skin wettedness can be produced by different combinations of dry-bulb temperature and RH, and those combinations that produce the same level of wettedness then have the same ET^* value. Since ET^* is defined in terms of operative temperature (T_o), it combines the effect of three parameters, mean radiant temperature (T_{mrt}), dry-bulb or air temperature (T_a), and ambient partial vapor pressure (P_a) into a single index. At the upper limit of regulation, w approaches 1.0 and at lower limit, w approaches 0.06; skin wettedness equals one of these values when the body is outside the zone of evaporative regulation. Since, ET^* is a function of skin wettedness and clothing moisture permeability, the effective temperature for a given temperature and humidity depends on physical activity and clothing. This makes it impossible to generate a universal ET^* chart. One of the other limitations of the effective temperature index is its empirical nature. Also, it is developed on the basis of subjective assessment of the human/thermal environment interaction. Although it is partially based on the principle of energy balance between the human body and the environment, it lacks the basis of a sound scientific theory. Further, calculation of ET^* is quite tedious, requiring the solution of multiple coupled equations to determine skin wettedness.

(2) Heat Stress Index (HSI)

The Heat Stress Index was originally developed by Belding and Hatch [12], and it has been modified by Hatch [13] and Hertig and Belding [14]. This rational index is the ratio of the total evaporative heat loss (E_{skin}) from the skin surface required for thermal equilibrium (the sum of metabolism and dry heat load) to the maximum evaporative heat loss (E_{max}) possible for the environment, multiplied by 100, for steady-state conditions, and with skin temperature held at 35° C. The index is mathematically defined as follows:

$$HSI = (E_{skin} / E_{max}) \times 100 \tag{1.2}$$

When HSI is greater than 100, body heating occurs; when HSI is less than zero, body cooling occurs. Two important physiological criteria in the HSI concept are (i) in order to limit rise of body temperature, average skin temperature should not exceed 95° F, and (ii) in order to limit the loss of body fluids, the sweat rate should not exceed one liter per hour (2400 Btu/hr). HSI is very restricted in its applicability because it can be used only for steady-state conditions. Also, due to emphasis on sweating aspect, it gives only the measure of heat stress. Further, it is an empirical index and excludes all the physical factors like air temperature, RH, physical activity, and clothing.

(3) Wet-Bulb Globe Temperature (WBGT)

The WBGT is an environmental heat stress index that combines dry-bulb or air temperature (T_a), a naturally ventilated (not aspirated) wet-bulb temperature (T_{nwb}), and black globe temperature (T_g). According to the relationship developed by Dukes-Dobas and Henschel [7], it is expressed as

$$WBGT = 0.7\ T_{nwb} + 0.2\ T_g + 0.1\ T_a \tag{1.3a}$$

This form of equation is usually used where solar radiation is present. The naturally ventilated wet-bulb thermometer is left exposed to the sunlight, but air temperature sensor is shaded. In enclosed environments, Eq. (1.3a) is simplified as follows:

$$WBGT = 0.7\ T_{nwb} + 0.3\ T_g \qquad (1.3b)$$

The black globe thermometer is responsive to air temperature to air temperature, mean radiant temperature, and air movement, while the naturally ventilated wet-bulb thermometer responds to air humidity, air movement, radiant temperature, and air temperature. Thus, WBGT is a function of all four environmental factors affecting human thermal stress. Although WBGT is a better index of heat stress than the old ET, but it does not relate to any physiological responses or strain. Further, it is an empirical index developed from subjective analysis of thermal environment.

(4) Wind Chill Index (WCI)

The wind chill index (WCI) is an empirical index developed from cooling measurements obtained in Antarctica on a cylindrical flask partly filled with water [7]. The index describes the rate of heat loss from the cylinder by radiation and convection for a surface temperature of 33 ° C, as a function of ambient temperature and wind velocity. The equation is proposed as follows [5]:

$$WCI = (10.45 + 10\ v^{0.5} - v)\ (33 - T_a) \qquad (1.4)$$

where v and T_a are in m/s and ° C respectively. The 33 ° C surface temperature was chosen to be the representative of the mean skin temperature of a resting human. This index has severe limitations due to the fact that measurements were taken on a 57 mm diameter plastic cylinder. This makes it unlikely that WCI would be an accurate measure of heat loss from the human body.

(5) Predicted Mean Vote (PMV)

Traditionally, thermal comfort has been considered as a "condition of mind," which requires empirical equations to relate the perception of comfort to specific responses [7]. In addition to the primary environmental and personal factors influencing thermal response and comfort, factors like nonuniformity of the environment, visual stimuli, age, outdoor climate, etc. may also have some effect, but are generally considered to be secondary factors.

Large scale studies conducted by Rohles and Nevins [16] and Rohles [17] on 1600 college-age students revealed statistical correlations between comfort level, temperature, humidity, sex, and length of exposure. A regression equation from these studies for predicting thermal sensations from air temperature and vapor pressure for both men and women combined for one-hour exposure is selected from the set of equations provided [7]. The equation is as follows:

$$PMV = 0.245\ T_a + 0.248\ P_a - 6.475\ ) \qquad (1.5a)$$

where, T_a = dry-bulb or air temperature (° C), P_a = ambient vapor pressure (kPa). Vapor pressure is used rather than conventional relative humidity. This equation is valid for young adult subjects with sedentary activity and wearing clothing with a thermal resistance of approximately 0.5 clo, mean radiant temperature equals air temperature, and air velocities are less than 0.2 m/s.

The thermal sensation scale used in this equation is referred to as the ASHRAE thermal sensation scale or PMV scale. This scale is as follows:

+ 3 Hot
+ 2 Warm
+ 1 Slightly Warm
0 Neutral
- 1 Slightly Cool
- 2 Cool
- 3 Cold

The PMV index predicts the mean response of large group of people according to the ASHRAE thermal sensation scale. Fanger [2] related PMV to imbalance between the actual heat flow from the body in a given environment and the heat flow required for optimum comfort at the specified activity by the following equation:

$$PMV = [0.303 \exp(-0.036 M) + 0.028] L \tag{1.5b}$$

where L is the thermal load on the body defined as the difference between the internal heat production and heat loss to the actual environment for a person hypothetically kept at comfort values of skin temperature and sweat rate at the actual activity level.

In developing this index, the comfort data has been related to physiological variables, which leads to the fact that index is semi-empirical and statistically based. At a given level of metabolic activity M, and when the body is not far from thermal neutrality, mean skin temperature and sweat rate are the only physiological parameters influencing the heat balance. The heat balance technique alone is not sufficient to establish thermal comfort [7]. On the wide range of environmental conditions where heat balance can be obtained, only a narrow range provides thermal comfort. Thus, PMV is limited in its application to a narrow range of environmental conditions and to only steady-state analysis of thermal comfort.

It can be concluded that all of the previous studies that have led to the development of thermal stress indices were either statistically based or at most used the energy balance principle from first law of thermodynamics. However, Aoki [18, 19] was the first to introduce the concept of entropy in human thermal physiology. In these studies, he calculated the entropy production in the human body under basal conditions and during exercise. The limitation of this study lies in the fact that only static experimental data is used to verify the second law of thermodynamics and the issue of thermal comfort or stress is not at all addressed. So far, there has been only one study conducted by Boregowda et al. [9] dedicated to the development of an Objective Thermal Stress Index (OTSI), a global measure of thermal stress from a thermodynamic standpoint based on the second law of thermodynamics applied to the human thermal system.

1.2.2 Mental Stress

Several studies have been conducted to examine the relationship between psychological and physiological processes [20]. Among these investigations, the ones relevant to the field of human factors engineering research include the studies that demonstrate the effects of information processing or mental workload on physiological responses to assess the human performance and efficiency in human-machine systems.Thus, the present literature review is mainly focussed on studies related to physiological responses to mental workload.

Mental stresses cause a wide range of effects. As discussed by Hancock et al.[5] and Mital and Mital [6], these could be physiological (elevated heart rates, blood pressure, etc.) or psychological (lack of attention, boredom, anxiety, etc.). Increases in heart rate [21 - 23], changes in blood pressure [24], body temperature [25, 26], and skin temperature

[27, 28] are some of the physiological responses to mental workload. There is no doubt that blood pressure is one of the responses which increases with most types of mental and physical activities. Questions that investigators are interested in, concern the amount of change, moderating effects of various kinds of mental activities, emotional and stress effects, environmental effects, and personality factors. The relationship between a number of physiological variables and mental workload was investigated by Ettema and Zielhus [29]. The physiological measures included blood pressure, heart rate, and respiration rate. The researchers manipulated the mental workload by varying the amount of information processed by subjects in a given period of time. The systolic and diastolic blood pressure showed systematic increases as information-processing load increased. The same was true for heart rate and respiration rate. It was concluded in this study [29] that increased cardiovascular and respiratory functions are useful indices giving the measure of mental workload which may be important in assessing different aspects of cognitive tasks. The effects of solving difficult problems on blood pressure and other cardiovascular measures was studied by McCubbin et al. [30].

Several different methods have been used to quantify mental stress. These may be classified as physiological and psychological. The efforts to quantify mental stress range from measuring the cause of stress to measuring the individual's reaction to stress [31]. Physiological methods of measuring mental stress include measurement of heart rate, blood pressure, and oral body temperature [6, 32]. Questionnaires and interviews (psychological methods) have also been used to measure the individual's reaction to different kinds of stresses [33, 34]. Measurement of the concentration of attention has also been used as a measure of mental stress [35]. Despite all these efforts, an accurate method to quantify mental stress has not been developed. One of the major drawbacks in all these studies is that only one physiological variable is used an indicator of mental stress. Since, human body comprises of many interconnected physiological processes controlled by a complex nervous system, these single physiological indicators of stress provide a very narrow representation of the human response. There has been no effort made to combine these physiological responses such as blood pressure, heart rate, and body or skin temperature in the form of an equation to form an index that provides an overall objective measure of mental stress. However, the studies conducted by Boregowda et al. [36 - 39] are quite unique in which an objective stress index to quantify mental stress has been developed on the basis of Maxwell relations and second law of thermodynamics as applied to the human body. Further, this objective stress index is validated in a clinical study by Palsson et al. [40].

1.3 Objectives

After reviewing the literature relevant to thermal stress, it is apparent that the search for a universal thermal stress index has been vigorously pursued for the past half century. The people who have been part of this search include Engineers, Psychologists, Physiologists, and Physicians. Each one of them have their own objective, unique to their professional and research interests. Engineers began their search in 1920s by developing methods to predict the thermal stress response of occupants to temperature and humidity in building enclosures with the newly developed central heating and air conditioning systems. Psychologists emphasize in knowing about thermal sensations of warmth and cold that relate to the thermal environment. On the other hand, Physiologists deal with the effects of thermal environment on the body temperature regulation. They are mainly interested in examining the effector processes necessary for thermoregulation (i.e., sweating, vascular changes, shivering, and behavioral changes) which affect human judgements of heat and cold [41]. Finally, the Physician is interested in the impact of extreme heat and cold on the health and well-being of human beings.

All of these professional groups have at one time or another developed indices of thermal stress or comfort, of heat and cold tolerance, and of performance to meet their own professional and research needs. As a result of this division among the disciplines, earlier indices developed on the basis of subjective assessment of thermal sensations to the thermal environment are acceptable to Engineers and Psychologist, but not fully acceptable to Physiologists. This is because Physiologists have recognized that thermal sensation is associated with thermoregulatory responses like sweating, vascular changes, and shivering. Thus, there is a lot of confusion and disagreement among these different research groups which is hindering their progress in research activity to develop a universal index mainly due to lack of a unified approach. One of the major objectives of the present study is to overcome this problem by introducing a unified approach to develop an **Objective Thermal Stress Index (OTSI)** based on the second law analysis of human thermal system. In this regard, a unified field of study called **Thermal Environmental Psychophysiology** is defined which would be acceptable to researchers in different fields like engineering, psychology, physiology, and medicine to clearly examine **human-thermal environment** interaction.

The literature review concerning mental stress reveals the fact that there is no accurate method to quantify mental stress. There is a situation similar to that in thermal stress, with regard to search for a universal index to quantify mental stress. The search has been going for last fifty years since Selye [42] introduced the concept of stress to the scientific community. Numerous approaches have been devised by Engineers, Psychologists, Physiologists, and Physicians to quantify mental stress depending on their needs. For instance, Engineers are mainly interested in the effects of stress on human performance and eventually safety of the system. Psychologists focus on behavioral and cognitive aspects, showing little interest in physiology and performance. On the other hand, Physiologists emphasize on effects of exercise and physical stress on regulatory mechanisms, thus showing less interest in engineering and psychological aspects of stress. However, a new breed of professionals called Engineering Psychologists (sometimes called Human Factors Engineers or Ergonomists) combine different aspects of engineering and psychology to understand better the effects of mental work load on both behavioral and performance capability of human beings. This group of Engineering Psychologists underemphasize the impact of stress on physiological responses. Finally, Physicians and Clinical Psychologists who work in the primary care are mainly interested in the deleterious effects of stress on health and diseases.

This division in the stress research community has resulted in the lack of a unified approach to come up with a universal index to quantify mental stress. Although numerous studies have been conducted in the past to assess the impact of mental workload or information processing by different researchers, there has been no accurate method to quantify mental stress. The second objective of the present study is to develop an **Objective Mental Stress Index (OMSI)** to bridge the gap by applying the Maxwell relations and second law of thermodynamics to the human psychophysiological system. In order to create a common platform for different researchers, a new unified field of study called **Cognitive Psychophysiology** is introduced to understand better the **human-machine** interaction.

The two fields of Thermal Environmental and Cognitive Psychophysiology are combined together to form an academic discipline called **Engineering Psychophysiology**. This field is expected to investigate different aspects of human-machine-environment interaction using three-legged approach. Later, by combining the methods to quantify thermal stress and mental stress, a **Unified Stress Response Theory (USRT)** is developed. The USRT provides a universal approach to quantify human stress level based on a strong scientific theory. The second law of thermodynamics, being the basis of USRT, forms the underlying principles for the formulation of OTSI and OMSI.

In order to validate OTSI and OMSI, the human thermal responses and other measures like blood pressure, and heart rate have to be obtained by simulation or experimental methods. A human thermal model based on finite element method [43, 44] is implemented to obtain human thermal responses to different environmental conditions, physical activity, and clothing. The human thermal model is validated against the experimental data for conducting further simulations. Thus, human thermal model is utilized as a **"Computational Environmental Chamber"** to conduct a series of simulations to examine the human thermal behavior under different conditions. In order to develop an efficient method for conducting human thermal experiments, a **hybrid technique** combining the theory of experimental design [45, 46] and entropy approach is implemented. The transient analysis of human thermal system provides moment-to-moment values of OTSI. The OTSI is validated against the regression equation for Predicted Mean Vote (PMV) obtained from a large scale experimental study [7]. Physiological data from an existing experimental study is used to test the concept of OMSI. Also, a pilot study at NASA Langley Research Center is conducted to demonstrate the technique of mental stress level monitoring and some important psychophysiological concepts. Finally, a clinical study is conducted in the Division of Behavioral Medicine of Eastern Virginia Medical School to validate OMSI for clinical use.

The present study is organized in the following manner. Different areas of application are discussed in Chap. 2. Chapter 3 discusses thermodynamic theory behind the objective stress indices and psychophysiology of human stress responses. The formulation of human thermal model which includes the description of physical model, governing equations, and method of solution are presented in Chap. 4. In Chap. 5, detailed formulation of OTSI and OMSI are provided. The results are presented and discussed in Chap. 6. Finally, concluding remarks on thermodynamic modeling and analysis of human stress responses are provided in Chap. 7.

CHAPTER II

APPLICATIONS

In this chapter, some practical human factors engineering and medical applications for the implementation of objective measures of stress level are presented. In Sec. 2.1, the feasibility of using Objective Thermal Stress Index (OTSI) in the area of Environmental Ergonomics is discussed. The use of objective stress indices in transportation and aerospace applications for enhancing safety and performance is presented is Sec. 2.2. Finally, some medical applications related to the emerging fields of Psychophysiology and Behavioral medicine are outlined in Sec. 2.3.

2.1 Environmental Ergonomics

Ergonomics is the application of scientific principles, methods, and data drawn from a variety of disciplines to the development of engineering systems in which human beings play a significant role [47]. The field of ergonomics which specializes in the study of interaction between humans and physical environment is called **Environmental Ergonomics**. The present study pertains to the study of impact of thermal environment on human thermal responses which determine the performance capability.

The innate nature of human beings to maintain homeothermic state makes them unique with ability to "bioengineer" the environment to protect from the thermal extremes. Despite the human ability to engineer comfort over a wide range of ambient conditions, human being still faces the challenge to quantify the range of deviations from thermal equilibrium. This limitation is overcome with the use of Objective Thermal Stress Index (OTSI) which quantitatively represents the processes taking place in psychological and physiological domains of human being in response to changes in thermal environment. The OTSI has the potential to become a "product" and could be sold to the HVAC industry that is responsible for maintaining indoor climate in aerospace and civilian environmental control systems. OTSI would provide a measurement standard that takes into account both environmental variables and human thermal responses. Also, it could be used in performing the transient analysis of cabins in high speed mass transit vehicles where there is a rapid turnover of passengers in very short time intervals.

2.2 Aviation Safety

During the recent years, with growth of demand for air travel, there has been a lot of research emphasis to achieve maximum aviation safety. The field of aviation safety includes all kinds of aerospace vehicles and a wide spectrum of technologies. Human factors issues are important because individuals must interact with the large, complex automated systems of modern forms of aviation systems. Air accidents receive wide publicity due to loss of lives, high insurance and other related costs. Investigations of aviation mishaps typically invoke contributory human factors issues, thus enhancing research opportunities [48].

Human error accounts for more than 70% of all aviation accidents. Thus, the Crew Hazardous and Error Management (CHEM) group at NASA Langley Research Center is working an "error proof" flight deck. There is a strong need to build "human-centered" flight decks for superior flight management and maximum safety. In order to achieve this goal, the quantitative measures of excessive information processing or mental overload are important to assess their effects on physiological responses and thus human behavior. In this regard, Pope et al [49] conducted a study to examine the impact of information processing on brain activity. In this study, an Engagement Index (EI) which combines different kinds of brain waves like alpha, beta, and theta was developed. The EI is based on a valid equation and it provides a quantitative measure of human attention and vigilance capability. In contrast to this approach, the present study employs Objective Mental Stress Index (OMSI) to provide a quantitative measure of mental stress in terms of physiological responses like blood pressure, heart rate, and skin or core temperatures. The OMSI indicates the impact of information processing on human performance; thus, it would play a key role in the design of human-machine systems, ultimately leading to the "human-centered error-proof and stress-proof" flight decks.

Finally, several studies by Hancock [50] establish the fact that uncomfortable thermal environmental conditions degrade human performance. Hancock and Pierce [51] have related attention and vigilance to changes in ambient environment. It has been shown that sustained attention is disturbed by conditions sufficient to induce a change in human thermal equilibrium. At this point of perturbation to thermal equilibrium, resulting state drains attentional resources and thus reduces vigilance capability. The OTSI could be utilized as an objective measure of deviation from thermal equilibrium to quantify the drain in attentional resources and reduction in vigilance capability. Also, OTSI could be employed in a rapid descent scenario of a High Speed Civil Transport (HSCT) plane to quantify the effects of rapidly changing thermal environment on physiological responses of aircrew and passengers. This methodology would lead to the development of a safety standard for designing a robust environmental control system.

2.3 Psychophysiology and Behavioral Medicine

Psychophysiology is the study of relations between psychological manipulations and resulting physiological responses, measured in the living organism, to promote understanding of the relation between mental and bodily processes [20]. In other words, the field of psychophysiology is concerned with the measurement of physiological responses as they relate to the behavior. In this regard, Wickramasekara [52] defines Behavioral Medicine as the interfacing of behavioral and biomedical sciences in the areas of research, diagnosis, prevention, and therapy of physical diseases and dysfunctions. While the field of Psychophysiology focuses mostly on basic research and some applications, Behavioral medicine emphasizes on actual treatment of physical diseases or disorders caused due to psychological stresses.

The behavioral medicine revolution originates from various changes that have taken place in the health care during the past century. In the past, most of the deaths and diseases occurred due to biochemical and microbial agents (eg., plague, small pox, polio, etc.). The development of vaccines, antibiotics, and immunzation procedures, the public health treatment of water and sewage, and the sterile surgical procedures have eradicated these diseases. In contrast to the past, today's diseases and deaths are caused by chronic-stress-related disorders such as heart attacks, strokes, cancer, pulmonary diseases, diabetes, automobile accidents, and alcoholism [52]. With regard to these stress-related modern day diseases, the sources of stress and their impact on the human physiology need to identified and quantified. This is one of the major challenges facing the behavioral medicine and the field of psychophysiology. A psychophysiological profile to detect the vulnerability of different kinds of individuals to different stimuli is being well established by Wickramasekara [52]. In this profile, it has been shown that the different human beings show their vulnerabilities in different subsystems of their body. For example, one may show high cardiovascular reactivity during the stressor test indicating proneness to heart diseases, while someone else may show reactivity in skin temperature showing proneness to peripheral vascular diseases such as Raynaud's syndrome. Thus there is a strong need to identify these vulnerabilities or "window of vulnerability" to diagnose the psychological basis of a physiological disorder caused due to acute or chronic stress.

At the present time, there are no objective measures other than single physiological parameters to diagnose these diseases as stress-related ones. The present study fills the gap by developing an Objective Mental Stress Index (OMSI) to link psychological and physiological properties of the human body. The OMSI is regarded as a parameter that quantifies the mind-body interaction. A study by Boregowda and Tiwari [53] have shown the utility of both OTSI and OMSI in understanding the peripheral diseases such as diabetic neuropathy in a microgravity environment. Diabetic neuropathy, like Raynaud's disease is caused mainly due to lack of blood flow and heat transfer to the peripheral parts of limbs. In another clinical study conducted by Palsson et al. [40], it has been shown that OMSI has a great potential to become a valid index to quantify clinical stress and a measure of stress-related symptoms. In summary, OMSI would become a valid tool to quantify, detect, and diagnose the onset or cause of stress-related disorders, thus providing a global measurement standard in the area of preventive health.

CHAPTER III

THERMODYNAMICS OF HUMAN STRESS RESPONSES

Thermodynamics is the study of energy interactions in systems and surroundings in the universe. A system could be any system in the universe. In the scope of the present study, two subsystems in the human body which include thermal system and cardiovascular system are considered.

3.1 The Nervous System

The nervous system is highly complex and integrated as shown in Fig. 3.1, but for the sake of convenience, the various physiological measures which are considered to be controlled by different subsystems of the nervous system are listed in Table 3.1 [20]. The two main branches of nervous system include central nervous system (CNS) and peripheral nervous system. The CNS includes the brain and spinal cord. The peripheral nervous system refers to nervous tissue outside the brain and spinal cord, including the cranial and spinal nerves. The peripheral nervous system is further divided into the somatic system, concerned with muscular activities, and the autonomic nervous system (ANS), which controls visceral structures (glands and organs of the body).

The ANS is subdivided into the parasympathetic nervous system (PNS), which plays a major role when the individual is at rest, and the sympathetic nervous system (SNS), which is dominant in situations requiring mobilization of energy. The PNS can be thought

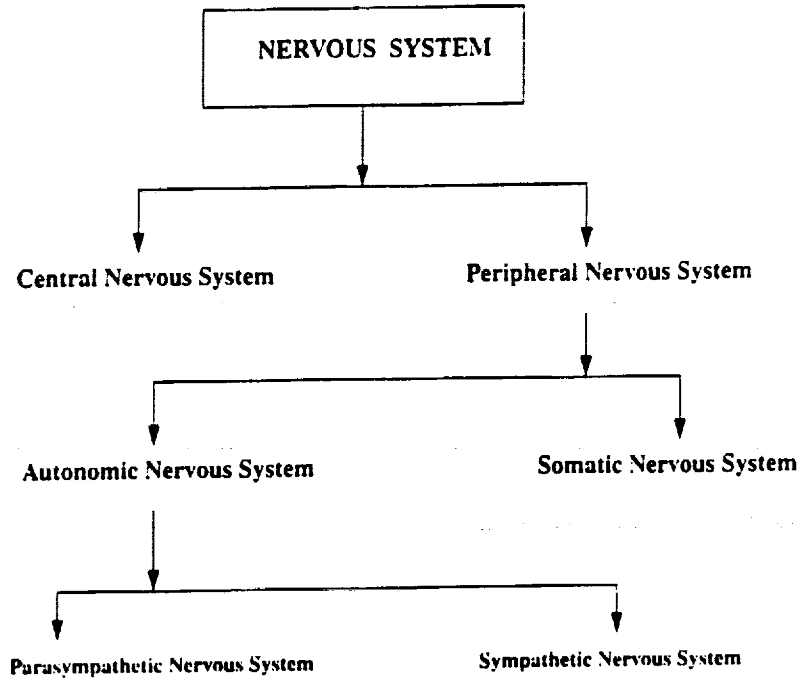


Figure 3.1 The Classification of Nervous System [20]

Table 3.1 Physiological Responses Controlled by Nervous System [20]

Central Nervous System	Autonomic Nervous System	Somatic System
Electroencephalogram (EEG) - Brain Activity	Core Body Temperature	Electromyogram (EMG)
Event-related Potentials	Skin Temperature	Electroculogram (EOG)
	Blood Pressure	
	Heart Rate	
	Blood Volume	
	Skin Conductance	
	Thermal Responses	

of as a system of rest and repair, whereas the SNS is a system of energy mobilization and work. Figure 3.1 does not provide the exact classification because some of the measures controlled by ANS are also under the control of CNS. For example, the hypothalamus and medulla of the brain are important in the control of ANS functions such as temperature regulation. Many of the physiological responses of interest are controlled by the ANS, and thus it is a very important system for the field of psychophysiology.

3.2 Homeostasis

The autonomic nervous system (ANS) is the regulator and coordinator of important bodily activities, including body and skin temperatures, blood pressure, and heart rate. These activities have traditionally been regarded to be automatic or taking place without conscious control. However, research in the area of self-regulation of physiological responses through biofeedback and other psychophysiological techniques suggests that it might be possible to alter one's own level of ANS activity [52]. In general, the main function of the ANS is to keep a constant internal body environment in the face of internal or external changes that could upset the balance. The term for the concept that describes the maintenance of a stable internal environment is **homeostasis**, coined by the physiologist Claude Bernard [20].

3.2.1 Thermal Homeostasis

With regard to human thermal system, it is well established that human beings continuously exchange heat with their environment to maintain a constant internal body temperature. This ability to compensate for disturbances, to maintain internal thermal equilibrium is called **thermal homeostasis**. The state of constant internal body temperature is called **homeothermic state**. Thus, all the human beings who possess this ability are called **homeotherms**. For a healthy, sedentary human, core temperature is typically around 37° C (98.6° F). Deviations of 2° C in core temperatures from its normal level may cause discomfort. As the core temperature rises above this narrow range, body functions begin to deteriorate, which lead to a condition called **hyperthermia**. When the body temperature falls below the normal range, it results in a condition called **hypothermia**. The maintenance of a homeothermic state is very important for the existence and support of life. The study of thermal responses of homeotherms, especially human beings occupies an important position in the fields of life sciences and human engineering.

The thermoregulatory or control system is a psychophysiological system responsible for maintaining the core temperature at a normal level by enhancing or inhibiting heat production and heat loss. **Thermoreceptors**, located in the skin, brain, spinal cord, and other sites of the body respond to both local temperature and its changes [43]. Signals from the thermoreceptors are transmitted by the central nervous system to the hypothalamus where they are integrated in a manner which is not completely understood at this time. Regardless of the relative significance of the temperature signals from the various thermoreceptor locations, the hypothalamus determines the overall thermal state of the body from these signals and issues commands that finally result in physiological responses. The details of these responses and the control system are presented in Chap. 4 (Sec. 4.1.2).

3.2.2 Cardiovascular Homeostasis

The cardiovascular responses such as blood pressure and heart rate are controlled by **baroreceptors**. The baroreceptors are pressure-sensing cells situated mainly around blood vessels in the neck region. These receptors are important in regulating blood pressure just as a thermostat regulates in a central heating system [54]. If blood pressure falls sharply, the baroreceptors will send nerve messages to quicken the heartbeat and cause constriction of blood vessels, thus leading to increase of blood pressure. Conversely, if blood pressure rises during exercise or anger, the baroreceptor will send different messages; the result will be slowing of the heart rate and vasodilation, both of which will tend to lower the blood pressure. Thus, baroreceptors play a key role in maintaining **cardiovascular homeostasis**, in a manner similar to thermoreceptors which are responsible for thermal homeostasis.

3.3 Engineering Psychophysiology

Any disturbance to homeostasis causes specific changes in physiological responses depending on the nature of stressors. The disturbances might come from diverse sources. For the present study, two major categories of stressors are identified which include (1) environmental factors that are external to the individual (outside-the-skin) and (2) internal environmental factors [55]. External events that occur outside of the skin, include factors such as environmental temperature, humidity, wind, and exposure to other weather-related variables of the physical environment. Internal events consist of complex communication network inside the skin. They are influenced by physiologic reactions to one's own thoughts, images, fantasies, and emotional states [56]. Internal events fluctuate continually as both internal and external events are processed at conscious and unconscious levels. In the context of the present study, the thermal environment and information-processing machines are the sources that lead to external and internal events respectively.

In order to address the issues related to the interaction of human beings with both thermal environment and machines, a new field of study called Engineering Psychophysiology is introduced. The field of Engineering Psychophysiology is defined under Postulate I as follows:

Postulate I. Engineering Psychophysiology is the field of study that examines the relationship between the human psychological and physical properties of the human-machine-thermal environment composite system using the second law of thermodynamics.

The engineering psychophysiology focuses on human-machine-environment interaction issues. This field is further subdivided into two groups namely: Thermal Environmental Psychophysiology and Cognitive Psychophysiology.

3.3.1 Thermal Environmental Psychophysiology

Traditionally, ecological science emphasizes the study of biological bases of energy transactions between animals and their physical environments across cellular, organismic, and population scales [57]. However, the traditional emphasis lacks the psychological emphasis and the basis of second law of thermodynamics. Thus, the present study incorporates the principles of thermodynamics to investigate the human-thermal environment interaction. The result is the creation of a new field of study called Thermal Environmental Psychophysiology which is defined under Postulate II as follows:

Postulate II. Thermal Environmental Psychophysiology is a science that involves the development of functionally dependent relationships between the psychological (thermal stress) and physical (thermal responses and environmental factors) properties of the human-thermal environment system.

One of the major objectives of creating this field of Thermal Environmental Psychophysiology is to develop parameters that would indicate human-thermal environment interaction quantitatively and provide a measure of thermal stress or discomfort experienced by humans.

3.3.2 Cognitive Psychophysiology

The main purpose of developing the field of Cognitive Psychophysiology is to discover the natural metrics of human behavior, not to uncritically import metrics from other domains of physics. In this regard, Cognitive Psychophysiology examines the impact of information-processing or mental load on the human physiology leading to the development of stress indices to indicate mental stress level. It is defined under Postulate III as follows:

Postulate III. Cognitive Psychophysiology is a study that involves the development of functionally dependent relationships between the psychological (mental stress) and physiological (blood pressure, heart rate, skin, and skin or body temperature) properties of the human-machine system.

Cognitive Psychophysiology would lead to the development of indices that would quantify the mind-body interaction in human-machine systems design. Thus, it would play a key role in the effective design of systems that will result in the improvement of safety and performance.

3.4 Unified Stress Response Theory (USRT)

When a human being is exposed to an environmental or cognitive stressor, a number of physiological changes are observed. Some of the significant changes include thermal responses, blood pressure, and heart rate. Usually, there is very little or no correlation between these various physiological measures [58]. As a result of these diverse responses, the response to stress cannot be considered as a simple response of a single system [59]. Rather, the response to a stress comprises a number of different variables and appears as a complex pattern of responses in different systems. Although numerous views about the multidimensional nature of human thermal behavior has been put forward, at present there is no unified theory that provides an approach to predict the effects of different forms of stress on human performance capability [60]. The present study fulfills this need through the development of a Unified Stress Response Theory (USRT). The USRT combines the two human subsystems (thermal system and cardiovascular system) and their corresponding stressors. It is defined under Postulate IV as follows:

Postulate IV. Human Stress is a mathematical function of both physiological strain and stressor. The stress is defined by its terminology depending on the nature of stressor, although the similar physiological reactions may be caused by different stressors or stimuli.

For example, a person may sweat due to either ambient conditions or emotional stress. The USRT is defined according to the following logic:

Human Stress = f (Physiological Strain, Stressor)

IF Stressor = Thermal Environmental Properties (T_{air}, RH)

THEN Human Stress = Thermal Stress

IF Stressor = Mental Workload or Cognitive Task

THEN Human Stress = Mental Stress

A unified theory is formulated by combining the concepts of thermal stress and mental stress. The USRT utilizes the second law of thermodynamics to analyze human thermal system and cardiovascular system to formulate Objective Thermal Stress Index (OTSI) and Objective Mental Stress Index (OMSI) which is described in Chap. 5. Both these indices are based on the second law of thermodynamics [61] which is restated under Postulate V as follows:

Postulate V. The Second Law of Thermodynamics

L. S. Carnot (1824): In any system, some loss of energy is inevitable. Complete conversion of input energy to output work is impossible. (A forecast for the existence of entropy.)

R. Clausius (1887): The amount of energy in the universe is fixed; its distribution is uneven. Conversion of a energy to work in a system produces an inevitable loss of energy to a lower energy area of the universe (entropy). Entropy increases as the energy of the universe seeks uniform distribution. The drive to attain this uniformity is the fundamental force of the universe.

All systems in the universe obey second law of thermodynamics. The two human subsystems that are being analyzed include thermal and cardiovascular systems to develop indices for quantifying thermal and mental stresses respectively. Entropy is a measure of disorder or chaos in any system in the universe [62]. The present study considers the human body as a system of interest. In this regard, human stress of the whole body is generally defined under Postulate VI as follows:

Postulate VI. Human Stress is equivalent to entropy generation and is a measure of disorder or chaos or activeness in the human psychophysiological system in response to stressors from thermodynamic and holistic (whole body) viewpoints.

3.4.1 Thermal Stress

The entropy production provides a global measure of violent motions and reactions occurring in nature. Hence, the entropy production or generation in the human thermal system shows the extent of activeness of (1) heat flows and (2) motions and reactions of substances within the body as a whole [18, 19]. Therefore, the entropy generation is a significant psychophysiological quantity which characterizes the human thermal system from thermodynamic and holistic (i.e., considering a human body as a whole) viewpoints. Thermal stress is equated to entropy generation in the human thermal system in accordance with the philosophy of Nicolis and Prigogine [63] and defined under Postulate VI as follows:

Postulate VII. Thermal Stress is defined as the measure of disorder or chaos or activeness in psychological domain as a result of physiological changes in human thermal system in response to thermal environmental stressors from a thermodynamic and holistic (whole body) viewpoints.

Thus, thermal stress is mathematically defined using a thermodynamic function in the following manner.

$$\text{Thermal Stress} = f\,(\text{Physiological Strain, Thermal Environmental Properties})$$

3.4.2 Mental Stress

If the mental workload or information processing causes changes in physiological responses that can be measured, then using thermodynamic Maxwell relations, entropy change in the absence of flow entropy indicates the level of mental stress. Also, it represents disorder in the non-physical or psychological domain of the human body. In other words, entropy change provides a quantitative measure of psychological process in terms of physiological responses to mental workload or information processing. The mental stress is defined under Postulate VIII as follows:

Postulate VIII. Mental Stress is defined as the measure of disorder or chaos or activeness in psychological domain as a result of physiological changes in both human thermal and cardiovascular systems in response to mental workload or information processing from a thermodynamic and holistic (whole body) viewpoints.

Thus, the mental stress is mathematically defined using a thermodynamic function in the following manner.

Mental Stress = f (Physiological Strain, Mental Workload)

For the sake of convenience, the postulates and definitions related to objective measures of stress level are described in Fig. 3.2. The details pertaining to the formulation of stress indices corresponding to thermal stress (OTSI) and mental stress (OMSI) are presented in Chap. 5. In order to validate OTSI, thermal stress responses are obtained by implementing a human thermal model which is described in Chap. 4. A series of computer simulations are conducted using this model to obtain thermal responses to different environmental conditions. The OMSI is validated using experimental data described in Chap. 6.

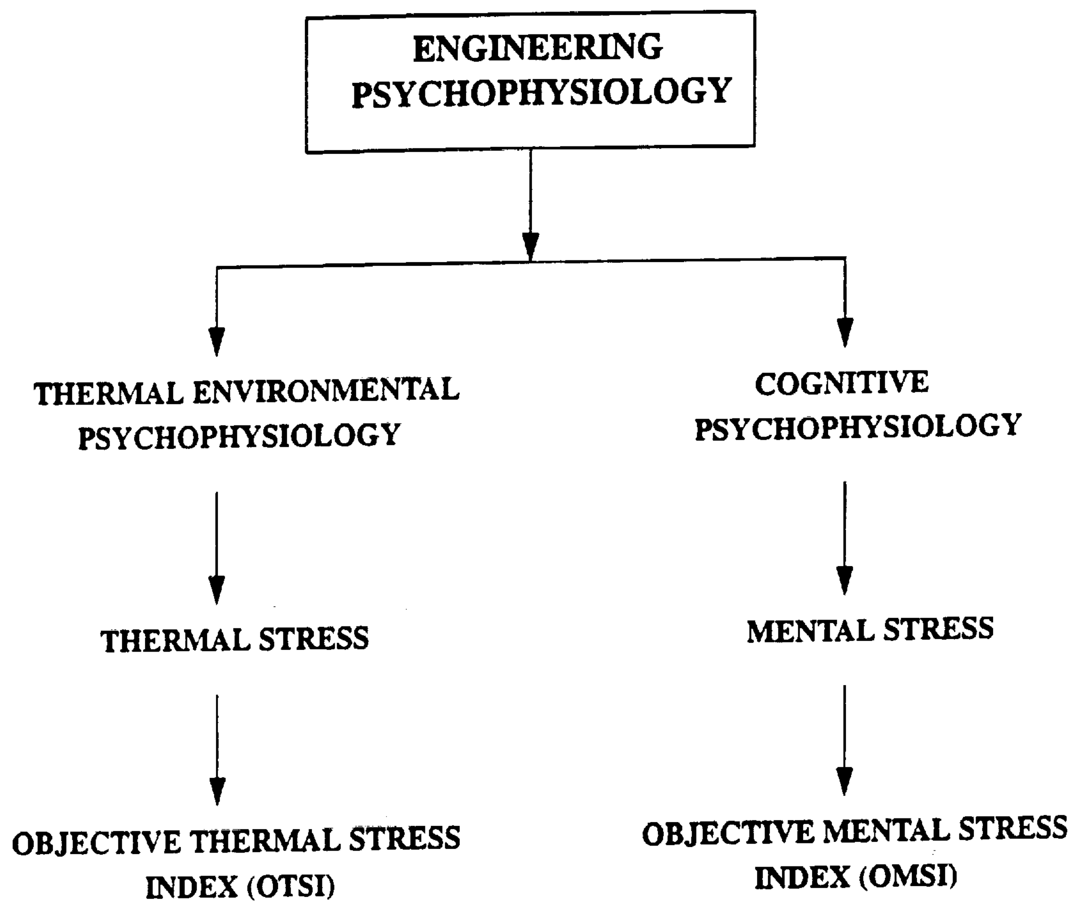


Figure 3.2 Hierarchy of Concepts and Definitions Related to Engineering Psychophysiology

CHAPTER IV

HUMAN THERMAL MODEL

In this chapter, different physical systems for the human thermal model are identified, and pertinent governing equations for each system are presented. Also, essential conditions for each system are specified, and appropriate solution procedure for the system is described.

4.1 Physical Model

The human thermal system consists of three important interactive systems and these are categorized as follows:

(1) Passive System
- (i) Tissues and Internal Organs
- (ii) Circulatory System
- (iii) Respiratory System

(2) Control System
- (i) Vasomotor Response
- (ii) Sudomotor Response
- (iii) Metabolic Response
- (iv) Cardiac Output Response

(3) Clothing System

4.1.1 Passive System

The passive system includes the body tissues, internal organs, circulatory, and respiratory systems. It represents the heat transfer mechanisms within the body parts such as heat conduction, convection, momentum and mass transfer, and metabolic heat generation. Also, this system takes into account the thermal energy exchange between the body and the environment.

(i) Tissues and Internal Organs

The individual human body parts are being treated as cylindrically shaped objects for the purpose of modeling. It is convenient to use cylinders to model the parts which include head, neck, torso, upper arms, thighs, forearms, calves, hands, and feet. Totally, fifteen cylindrical body parts are chosen [43] as shown in Fig. 4.1 and their dimensions are outlined in Table 4.1. The tissues and internal organs are contained in these body parts. Heat transfer processes in tissues and internal organs is a very complex phenomenon. The heat produced due to cellular metabolism is distributed in a complex manner among the tissues. The removal or addition of heat to maintain thermal equilibrium is passively controlled by the tissue thermal properties, capillary blood flow or perfusion, macrocirculatory blood flow, and heat generation within the tissue space. The structures of tissues and internal organs are highly nonhomogeneous and anisotropic.

(ii) Circulatory System

The human circulatory system is a complex network of blood vessels which carry blood to the body tissues. As shown in Fig. 4.2 [64], blood flow begins at the heart which acts as a pump forcing blood from the left ventricle into the aorta. From the aorta, blood flows into several large arteries which divide into medium-sized blood vessels that branch off to all other parts of the body except the lungs. These medium-sized arteries, in turn, divide into arterioles, the smallest arteries. Blood travels through the arterioles, across the capillaries, where gases and nutrients are exchanged between the blood and surrounding

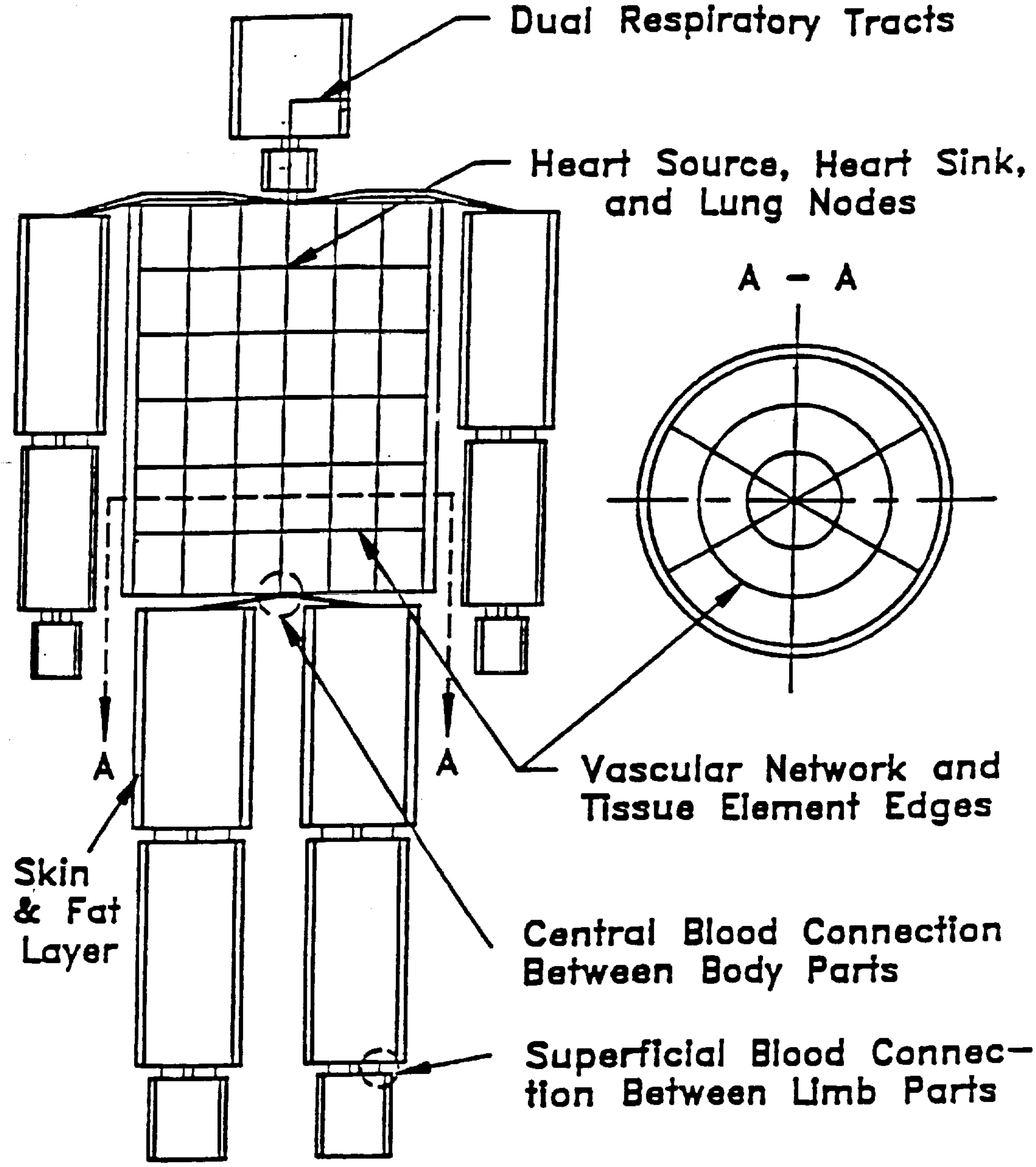


Figure 4.1 Schematic of the Passive System (Source: Smith [43])

Table 4.1 Body Part Dimensions [43]

Body Part	Radius, mm	Length, mm	Surface Area, cm2	Volume, cm3
Head	73	207	1117	3466
Neck	57	83	297	847
Torso	130	798	6666	42,368
Right or Left Upper Arm	45	353	998	2246
Right or Left Thigh	67	352	1482	4964
Right or Left Forearm	37	292	679	1256
Right or Left Calf	43	379	1024	2202
Right or Left Forearm	23	300	450	499
Right or Left Foot	36	241	586	981
Total			18,200 cm2 (1.82 m2)	

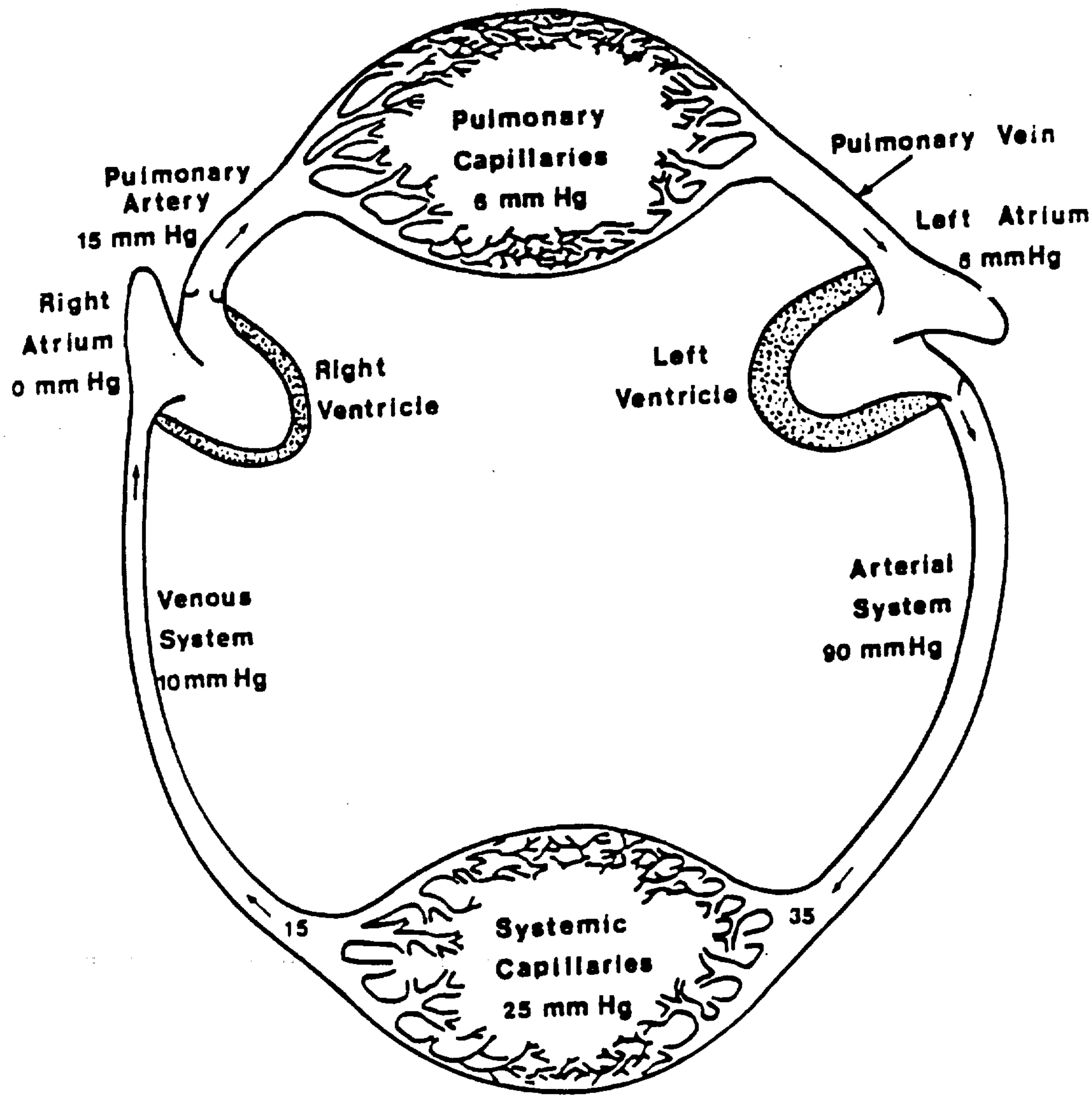


Figure 4.2 The Circulatory System (Source: Cooney [64])

tissue. After that blood flows into larger veins and is transported back to the right atrium. This is called systemic circulation. Leaving the right atrium, blood flows into the right ventricle, from where it enters the lungs and loses carbon dioxide and takes on oxygen. The blood then travels through the left atrium into the left ventricle completing its cycle. The circulatory path from the right atrium to the left ventricle is called the pulmonary circulation.

(iii) Respiratory System

The respiratory system plays an important rôle in the heat transfer between the human body and environment. Approximately 15% of the total heat generated by the body is transferred to the environment by the respiratory system in moderate conditions [65]. Air inhaled at the mouth is transported through a series of circular tubes to the lungs. In route, heat and mass transfer processes occur between the air in the respiratory tract and the surrounding tissue. Upon reaching the lungs, the air is then exhaled back through a second series of circular tubes to the environment. The periodic nature of respiration is simulated using a dual respiratory tract model as shown in Fig. 4.3. The combined surface area of this dual respiratory tract is assumed to equal the surface area of the actual human respiratory tract. The human trachea, or windpipe, has an average diameter of approximately 25.4 mm [65]. With this, each branch of the dual respiratory tract is modeled as having a diameter of 12.7 mm.

4.1.2 Control System

The control or thermoregulatory system is the psychophysiological system responsible for maintaining the core temperature at a normal level by enhancing or inhibiting heat production and heat loss. Thermoreceptors, located in the skin, brain, spinal cord, and

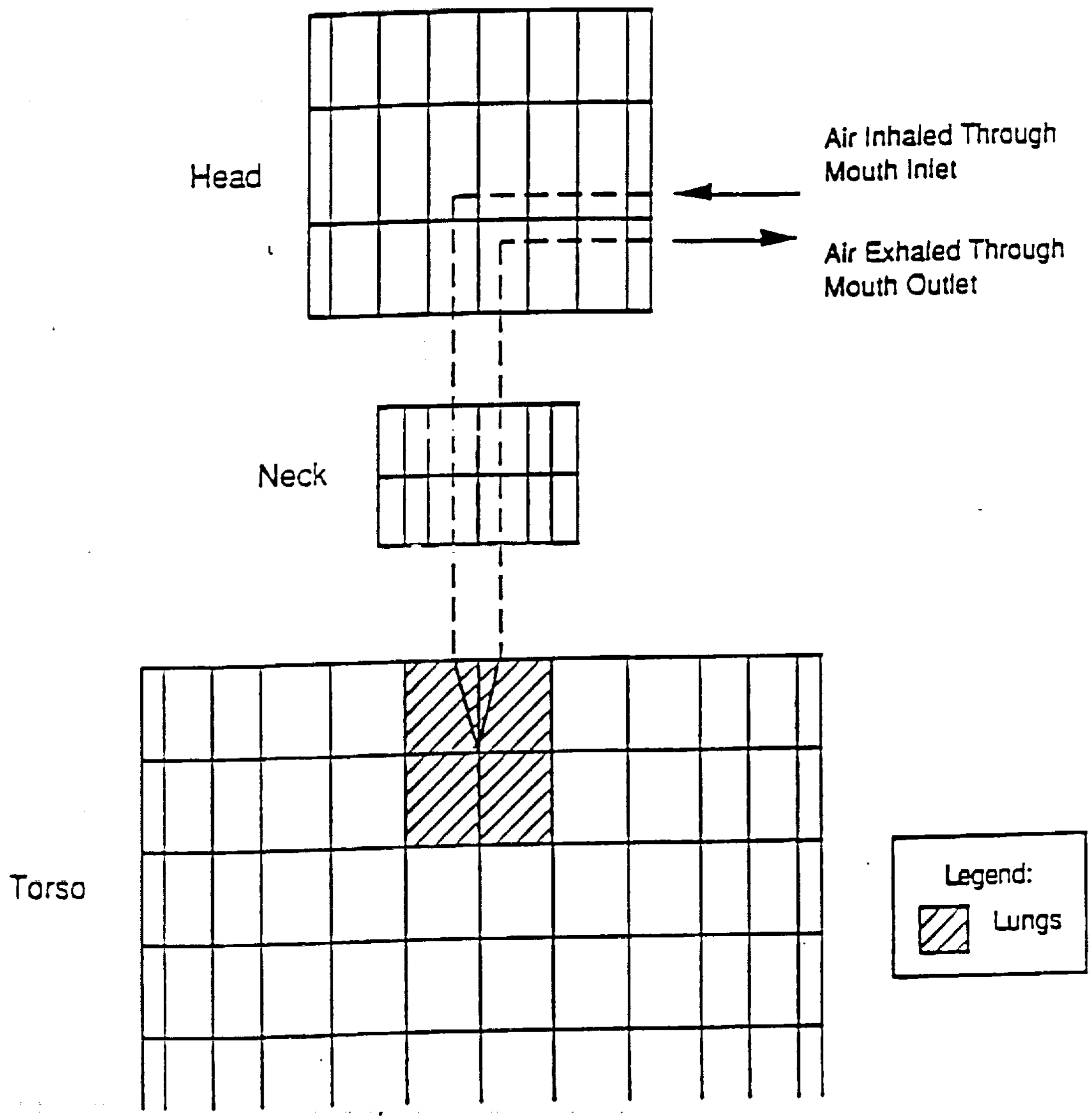


Figure 4.3 The Dual Respiratory Tract System (Source: Smith [43])

other sites in the body respond to both local temperature and its changes [43]. Signals from the thermoreceptors are transmitted by the central nervous system to the hypothalamus where they are integrated in a manner which is not clearly understood at this time. Regardless of the relative significance of the temperature signals from the various thermoreceptor locations, the hypothalamus determines the overall thermal state of the body from these signals and issues the appropriate commands. The three major types of thermoregulatory functions which either inhibit or enhance heat production and heat loss are vasomotor, sudomotor, and metabolic responses.

(i) Vasomotor Response

The body's response to dilate or constrict skin blood vessels is a vasomotor response where dilation of blood vessels is referred to as vasodilation and constriction of those same blood vessels is called vasoconstriction. When the core temperature rises above the normal level, in most parts of the body the skin blood vessel start dilating to increase the blood flow rates which in turn helps in transferring heat to the skin surface. During vasodilation, much of the blood that passes near the skin surface where it gets cooled before it returns to the body core. The skin temperature closely reflects minor changes in the deep body temperature. Depending on the ambient temperatures, the body will either lose or gain heat to or from the environment respectively. If the ambient temperature is higher than the skin temperature, then the heat transfer takes place from the environment to the body. In other words, vasodilation becomes undesirable allowing more heat from the environment to enter the body and thus increasing the temperature of the body core and affecting the human comfort.

When the core temperature begins to drop below the normal level, the posterior hypothalamus sympathetic centers in the thermoregulatory system cause the blood vessels of the skin to constrict [44]. This reduces the flow of warm blood from the arteries to the veins near the skin surface, thereby decreasing the rate of heat transfer. During vasoconstriction, the skin temperature falls to near the temperature of the surroundings which reduces the heat loss from the body and thus allows the body core to retain heat and maintain its normal temperature level. Further, due to constriction of skin blood vessels, the blood will flow through deeper veins back to the heart. The blood returning to the heart via deeper veins will be heated to some degree by the nearby arteries. In this manner, the blood that is supplied to the extremity could be 10 to 20 degrees cooler than the body core, yet the blood that returns to the core may only be cooled 1 or 2 degrees. Therefore, the temperature of the trunk is maintained while the extremities are allowed to cool.

(ii) Sudomotor Response (Sweating)

When the vasodilation is not sufficient to bring the core temperature back to normal, the anterior hypothalamus in the thermoregulatory system initiates the sweating process by sending signals to all of the sweat glands of the body through the sympathetic nerves [44]. Sweating is a powerful and sensitive thermoregulatory mechanism. Increase of core temperature by 1°C can produce an increase in sweat rate by a factor of 10-20 times. Under extreme conditions, as much as 1.5 liters of sweat can be secreted onto the surface of the skin in an hour, and under favorable conditions a large proportion of this will evaporate. The evaporation of sweat on the skin surface allows large amounts of heat (up to 1300W, which is about 12 times the basal level of heat production) to be dissipated in hot environments. In fact, when the environmental temperature is higher than skin temperature, the only way that the body can rid itself of heat is by the evaporation of sweat. Therefore, any factor that prevents the evaporation of sweat (such as clothing or the congenital absence of sweat glands) will cause the core temperature to rise when the surrounding temperature is higher than the skin temperature.

(iii) Metabolic Response

The total metabolic heat production arises from three sources: basal metabolism, voluntary physical activity, and shivering or involuntary metabolism for thermoregulation. The basal metabolism corresponds to heat generation during the resting condition and remains almost constant. The voluntary physical activities produce heat depending on the level of activity. The shivering is controlled by the thermoregulatory system. When other means, such as the vasoconstriction, the basal and voluntary metabolism are not sufficient to return the core temperature to its normal level, shivering (involuntary muscle contractions) begins to generate heat in muscle tissue. This muscular activity caused by the shivering increases the rate of heat generation in the body to counter the extreme cold environment [44].

4.1.3 Clothing System

The clothing plays a vital role in affecting the transient responses as humans wear clothes under normal conditions. The transfer of heat and mass (moisture) from the skin through the clothing to the environment is an important factor in thermal comfort. Removal of body heat is accomplished primarily by convection and radiation at low activity levels. Evaporation of perspiration is employed as the most effective thermoregulatory mechanism at intermediate and high metabolic rates and in environments which pose high heat stresses.

The development of the thermal model for the clothed human includes governing energy equations of the these three systems (passive, control, and clothing systems). The human thermoregulatory responses are obtained by solving these system of energy equations. Auxiliary equations, such as the blood pressure governing equation of the macrocirculatory system, the humidity ratio equation of the respiratory system, mass transfer equation of the clothing system, etc., form the complete system of governing equations.

4.2 Governing Equations

The governing equations for the three systems are categorized as follows:

1. Passive System Governing Equations
   - (i) Blood Pressure
   - (ii) Humidity Ratio
   - (iii) Thermal Energy
     - (a) Tissue Energy
     - (b) Blood Energy
     - (c) Air Energy
3. Control System Governing Equations
   - (i) Vasomotor Response
   - (ii) Sudomotor Response
   - (iii) Metabolic Response
   - (iv) Cardiac Output
3. Clothing System Governing Equations

4.2.1 Passive System Governing Equations

(i) Blood Pressure Equation

The Navier-Stokes equations are applied to blood flow in the macrocirculatory system to determine the pressure distribution. The basic assumptions include: blood is a Newtonian fluid flowing in the axial direction, 1-D, incompressible, steady, constant viscosity, laminar, fully developed, and axisymmetric flow. Thus, the N-S equations in cylindrical coordinates simplify to [43]

$$V_{bl} = \frac{-r_o^2}{8\mu} \frac{dP}{dz} \tag{4.1}$$

or

$$\frac{-r_o^2}{8\mu} \frac{d^2P}{dz^2} = 0 \tag{4.2}$$

where z is the coordinate along the axial direction of the blood vessel, V_{bl} is the mean blood velocity in the blood vessels, r_o is the radius of blood vessel, μ is the blood viscosity, and P is blood pressure. Equation (4.2) may be written in terms of the average volumetric blood flow rate, V_b, as

$$V_b = \frac{-\pi r_o^4}{8\mu} \frac{dP}{dz} \tag{4.3}$$

(ii) Humidity Ratio Equation

The humidity ratio is the quantity of water vapor in a mixture relative to the amount of dry air present. Latent heat loss due to respiration is a function of the humidity ratio inside the respiratory tract. Air inhaled at the mouth flows down the respiratory tract to the lungs. In route, heat and mass transfer occur between the air and the surrounding tissue. As a result of this evaporation process, the respiratory tract walls experience a cooling effect.

For any given respiratory tract element, a mass balance equation may be written in terms of the humidity ratio, W_{air} as [44]

$$D_{AB}\frac{d^2W_{air}}{dz^2} - v_{res}\frac{dW_{air}}{dz} + \frac{m_{res}}{A_{res}} = 0 \tag{4.4}$$

Equation (4.4) assumes one-dimensional steady flow, constant air velocity, v_{res}, and constant mass diffusivity, D_{AB}, for water in air. Here, m_{res} is water vapor transfer between air in the tract and the surrounding tissue and A_{res} is the cross-sectional area of the windpipe.

The magnitude of the air velocity can be calculated from the volumetric oxygen consumption rate, V_{O2}, and is, therefore, a function of the metabolic rate, M. Given the metabolic rate, the volumetric oxygen consumption rate is [43, 44]

$$V_{O2} = \frac{M}{21.12(0.23RQ + 0.77)} \tag{4.5}$$

$$v_{res} = 4.762\frac{V_{O2}}{\pi r_o^2} \tag{4.6}$$

where RQ is the respiration quotient, defined as the ratio of volumetric flow rate of exhaled carbon dioxide to that of inhaled oxygen.

(iii) Tissue Energy Equation

For a tissue element, the energy balance equation is expressed as [44]

$$\rho C\frac{\partial T}{\partial t} = \nabla \cdot k\nabla T + q_b + q_m + q_a + q_v + \alpha q_{res} \tag{4.7}$$

The term on the left-hand side of Eq. (4.7) is the rate of accumulation of thermal energy per unit volume due to changing temperature of the tissue. The quantity equals the sum of six terms on the right-hand side which are summarized as follows:

$\nabla \cdot k\nabla T$ = net rate of heat conduction into a unit volume,

$q_b = \rho_b w_b C_{p,b}(T_a - T_v)$ = rate of heat transfer into unit volume due to capillary blood perfusion (microcirculation),

q_m = rate of heat generation by metabolic reactions,

$q_a = 2\pi r_a h_a(T_a - T)$ = rate at which heat is transferred from the blood in large arterial vessels to the tissue,

$q_v = 2\pi r_v(T_v - T)$ = rate at which heat is transferred from the blood in large venous vessels to the tissue, and $q_{res} = 2\pi r_{res} h_{res}(T_{res} - T) + 2\pi r_{res} h_{res} \rho_{da} h_{fg}(W_{air} - W_{sat})$ = rate at which heat is transferred from the respiratory system to the tissue. This term appears only in the head, neck, and torso where $\alpha = 1$; for other parts of the body, $\alpha = 0$.

In particular, the term q_b in Eq. (4.7) is the rate of heat transfer by blood flow in microcirculation and is given by [4]

$$q_b = \rho_b w_b C_{p,b}(T_a - T_v) \tag{4.8}$$

where w_b is the average volumetric blood perfusion rate, ρ_b is blood density, $C_{p,b}$ is the heat capacity of blood, T_a is the arterial blood temperature, and T_v is the venous blood temperature. Assuming thermal equilibrium between the exiting bloodstream and the tissue ($T_v = T$), Eq. (4.8) may be written as

$$q_b = \rho_b w_b C_{p,b}(T_a - T) \tag{4.9}$$

In this study, Eq. (4.8) is used instead of Eq. (4.9) since the temperature T_v can be solved explicitly. Equation (4.8) or (4.9) provides a good approximation for the amount of heat transported by blood in the smaller blood vessels associated with microcirculation. Researchers have found that the local perfusion rate depends on the tissue temperature and local position [43, 66 - 68]. One commonly used function is the following exponential expression [44]:

$$w_b = w_{b,\,basal} k^{\Delta T/10} \tag{4.10}$$

where $w_{b,\,basal}$, whose value depends on local positions, is the volumetric blood perfusion rate at thermoneutrality, ΔT is the tissue temperature change with respect to the thermoneutral tissue temperature, and k is a constant in the range 2.0-3.0.

(iv) Blood Energy Equation

For a blood vessel element, the energy balance equation is expressed as [44]

$$\rho_b C_{p,b} \frac{\partial T_b}{\partial t} = K_b \frac{d^2 T_b}{dz^2} - \rho_b C_{p,b} v_{bl} \frac{dT_b}{dz} + \frac{q_{bd}}{A_b} \tag{4.11}$$

where q_{bd} is either q_a for arteries or q_v for veins and T_b is the blood temperature, which is either T_a for arteries or T_v for veins. A_b refers to the cross-sectional area of the large blood vessels.

(v) Air Energy Equation

For a respiratory tract element, the energy balance is given by [44]

$$\rho_{res} C_{p,\,res} \frac{\partial T_{res}}{\partial t} = K_{res} \frac{\partial^2 T_{res}}{\partial z^2} - \rho_{res} C_{p,\,res} v_{res} \frac{\partial T_{res}}{\partial z} + \frac{q_{res}}{A_{res}} \tag{4.12}$$

where subscript "res" stands for the air in the respiratory system.

4.2.2 Control System Governing Equations

The detailed realistic development of any thermoregulation model is limited mainly due to lack of understanding of thermal control functions of the human body. It is known that thermoreceptors sense local temperature changes and transmit these thermal signals to the hypothalamus. However, at this time it is not understood how the hypothalamus integrates these incoming signals. Whatever the form and relative significance of thermal signals utilized by the hypothalamus, the thermoregulatory responses are clear: vasodilation and sweating to enhance heat loss, vasoconstriction to inhibit heat loss, and shivering to increase metabolic heat production.

(i) Vasomotor Response Equations

The relations for the skin blood vessel radii are expressed as [43]

$$r_{o,\,dil} = r_{o,\,basal} (\text{for } T_{core} \le 36.9°C) \tag{4.13a}$$

$$r_{o,\,dil} = 2.5(T_{core} - 36.8)(r_{o,\,max\ dil} - r_{o,\,basal}) + r_{o,\,basal} (\text{for} 36.8 < T_{core} < 37.2) \tag{4.13b}$$

$$r_{o,\,dil} = r_{o,\,max,\,dil} (\text{for} T_{core} \ge 37.2°C) \tag{4.13c}$$

where $r_{o,dil}$ is the skin blood vessel radius including the effects of vasodilation for the given blood vessel and $r_{o,basal}$ and $r_{o,max\,dil}$ are the skin blood vessel radii at thermoneutrality and maximum dilation, respectively. Also,

$$_{,con} = r_{o,max,con}(for T_{skin} \le 10.7°C \qquad (4.14a)$$

$$r_{o,con} = (1/23)(T_{skin} - 10.7)(r_{o,basal} - r_{o,max,con}) + r_{o,max,con}(for 10.7°C < T_{skin} < 33.7°C) \qquad (4.14b)$$

$$r_{o,con} = r_{o,basal}(for T_{skin} \ge 33.7°C) \qquad (4.14c)$$

where $r_{o,con}$ is the skin blood vessel radius including any effects of vasoconstriction and $r_{o,max,con}$ is the skin blood vessel radius at maximum constriction.

The skin blood vessel radius, r_o, is calculated from the relation

$$r_o = \frac{r_{o,dil} \cdot r_{o,con}}{r_{o,basal}} \qquad (4.15)$$

During conditions when core temperature is above 36.8°C and mean skin temperature is below 33.7°C, the ratio $r_{o,con}/r_{o,basal}$ inhibits the degree of vasodilation.

(ii) Sudomotor Response Equations

The sweating threshold, T_{sweat} is a function of mean skin temperature, T_{skin}, and is expressed as [43]

$$T_{sweat} = 42.0 - 0.16T_{skin}(for T_{skin} < 33.0°C) \qquad (4.16a)$$

$$T_{sweat} = 36.85(for T_{skin} \ge 33.0°C) \qquad (4.16b)$$

If, for a given skin temperature, core temperature exceeds either the sweating threshold or 37.1°C, the sweating occurs. The sweat rate can be determined by the following equation:

$$m_{sw} = 45.8 + 739.4(T_{core} - T_{sweat})(\text{for} T_{core} > T_{sweat}) \tag{4.17}$$

where T_{core} and T_{sweat} are in degree Celsius and m_{sw} is in grams per hour. The sweat rate calculated using Eq. (4.17) is limited to a maximum value of 696 g/hr.

(iii) Metabolic Response Equations

The point at which shivering begins, referred to as the shivering threshold, T_{shiver}, is given by the following expression:

$$T_{shiver} = 35.5(\text{for} T_{core} \leq 35.8°C) \tag{4.18a}$$

$$T_{shiver} = -1.0222 \times 10^4 + 570.97T_{core} - 7.9455(T_{core})^2$$
$$(\text{for} 35.8°C < T_{core} < 37.1°C) \tag{4.18b}$$

If, for a given core temperature, the mean skin temperature is less than the shivering threshold, then shivering occurs.

The maximum increase in metabolic rate caused by shivering, $M_{shiv\ max}$, occurs at a mean skin temperature of 20°C and is a function of the core temperature, i.e.,

$$M_{shiv\ max} = -1.1861 \times 10^9 + 6.552 \times 10^7 T_{core} - 9.0418 \times 10^5 (T_{core})^2$$
$$(\text{for} T_{core} < 37.1°C) \tag{4.19a}$$

where $M_{shiv\ max}$ is in units of Joules per hour. The shivering metabolic rate, M_{shiv}, can be calculated in Joules per hour using

$$M_{shiv} = M_{shiv\,max}[1.0 - ((T_{skin} - 20)/(T_{shiver} - 20))^2]$$
$$[for(40°C - T_{shiver}) \le T_{skin} \le T_{shiver}] \quad (4.19b)$$

(iv) Cardiac Output Equations

The cardiac output is obtained by utilizing the following expressions:

$$CO_{con} = 29000(for T_{skin} \ge 33.7°C) \quad (4.20a)$$

$$CO_{con} = 870(T_{skin} - 10.7) + 290000(for 10.7°C < T_{skin} < 33.7°C) \quad (4.20b)$$

$$CO_{con} = 270000(for T_{skin} \le 10.7°C) \quad (4.20c)$$

where CO_{con} is the cardiac output (cm^3/hr) considering the effects of vasoconstriction. The value 290000 (cm^3/hr) is the cardiac output at thermoneutrality and 270000 (cm^3/hr) is the cardiac output at the condition of maximum vasoconstriction. Also,

$$CO_{dil} = 427500(for T_{core} \ge 37.2°C) \quad (4.21a)$$

$$CO_{dil} = 343750(T_{core} - 36.8) + 290000$$
$$(for 36.8°C < T_{core} < 37.2°C) \quad (4.21b)$$

$$CO_{dil} = 290000(for T_{core} \le 36.8°C) \quad (4.21c)$$

where CO_{dil} is the cardiac output (cm^3/hr) considering the effects of vasodilation. The value 427500 is the cardiac output at the condition of maximum vasodilation. Therefore,

$$CO = \frac{CO_{dil} \cdot CO_{con}}{290006.0} \quad (4.22)$$

The cardiac output expressed by Eq. (4.22) is only a function of the body thermostat [43] which is not completely true. However, it has been found that CO depends on metabolic rate and is proportional to the volumetric oxygen consumption rate. Thus, Eq. (4.22) becomes,

$$CO = \frac{V_{O2}}{V_{O2basal}} \cdot \frac{CO_{dil} \cdot CO_{con}}{290006.0} \tag{4.23}$$

where V_{O2} is obtained from Eq. (4.5). The value of $V_{O2basal}$ the volumetric oxygen consumption rate at thermoneutrality, is also obtained from Eq. (4.5).

4.2.3 Clothing System Governing Equations

The clothing system plays a very important role in affecting the thermal responses because of its moisture adsorbing or desorbing mechanisms. The clothing model implemented by Fu [44] includes the following aspects:

(a) Driving force: The actual driving force is the chemical potential gradient which is incorporated in the present model.

(b) Human body geometry: The clothing is treated as a cylindrical cover along the human body.

(c) Moisture in the interfiber void: The moisture in the interfiber void of clothing is important for low absorptive clothing.

(d) Condensation diffusion: It is found that condensation diffusion does not occur in clothing under normal conditions, wicking effect is not considered in the model.

Considering the above four factors, heat and mass (moisture) balance equations for a clothing element are developed as

Moisture Transfer Equation:

$$\rho_{fab}\frac{\partial R}{\partial t} + \varepsilon_{fab}\frac{\partial c}{\partial t} = \frac{t_{fab}}{R_{efab}L}\left(\frac{1}{r}\frac{\partial p}{\partial r} + \frac{\partial^2 p}{\partial r^2}\right) \quad (4.24)$$

Energy Equation:

$$C_{pfab}\rho_{fab}\frac{\partial T}{\partial t} = \frac{t_{fab}}{R_{dfab}}\left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right) + \rho_{fab}(\Delta H)\frac{\partial R}{\partial t} \quad (4.25)$$

$$\frac{p}{c} = R_{H_2O}T \quad (4.26)$$

where r is the radius of the clothing layer, R is the regain, $R_{d,\,fab}$ is the resistance to the dry heat transfer, and $\partial R/\partial t$ is the unsaturated moisture term.

4.3 Method of Solution

The clothed human thermal model utilized in the simulation consists of a set of parabolic differential and algebraic governing equations. The differential equations are solved numerically subject to appropriate initial and boundary conditions. Besides these governing differential equations for the passive and the clothing systems, there are a set of algebraic thermal control governing equations, Eqs. (4.13) - (4.23), that need not be solved numerically. However, these control equations play an important role in the overall simulation results.

4.3.1 Numerical Solution Method for the Passive System

In the past, most of the models have been developed based on either a lumped parameter approach or finite difference techniques. In this study, the finite element method, as described by Segerlind [69], is used to develop a solution procedure for solving the passive system governing Eqs. (4.1) - (4.12). There are two main advantages for choosing the finite element approach. First, it is easier to develop a general solution procedure for a large problem like this. Second, finite element techniques are well suited for irregularly shaped objects like human body. Although cylinders are used to represent the individual body parts, it may become necessary at some later time to include body parts such as fingers and toes. It will be much easier at that time to modify a finite element model.

The solution domain for the passive system is discretized into a number of small elements. Each element represents a tissue section, blood vessel, respiratory tract, or portion of an internal organ. After the element mesh is generated, the passive system thermal governing equations along with the clothing thermal model and the environmental conditions are integrated for each element in terms of its parameters and unknown variables, yielding a system of simultaneous equations which can then be solved for the unknown variables of interest.

The shape functions are derived for each different element shape [43]. According to Segerlind [69], the solution of time-dependent field problems using quadratic shape functions is often accompanied by spatial oscillations that violate the physical reality of the problem. The difficulty arises because the quadratic elements do not satisfy the sign criteria, such as positive diagonal and negative off-diagonal rule for the stiffness matrix. Therefore, the quadratic shape functions are not used to solve time-dependent field problems in this study. Thus, the linear shape functions developed by Smith [43] are presented as follows (see Fig. 4.4 for nomenclature):

(1) The shape functions for the triangular elements are

$$N_1 = [r\theta z]/[\Delta r\Delta\theta\Delta z]$$

$$N_2 = [r(\Delta\theta-\theta)z]/[\Delta r\Delta\theta\Delta z]$$

$$N_3 = [(\Delta r-r)\Delta\theta z]/[\Delta r\Delta\theta\Delta z]$$

$$N_4 = [r\theta(\Delta z-z)]/[\Delta r\Delta\theta\Delta z]$$

$$N_5 = [r(\Delta\theta-\theta)(\Delta z-z)]/[\Delta r\Delta\theta\Delta z]$$

$$N_6 = [(\Delta r-r)\Delta\theta(\Delta z-z)]/[\Delta r\Delta\theta\Delta z]$$

(2) The shape functions for the rectangular elements are

$$N_1 = [(r-r_o)\theta z]/[\Delta r\Delta\theta\Delta z]$$

$$N_2 = -[(r-r_o)(\theta-\Delta\theta)z]/[\Delta r\Delta\theta\Delta z]$$

$$N_3 = [(r-(r_o+\Delta r))(\theta-\Delta\theta)z]/[\Delta r\Delta\theta\Delta]$$

$$N_4 = -[(r-(r_o+\Delta r))\theta z]/[\Delta r\Delta\theta\Delta z]$$

$$N_5 = -[(r-r_o)\theta(z-\Delta z)]/[\Delta r\Delta\theta\Delta z]$$

$$N_6 = [(r-r_o)(\theta-\Delta\theta)(z-\Delta z)]/[\Delta r\Delta\theta\Delta z]$$

$$N_8 = [(r-(r_o+\Delta r))\theta(z-\Delta z)]/[\Delta r\Delta\theta\Delta z]$$

(3) The shape functions for the one-dimensional elements are

$$N_1 = [\Delta z-z]/\Delta z$$

$$N_2 = z/\Delta z$$

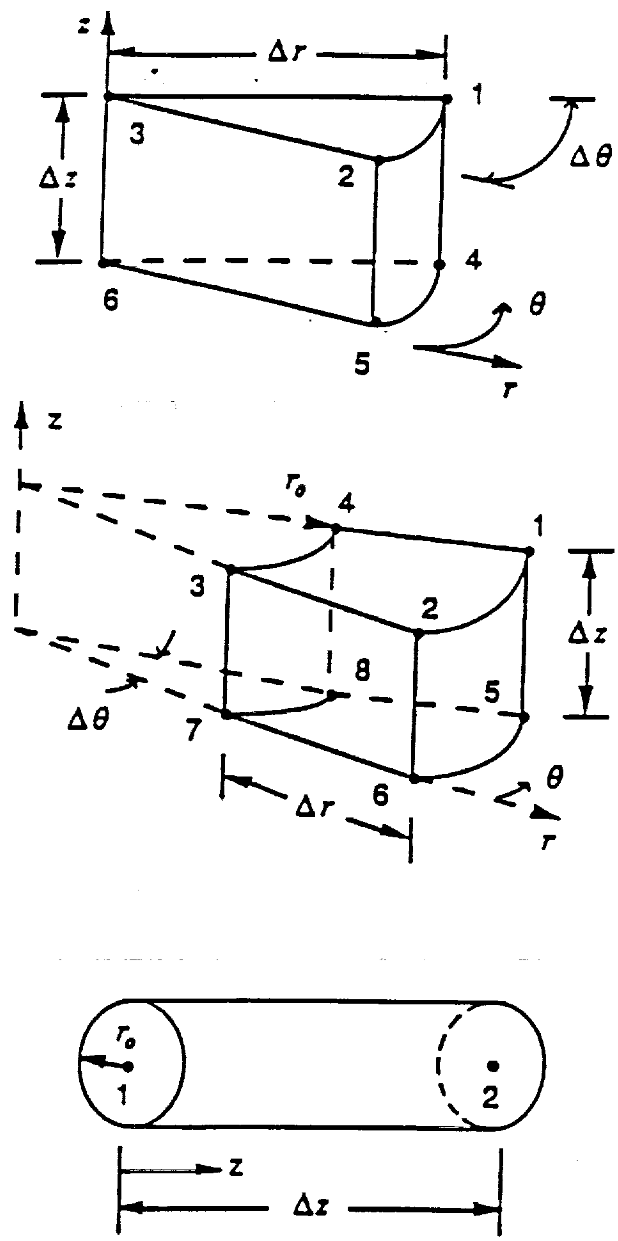


Figure 4.4 Element Mesh of Smith's Model [43]

The Galerkin's method of weighted residuals [69] is a commonly used method of discretizing governing equations which have first order derivatives. In this study, Galerkin's residual integral on the differential equations is evaluated with respect to the spatial coordinate(s) for each of the elements. The shape functions are used as weighting functions in the integral. In this regard, Galerkin's formulation is applied to all the passive system differential equations. Among these governing equations are the macrocirculatory blood pressure governing equation, Eq. (4.2), the respiratory air humidity ratio governing equation, Eq. (4.4), tissue energy governing equation, Eq. (4.7), the macrocirculatory blood energy governing equation, Eq. (4.11), and the respiratory air energy governing equation, Eq. (4.12). The details of the Galerkin's formulation and the implementation of boundary conditions are described by Smith [43], Fu [44], and Segerlind [69]. The convective transfer coefficients are determined using the appropriate empirical relationships before solving the governing equations [43,44].

The assembly of the resulting Galerkin's formulations are used to solve for the thermal responses of the passive system. Assembling these element equations by the direct stiffness method [69], a system of N linear first order differential equations in terms of N unknown temperature and their rates of change is expressed as

$$[C][T']^{T} + [K][T]^{T} = [F]^{T} \tag{4.27}$$

where $[C]$ is the capacitance matrix, $[K]$ is the stiffness matrix, $[T]^{T}$ is the temperature vector, and $[F]^{T}$ is the forcing vector. By applying the central difference method [69] to Eq. (4.27), the following equation is obtained [43]:

$$\left([C]+\frac{\Delta t}{2}[K]\right)[T]_{t+\Delta t}^{T} = \left([C]-\frac{\Delta t}{2}[K]\right)[T]_{t}^{T} + \frac{\Delta t}{2}\left([F]_{t}^{T}+[F]_{t+\Delta t}^{T}\right) \qquad (4.28)$$

Equation (4.28) can be rewritten in the simplified form as

$$[A][T]_{t+\Delta t}^{T} = [P][T]_{t}^{T}+[F^*] \qquad (4.29)$$

where Δt is the time step size. Equation (4.29) is a system of linear simultaneous equations which is solved by the computer for the nodal temperatures at time $t + \Delta t$.

4.3.2 Numerical Solution Method for the Clothing System

The Clothing system is represented as several cylindrical clothing layers covering the cylindrical body parts. The air layers in the clothing system can be treated as insulation with no thermal capacitance and the following lumped equations are treated as the thermal governing equations for a small air layer element in the clothing system [44]:

$$Q_d = A\frac{T_i - T_{i+1}}{R_d} \qquad (4.30)$$

$$Q_e = A\frac{P_i - P_{i+1}}{R_e} \qquad (4.31)$$

where Q_d and Q_e are dry and evaporative heat transfer respectively, A is area, T is temperature, P is moisture vapor pressure, R_d is thermal resistance of an air layer and R_e is evaporative resistance of an air layer. Subscripts i and $i+1$ denote two clothing layers surrounding air layers. Combining Eqs. (4.30) and (4.31) for the air layer elements and Eqs. (4.24) - (4.26) for the clothing layer elements, the complete thermal model for the clothing and air elements in the clothing system is established. These governing equations are solved using the finite difference method [44] subject to suitable initial and boundary conditions.

4.3.3 Initial and Boundary Conditions

Initial Conditions

The thermoneutral conditions are used as initial conditions for the human body. Instead of just the core and skin temperatures, the initial thermoneutral temperature distribution of the whole human body is needed because of the finite elements used in the body. In order to obtain this initial condition, the model is simulated for a nude sedentary human body starting with an approximate initial thermoneutral temperature distribution. The air temperature and relative humidity used in the simulation are 28°C and 32%, respectively. The temperature thus obtained is used as the initial condition for all other simulations. The initial condition for the clothing system is P_i and T_i for each clothing layer element.

Boundary Conditions

(1) Blood Pressure Equation: The volumetric flow rate of blood entering the arterial system at the left ventricle or source node and leaving the venous system at the right atrium or the sink node are both equal in magnitude to the cardiac output, CO. For the element that contains the left ventricle or source node, the boundary condition is

$$\frac{\pi r_o^4}{8\mu}\left(\frac{dP}{dz}\right)_{node1} = CO \qquad (4.32)$$

For the element which contains the right atrium or sink node, the boundary condition is

$$\frac{\pi r_o^4}{8\mu}\left(\frac{dP}{dz}\right)_{node2} = -CO \tag{4.33}$$

In Smith's model [43], one additional boundary condition is imposed on the heart sink node. The boundary condition states that the blood pressure at the heart sink node is equal to 3.0 mm Hg and thus forces the blood pressure to be positive at all nodal locations.

(2) Humidity Ratio Equation: In the Galerkin formulation of the humidity ratio governing equation, the effects of mass diffusion in the axial direction is neglected. This results in a first order ODE in humidity ratio W_{air}, requiring one boundary condition: the humidity ratio of air inhaled through the mouth is equal to the humidity ratio of the ambient air. That is, at the inlet node,

$$W_{air} = W_{amb} \tag{4.34}$$

(3) Thermal Energy Equations: The boundary conditions required are the temperature T and the vapor pressure P of the surroundings. If a skin area is covered by clothing, the values of T and P of the inner most clothing layer become the required boundary conditions. Otherwise, the values T and P of the environment become the required boundary conditions.

(4) Clothing System Equation: For the clothing system represented by Eqs. (4.24) - (4.26), the boundary conditions are the temperatures (T_{skin}, T_{env}) and vapor pressure (P_{skin}, P_{env}) of the human skin surface and environment respectively. In particular, T_{i+1} and P_{i+1} in Eqs. (4.30) and (4.31) for the outer most clothing layer element will be the air temperature (T_{env}) and the vapor pressure (P_{env}) in the environment. Similarly, for

the inner most clothing layer element, T_i and P_i will be the skin temperature T_{skin} and the skin moisture vapor pressure P_{skin} on the skin surface.

4.3.4 Overall Solution Scheme

The flowchart of the computer program used to solve the human thermal model is provided in Fig. 4.5. The steps involved in the solution procedure are summarized as follows [43, 44]:

Step 1: Input the clothing system data file from the clothing data base. This data base includes information about the geometric representation and fabric thermal properties.

Step 2: Specify all the passive system information such as geometric size of body parts, element mesh information, vessel radii at basal conditions, tissue thermal properties, basal metabolic rate, blood perfusion rate, activity level, and so on. The activity level might be a function of time.

Step 3: Specify the total simulation time and the time step to be used in the numerical integration process.

Step 4: Locate and number nodes throughout the solution domain. Generate the element mesh. Number each element and assign each element a specific type, e.g., brain, blood vessel, etc. Calculate element dimensions and also locate surfaces exposed to ambient conditions.

Step 5: Input the environmental conditions, such as temperature and relative humidity as boundary conditions.

Step 6: Input the initial conditions for the passive system (thermoneutral temperature distribution).

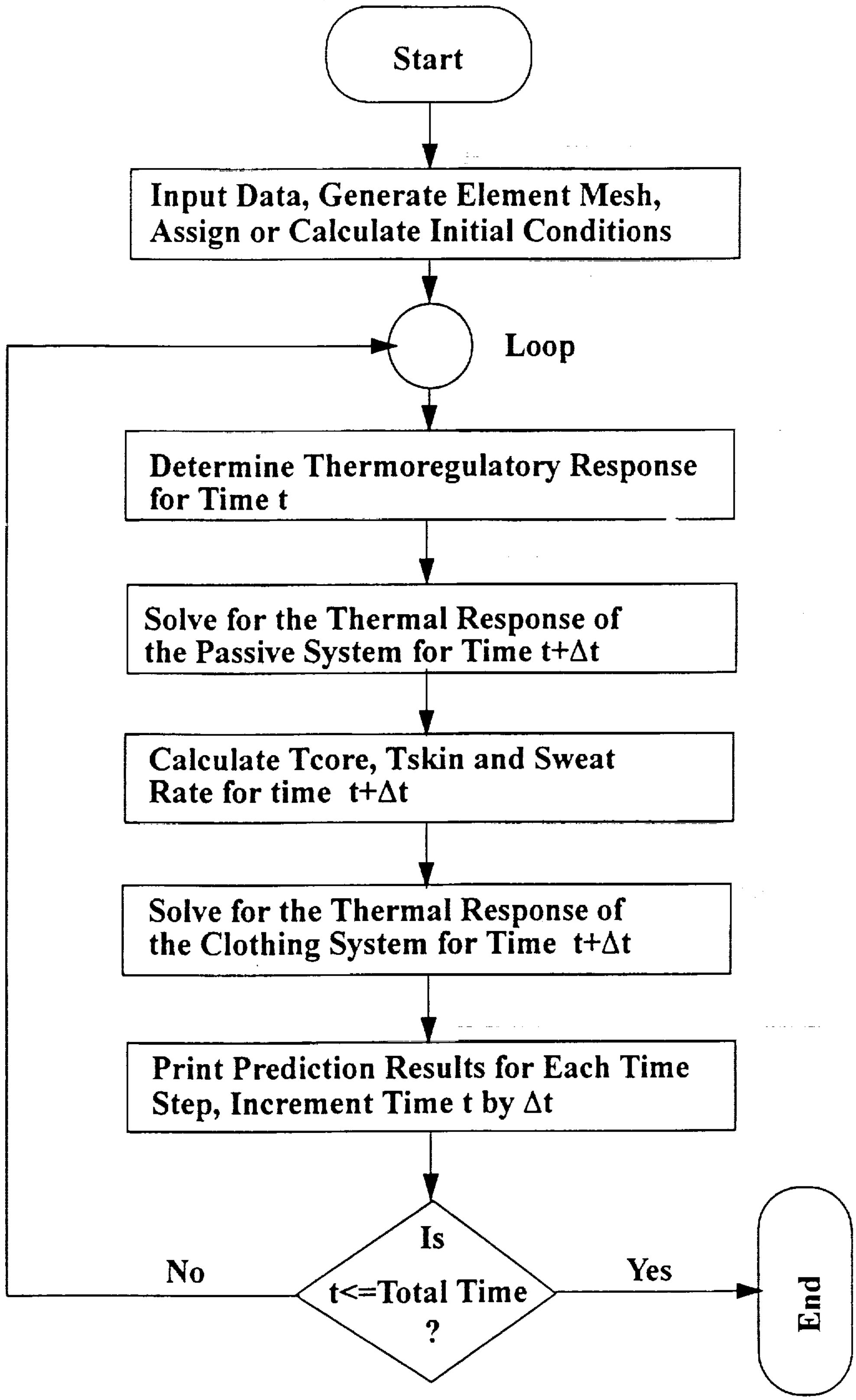


Figure 4.5 Flowchart of the Human Thermal Computer Model [44]

Step 7: Calculate the initial core and skin temperatures using the initial temperature distribution information of the passive system.

Step 8: Calculate the initial sweating rate of each skin element according to the values of the initial core and skin temperatures obtained in the Step 7.

Step 9: Calculate the initial conditions for each clothing element and input them.

Step 10: Determine the thermoregulatory responses, such as vasomotor, shivering, etc., as functions of time t using the core and mean skin temperatures and the thermal control governing equations.

Step 11: Solve for the thermal responses, such as temperature distribution, thermal load, etc., of the passive system as functions of time.

Step 12: Calculate the core and mean skin temperature as functions of time using the updated temperature distribution of the passive system obtained in Step 11.

Step 13: Calculate the sweating rate of each skin element as a function of time according to the values of the core and skin temperatures obtained in Step 12.

Step 14: Solve for the thermal responses, such as temperature, vapor pressure, regain, thermal load, etc., of the clothing system as a function of time.

Step 15: Print any information of interest, such as temperature distribution, core and mean skin temperatures, the thermal load of the clothed human, etc., as functions of time.

Step 16: If time t is less than the length of the simulation time, specified in Step 3, then return to Step 10. Otherwise, the computer simulation has ended.

CHAPTER V

OBJECTIVE MEASURES OF HUMAN STRESS LEVEL

The present chapter deals with the development of objective measures of stress level experienced by the humans in an environment. The stress could be experienced by humans either due to changes in thermal environment or due to cognitive or mental loading. In either cases, it is very important to know the quantitative measure of stress level in order to evaluate the human comfort and performance for optimum safety in the operation of flight management tasks. It is well established that the autonomic nervous system (ANS) controls both thermal (body and skin temperatures, skin heat loss, etc.) and cardiovascular (BP, HR, etc.) responses. In Sec. 5.1, a brief introduction to the concept of thermal stress is provided, followed by the development of Objective Thermal Stress Index (OTSI) in Sec. 5.2. The development of OTSI is justified mainly due to the evidence presented in a study by Hancock and Pierce [51] relating attention and vigilance to the changes in ambient environment. They have shown that sustained attention is disturbed by conditions sufficient to induce a change in human thermal responses. At this point of perturbation to thermal equilibrium, resulting homeostatic action drains attentional resources and thus reduces vigilance capability. In this regard, OTSI provides an objective measure of deviation from thermal equilibrium and thus quantifies the drain in attentional resources and reduction in vigilance capability.

Due to interaction between nervous system and physiological responses, a brief introduction is provided in Sec. 5.3 about the concept of mental stress. It is well established that the autonomic nervous system (ANS) controls both thermal (body and skin temperatures, skin heat loss, etc.) and cardiovascular (BP, HR, etc.) responses. In this regard, a psychophysical index that links human thermal activity to the cardiovascular functioning is developed and is discussed in Sec. 5.4. The Objective Mental Stress Index (OMSI) provides a thermodynamic representation of the autonomic nervous system (ANS) functioning.

5.1 Thermal Stress

It is established that an excessive thermal stress results in both psychological and physiological strain on the exposed individual [8]. The amount of thermal stress that is present in a work environment is a function of certain environmental measures such as air temperature, humidity, radiant heat load, and air movement. In addition, stress is a function of human thermal responses. The amount of acclimatization to which the human has been exposed affects the stress to which a specific individual is being subjected. The metabolic rate and work rate are also important. In addition, the body surface area-to-weight ratio can affect the human stress level.

Some of the other important factors include clothing, age, sex, and physical conditions. It has been shown that older individuals are more subject to strain resulting from thermal stress than younger individuals. The sex is also a factor since experiments have shown that tolerance to heat is higher among males than females. The individual's general health and physical condition are also important factors that affect the stress that is imposed on an individual human. Since each person represents a different mixture of various factors, there are individual variations in the ability to withstand heat stress. This alone presents some difficulties when attempting to determine how much warmth should be maintained in an environment to provide the optimum comfort and satisfy a given group of occupants.

On the other hand, the physiological strain that results from thermal stress is a function of the circulatory capacity of the individual, capacity for sweating, and tolerance to elevated body temperature. In addition, the exposure time is an important factor in determining the strain that is felt by an individual. The human body can withstand high temperatures for short periods of time without causing harmful effects to the health of the exposed individual. In order to determine the amount of thermal stress above which the occupants in an environment should not be exposed, it is desirable to develop an Objective Thermal Stress Index (OTSI) that combines both stressors and physiological strain to provide a quantitative measure of thermal stress.

Several attempts have been made in the past to develop such a universal thermal index to quantify thermal stress level. Although many indices have been developed, none are entirely satisfactory [8]. In developing criteria for a thermal stress index, it is important that the following factors be considered:

1. The index that is developed should be quantitative and yield scalar values relating to stress and strain.
2. The index should be calculated from available data concerning the conditions that are present in the environment.
3. The index should be tested and proved applicable through use.
4. All important factors should be included in the index.

5. The method should be simple to use and not lead to rigorous calculation or difficult measurements.

6. All factors should be related to physiological strain in a weighted manner.

7. The method should be applicable and feasible for determining regulatory limits or threshold limit values for exposure to heat stress.

Some of the widely used thermal stress indices are described in Sec. 1.2 and none of these indices meet all the criteria for universal index. At best, they provide an estimate of the relationship between thermal stress and physiological strain. The OTSI has been developed to overcome most of the limitations of earlier indices. However, OTSI with its simplified mathematical expression and based on second law of thermodynamics meets all the above seven requirements to be considered a universal thermal stress index. Also, the OTSI provides a direct measure of human thermal sensations and is based on the second law of thermodynamics and laws of psychophysics [70] as applied to the human thermal system.

5.2 Development of Objective Thermal Stress Index (OTSI)

The most important environmental variables that are responsible for maintaining the condition of thermal comfort are:

1. Thermal resistance of the clothing (I_{cl})
2. Air temperature (T_{air})
3. Relative humidity (RH)
4. Activity level or metabolic heat generation (M)

Thermal comfort can be achieved by altering or controlling different combinations of the above variables. The human thermal responses that are simulated for variation in conditions such as clothing, air temperature, relative humidity, and activity level are:

1. Skin temperature (T_{skin})
2. Core temperature T_{core}
3. Convective heat loss from the skin surface (E_{CNV})
4. Radiative heat loss from the skin surface (E_{RAD})
5. Evaporative heat loss from the skin surface (E_{EVAP})
6. Convective heat loss due to respiration ($E_{RES-CNV}$)
7. Evaporative heat loss due to respiration ($E_{RES-EVAP}$)

The entropy generation term is derived from the second law of thermodynamics as [63]

$$S_{gen} = \Delta S - S_{flow} \quad (5.1)$$

However, entropy generation is found to be a function of both environmental variables and human thermal responses [9], i.e.,

$$\begin{aligned} S_{gen} = f(&T_{skin}, T_{core}, E_{CNV}, E_{RAD}, E_{EVAP} \\ &E_{RES-CNV}, E_{RES-EVAP}, M, I_{cl}, T_{air}, RH) \end{aligned} \quad (5.2)$$

The concept of entropy has been introduced in human physiology by Aoki [18,19] with the help of experimental data. According to Aoki, the entropy concept is as important as the concept of energy from the thermodynamic standpoint. The entropy production in the human body provides a global measure that specifies the extent of chaotic motions and reactions occurring within the body. In other words, the entropy generation in the body shows the extent of activeness (or stress level) within the body as a whole; so the entropy generation is a significant quantity which characterizes the human body from thermodynamic and holistic (i.e., considering human body as a whole) viewpoints. Thus, the entropy generation is considered to be equivalent to Objective Thermal Stress Response (OTSR) and the Postulate IX defines the equivalence of these parameters.

Postulate IX. The entropy generation is the human thermal system in response to thermal environmental stressors provides the quantitative measure of thermal stress and is equivalent to Objective Thermal Stress Response (OTSR). That is, S_{gen} = Objective Thermal Stress Response (OTSR).

Incorporating the law of psychophysics [70, 71], that Psych = f (Physical), the following logic is established:

IF Stress = f (Strain) (a)

IF S_{gen} = f (Physiological Strain, Stressors) (b)

IF S_{gen} = OTSR (c)

THEN OTSR = f (Physiological Strain, Stressors) (d)

IF Psych = f (Physical) (e)

THEN Postulate X

From expressions (d) and (e), the Objective Thermal Stress Response is restated under Postulate X as

Postulate X. The Objective Thermal Stress Response (OTSR) provides the quantitative measure of thermal stress in the psychological domain in terms of physiological strain and thermal environmental stressors.

Thermodynamic approach originally developed by Boregowda et al. [9] is being implemented in this study to develop objective measures of human thermal stress level. The percentage deviation in entropy generation from the optimum value is being mathematically equated to the Objective Thermal Stress Index (OTSI). The OTSI is defined under Postulate XI as follows:

Postulate XI. The percentage deviation in the value of OTSR from the comfort or equilibrium condition provides a quantitative measure of deviation from thermal homeostasis and is termed as Objective Thermal Stress Index (OTSI). It is mathematically defined as

$$\text{OTSI} = \left[1 - \frac{(\text{OTSR})_{act}}{(\text{OTSR})_{com}}\right] \text{x } 100 \qquad (5.3)$$

where subscripts "act" and "com" stand for actual and comfort values of objective thermal stress response respectively. The mathematical and thermodynamic details pertaining to the formulation of OTSI are clearly presented in Appendix A.

The Objective Thermal Stress Index (OTSI) has the potential of becoming a "product" which can be used by the Heating-Ventilation and Air-Conditioning (HVAC) industry that is responsible for maintaining indoor climate in aerospace and industrial environmental control systems. The OTSI is expected to provide a measurement standard that takes into account both environmental variables and human thermal responses. It is for the first time an index such as OTSI has been developed that gives the direct measure of human thermal sensations. The OTSI also provides the direction of departure from the optimum value. The deviation may be on the positive or negative side of the optimum or equilibrium value depending on the imposed conditions or stressors.

5.3 Mental Stress

Several studies have shown that any form of human-machine interaction requires some combination of activities such as sensory, perceptual, mental, and physical in nature. The performance of these activities is accompanied by related psychophysiological changes in nature. In a human-machine system, the effectiveness of the system is dependent on the well-being of a human to a great extent. All kinds of stresses are bound to affect the human capabilities and health. Thus, it is very important to have quantitative information to analyze both physical and mental stresses. The concept of entropy using Maxwell relations has been treated for the first time in human psychophysiology by Boregowda et al. [36 - 39]. Mental stresses cause a wide range of effects. As discussed by Mital et al. [6], these could be physiological (elevated heart rates, blood pressure, etc.), performance related (decreased output, increased errors, etc.), or behavioral (lack of attention, anxiety, etc.). The literature survey in Sec. 1.2 establishes the fact that several investigators have studied the effects of mental/physical stresses and devised methods to quantify stress. Despite all these efforts, an accurate method to quantify mental stress has not been developed. However, there has been a strong need to develop a technique or methodology to measure and monitor stress level during cognitive tasks. The present study aims at fulfilling this need and demonstrates the validity of the innovative technique to measure and monitor human stress level through the development of an Objective Mental Stress Index (OMSI).

5.4 Formulation of Objective Mental Stress Index (OMSI)

A thermodynamic approach has been developed to quantify the stress level based on the physiological responses using an Objective Mental Stress Index (OMSI). The OMSI is derived from the entropy concept and the principles of second law of thermodynamics as applied to a human body considered as a system. The first law of thermodynamics is concerned with the concept of energy, while the second law with entropy. Entropy has been a hazy concept whose physical meaning is difficult to comprehend. However, using the definition of Maxwell relations, change in entropy can be expressed in terms of measurable quantities like changes in pressure, volume, and temperature. One of the important elements of this study is to relate the change in entropy to human mental stress level. In qualitative terms, entropy is defined as "measure of disorder or chaos" in any system in the universe. Could this concept be related to the human-machine system? If so, how? The answer is yes, and the change in entropy corresponds to the "measure of disorder" which in turn can be equated to the human stress level. This is done with the help of Maxwell relations of thermodynamics as applied to human psychophysiological system. It has been shown by Boregowda et al. [36-39] that the change in entropy is expressed in terms of physiological responses that can be measured experimentally like changes in blood pressure, heart rate, skin temperature, and oral body temperature. The concept of entropy and Maxwell relations from thermodynamics are clearly explained in Appendix B. However, for detailed treatment on entropy and second law, the reader should refer to Callen [62].

The changes in physiological variables such as blood pressure, heart rate, and skin temperature (or oral body temperature) are mathematically related to change in entropy which is being interpreted as Objective Mental Stress Index (OMSI). The OMSI indicates the level of mental stress based on the deviation in physiological responses from the equilibrium or homeostasis. The detailed formulation of OMSI is provided in Appendix B. This thermodynamic approach provides a deeper understanding of the psychophysiological stresses, since most work situations involve both physical and mental effort. Due to rapid technological changes, the nature of jobs would involve a lot of mental/cognitive effort in addition to manual labor. Further, these human efforts will demand even more physical and mental capabilities in the future. Thus, accurate scientific models based on strong theoretical foundations have to be developed to quantify and measure psychophysiological stresses. Finally, the OMSI is considered to be equivalent to entropy change and is defined under Postulate XII as

Postulate XII. The entropy change which represents the deviation from the equilibrium condition or homeostasis in both cardiovascular (blood pressure and heart rate) and thermal (skin or body core temperature) systems in response to mental workload is defined as Objective Mental Stress Index (OMSI).

The variables pertaining to mechanical system like changes in pressure, volume, and temperature correspond to physiological variables such as changes in blood pressure (both systolic and diastolic), heart rate, and skin temperature (or body temperature) respectively. By using the analogy between human and mechanical systems, as discussed in Appendix B, a modified relationship has been developed as

$$\mathrm{OMSI} = \frac{(\Delta \mathrm{BP})\mathrm{x}(\Delta \mathrm{HR})}{(\Delta \mathrm{T})} \tag{5.4}$$

where, OMSI = Objective Mental Stress Index (beats . mm Hg/min°C

ΔBP = Change in Blood Pressure (mm of Hg) from the baseline value

ΔHR = Change in Heart Rate (bpm) from the baseline value

ΔT = Change in Body or Skin Temperature (°C) from the baseline value.

If the information processing or mental workload causes changes in physiological responses, then according to Maxwell relations, change in entropy or OMSI indicates the measure of a non-physical factor which is mental stress in terms of physiological changes that can be measured. In this regard, information flow is considered to be equivalent to energy flow that impinges on the individual to cause certain physiological changes. These measures of physiology are combined using Maxwell relation to quantify mental stress in the form of a single summative number.

The Literature review in Sec. 1.2 indicates that several earlier studies conducted by investigators have been focusing on one parameter at a time as an indicator of stress. For example, blood pressure has been used as a good indicator of a long term mental/life stress. However, there have been no studies conducted to combine three different physiological variables to formulate a single index that gives the measure of stress level. This is the first time, a study like this has been under taken to quantify the mind-body interaction. In other words, besides quantifying stress level, OMSI acts as a parameter that quantifies the mind-body interaction from a thermodynamic viewpoint. Further, this model will provide an excellent basis for future research in different areas of human factors engineering, health care, and medicine. This approach has been validated with experimental data (Chap. 6) and has strong potential to become a diagnostic tool in the treatment of stress related disorders.

CHAPTER VI

RESULTS AND DISCUSSION

Human stress responses include both thermal and cardiovascular responses. Thermal stress responses are simulated using a computer model [43, 44]. However, cardiovascular responses (blood pressure and heart rate) are obtained from experimental studies such as those conducted by Boregowda et al. [36 - 39], Palsson et al. [40] and Mital et al.[6]. First, the computer model for simulating human thermal behavior is validated by comparing the model predictions with one of the independent sources such as experimental data. The experimental validation of the model is presented in Sec. 6.1. The effects of varying environmental conditions, physical activity, and clothing on mean skin temperature, blood vessel radii, and entropy generation are examined in Sec. 6.2. In Sec. 6.3, analysis of human thermal behavior is performed using a hybrid technique. This technique is based on the theory of experimental design [45, 46] to observe the interaction among physical variables such as air temperature, relative humdity, physical activity, and clothing which affect the overall human thermal comfort. In this regard, a natural variable, entropy generation (S_{gen}), which is a function of all human thermal stress responses, environmental conditions, physical activity, and clothing, is implemented. This is a novel approach and it provides a basis to design and conduct effective human experiments. In Sec. 6.4, thermal stress level monitoring technique is demonstrated with the help of an Objective Thermal Stress Index (OTSI). The OTSI is validated through a series of computer simulations condcuted for both comfortable and extreme environmental conditions. However, a relationship between thermal and cardiovascular activity is established in Sec. 6.5 through demonstration of mental stress level monitoring technique using an Objective Mental Stress Index (OMSI).

6.1 Experimental Validation of the Human Thermal Model

The accuracy of the human thermal model is established through a validation process. This process involves comparison of model predictions with those obtained from an independent experimental data source. Besides establishing the accuracy of the model, the validation process helps in defining the range of conditions for which the model is applicable. The model is validated for variation of the core and skin temperatures, and latent skin heat loss by comparing with the experimental data of Hardy [72]. Hardy measured and recorded at five minute intervals the ambient temperature, vapor pressure, oxygen consumption rate, weight loss, tympanic temperature, rectal temperature, and local skin temperatures at ten locations for sedentary male subjects exposed to a variety of environmental conditions. Prior to each test period, the subjects, dressed only in shorts, sat quietly in a room at 18°C for one hour, after which time the subjects were quickly transferred to the test chamber. During each test period, the subjects were seated quietly on chairs mounted on scales used to measure weight loss. This weight loss was used to calculate the rate of latent skin heat loss from the skin surface. Air movement about the subject was almost entirely due to natural convection and the subject's own body temperature. Thermocouples used to measure local skin temperatures were located as follows: forehead, left pectoral region, right scapular area, right upper abdominal quadrant, right thigh anterior, left thigh lateral, right calf, left foot dorsum, right biceps, and dorsum of the left hand. The first computer simulation was conducted for a period of 65 minutes at 286.15K air temperature and 45% relative humidity. The core and skin temperatures and latent skin heat loss as shown in Figs. 6.1 - 6.3 were simulated for the nude body. The second simulation was conducted for two hours at two different conditions of 31% and 30% relative humidities for the first and second hours respectively. In a manner similar to the first simulation, body core temperature, mean skin temperature, and latent skin heat loss were simulated for the nude body as shown in Figs. 6.4 - 6.6. Figures 6.1 - 6.6 show that model predictions approach and closely follow the experimental data. With this, it is concluded that model could be used for future extensive simulation studies for a wide range of environmental conditions. Also, earlier studies by Smith [43] and Fu [44] have established the accuarcy and robustness of this computer model through extensive experimental validation.

6.2 Effect of Physical Variables on Human Thermal Responses

The physical variables which affect overall human thermal comfort include both environmental and personal [73]. There are four environmental variables affecting human thermal comfort: air temperature, mean radiant temperature, relative humidity, and air velocity. The personal variables are the activity level and the clothing ensembles. For example, an active person requires a lower air temperature for comfort, while thick clothing allows a lower air temperature. Computer simulations were performed for a variety of environmental conditions, physical activities, and clothing ensembles. Some of the thermal responses simulated by the computer include mean skin temperature, blood vessel

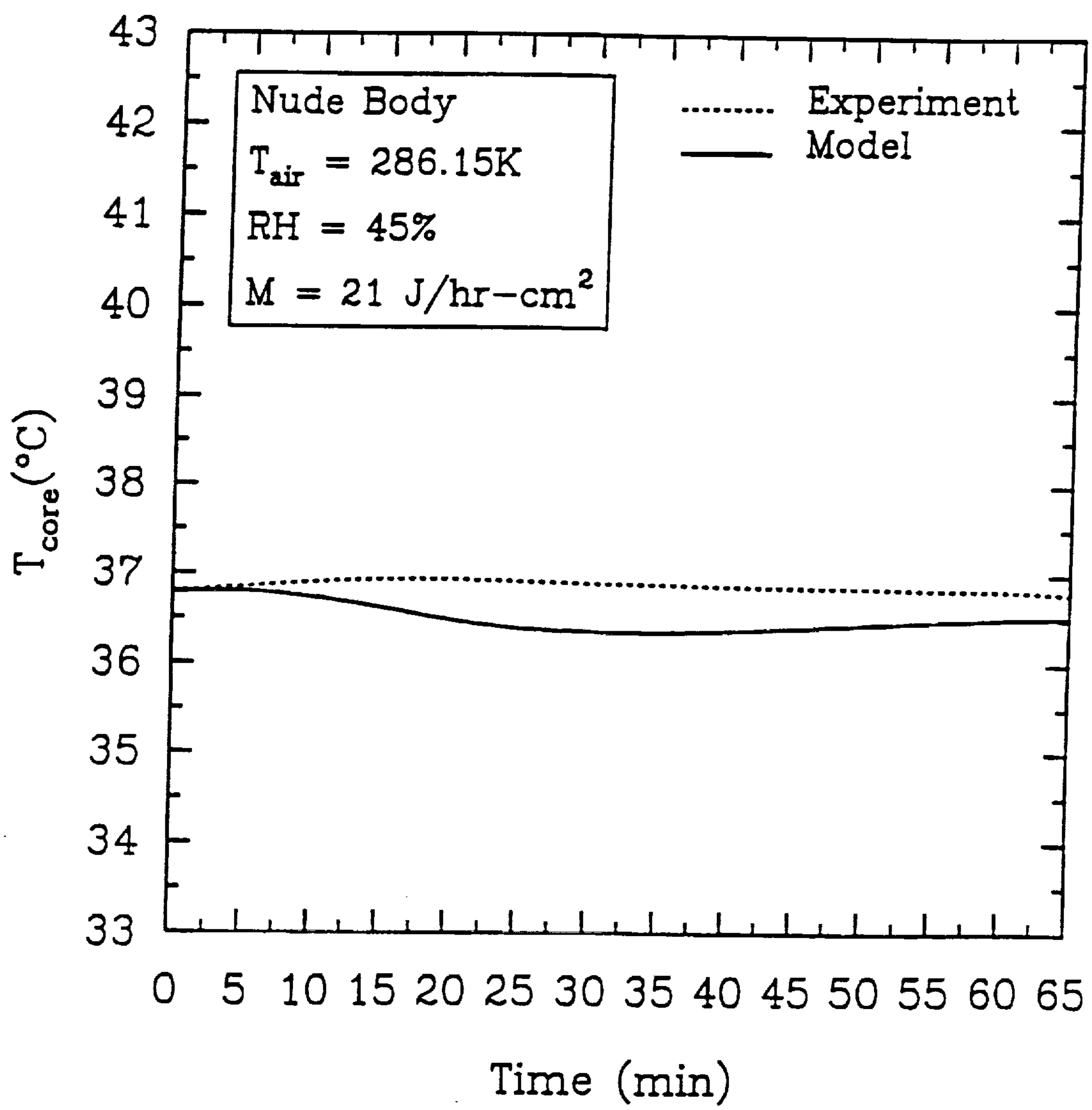


Figure 6.1 Core Temperature vs. Time; Experimental Data from Hardy [72]

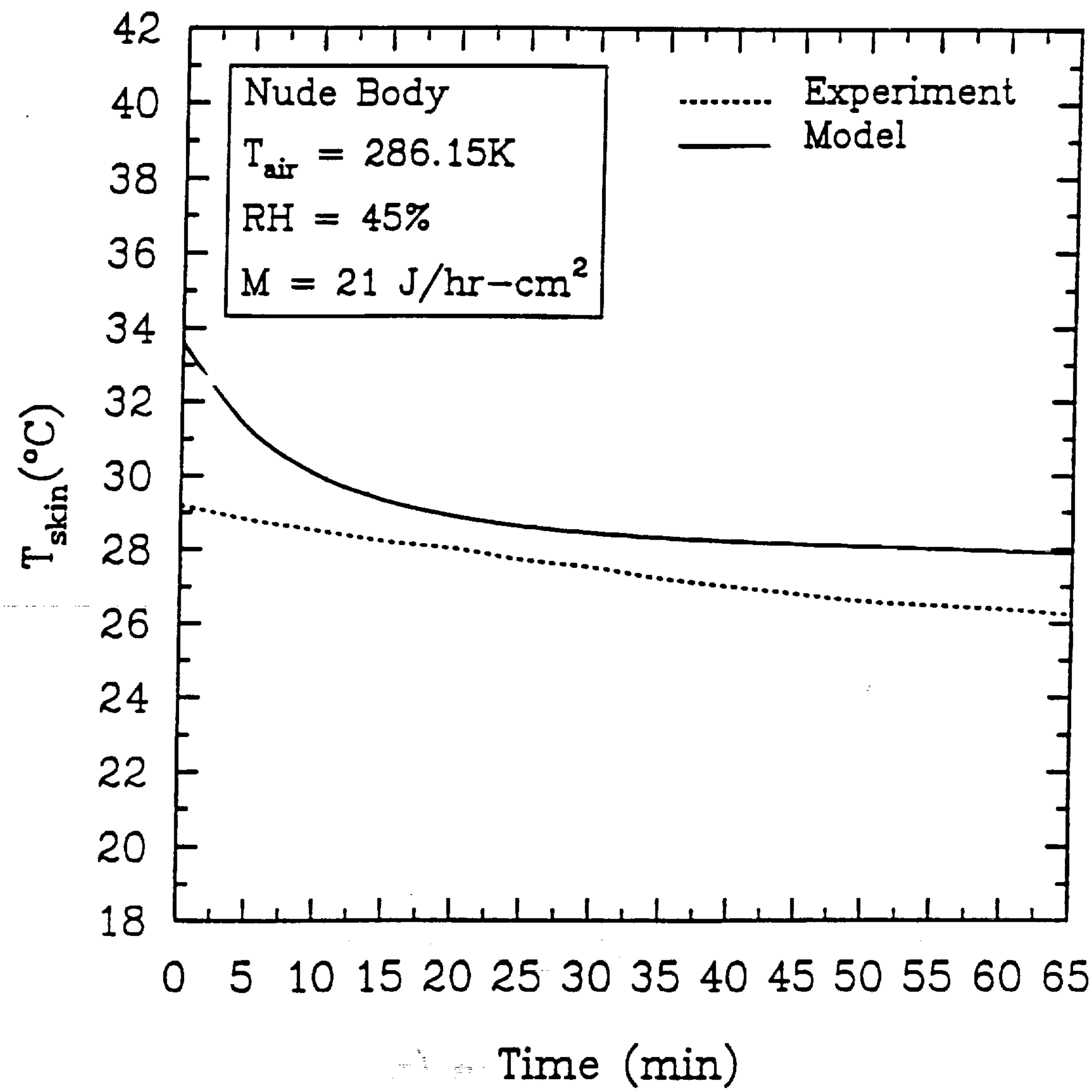


Figure 6.2 Mean Skin Temperature vs Time; Experimental Data from Hardy [72]

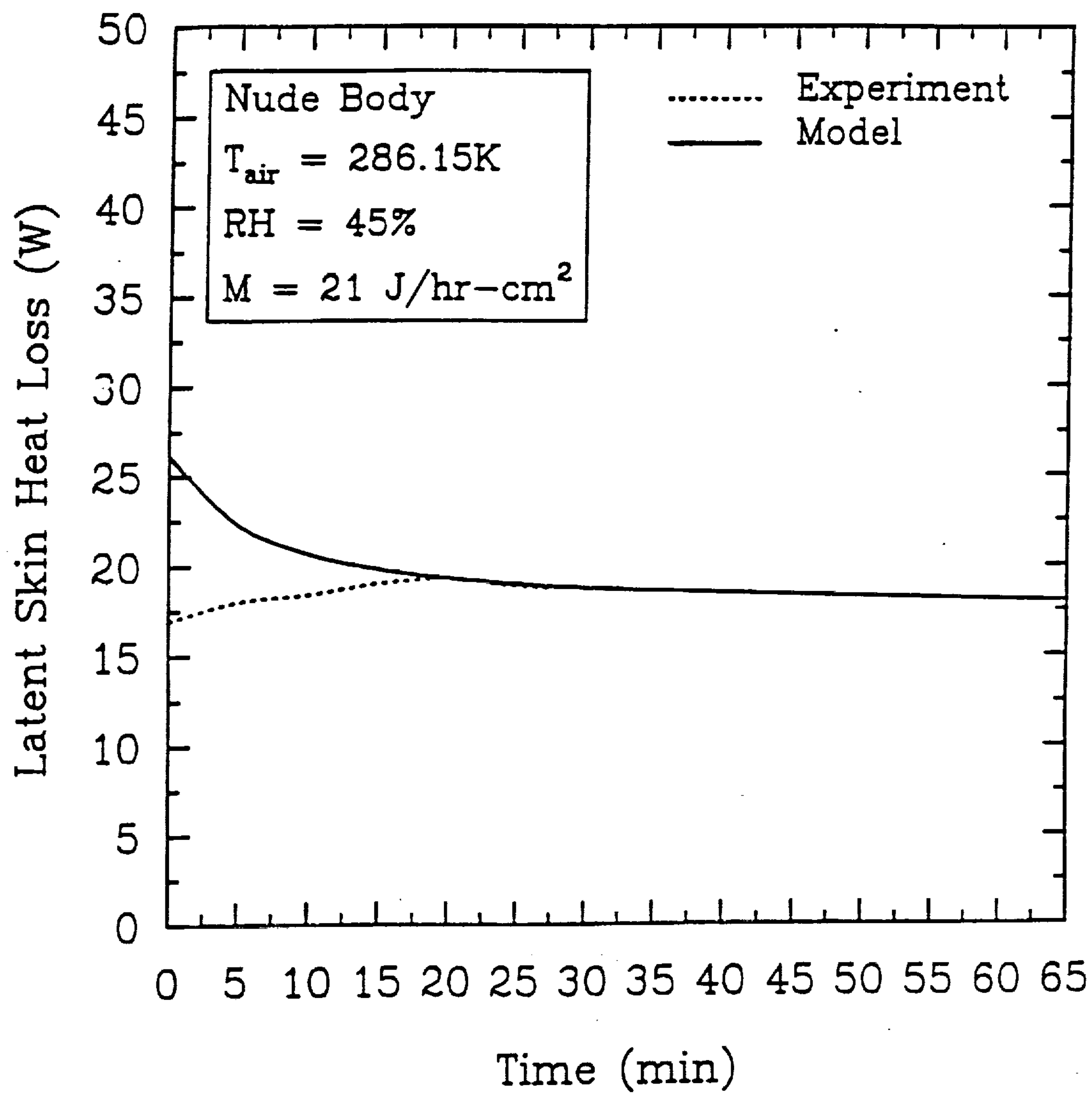


Figure 6.3 Laten Skin Heat Loss vs Time; Experimental Data from Hardy [72]

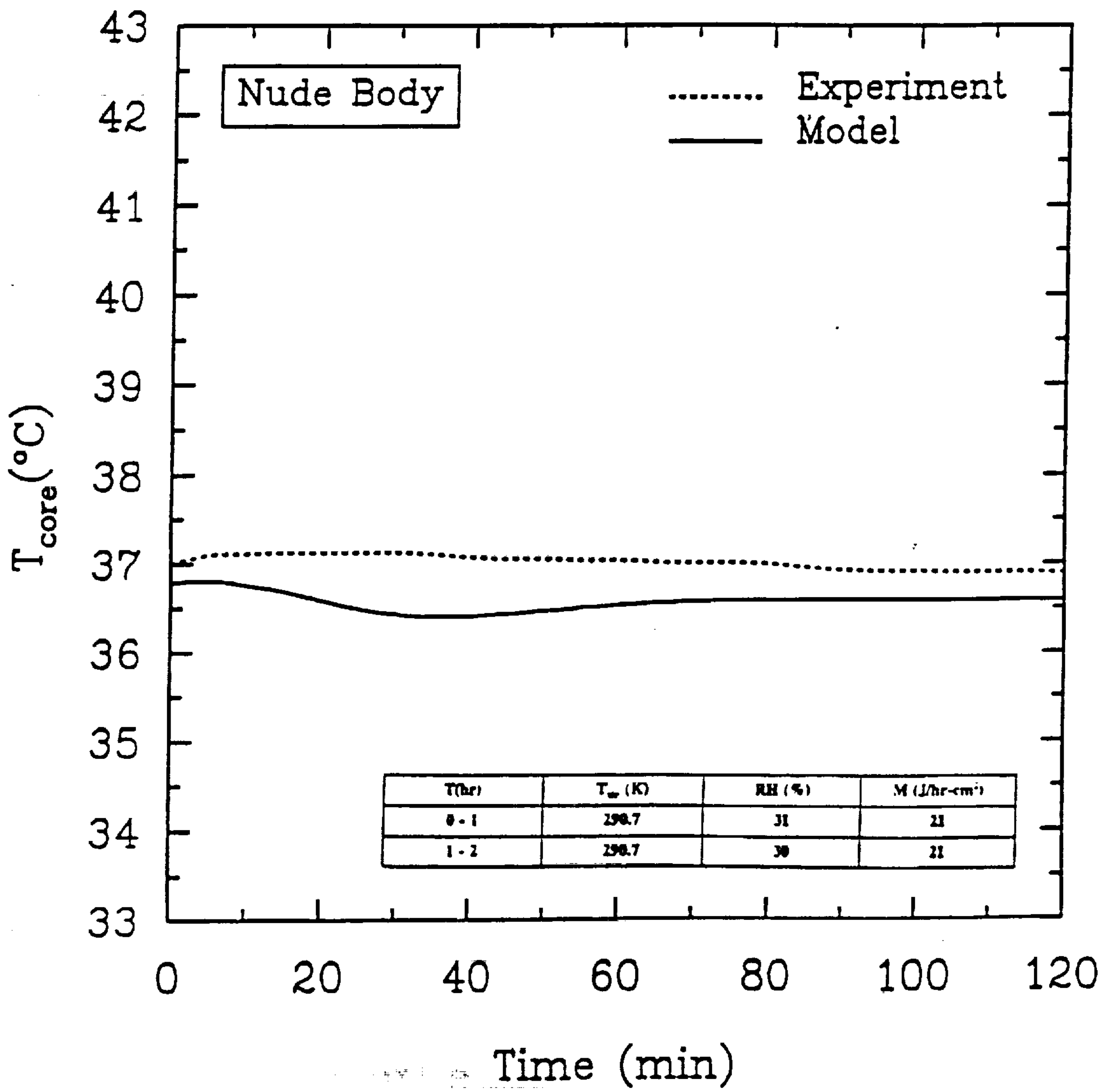


Figure 6.4 Core Temperature vs Time; Experimental Data from Hardy [72]

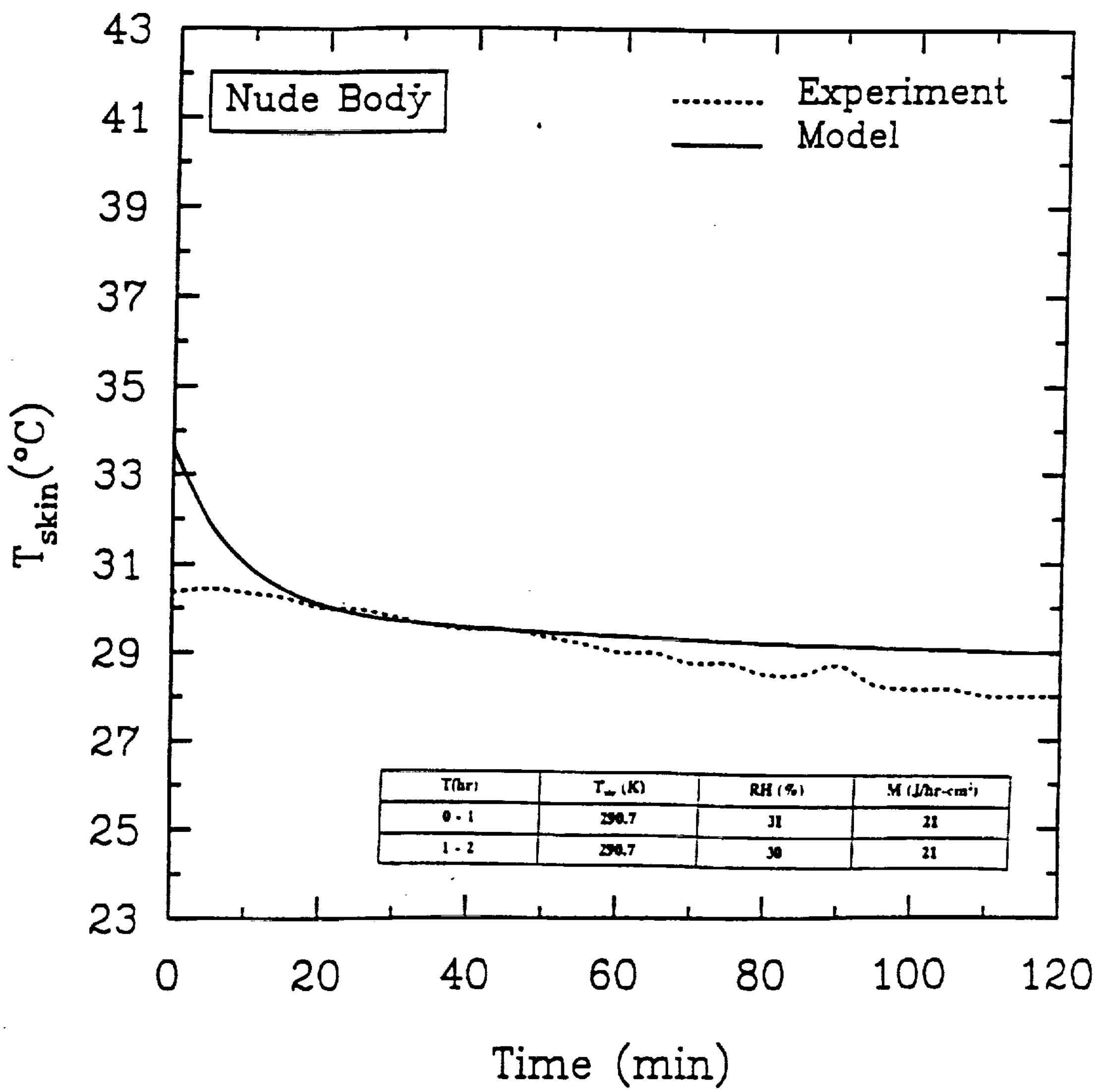
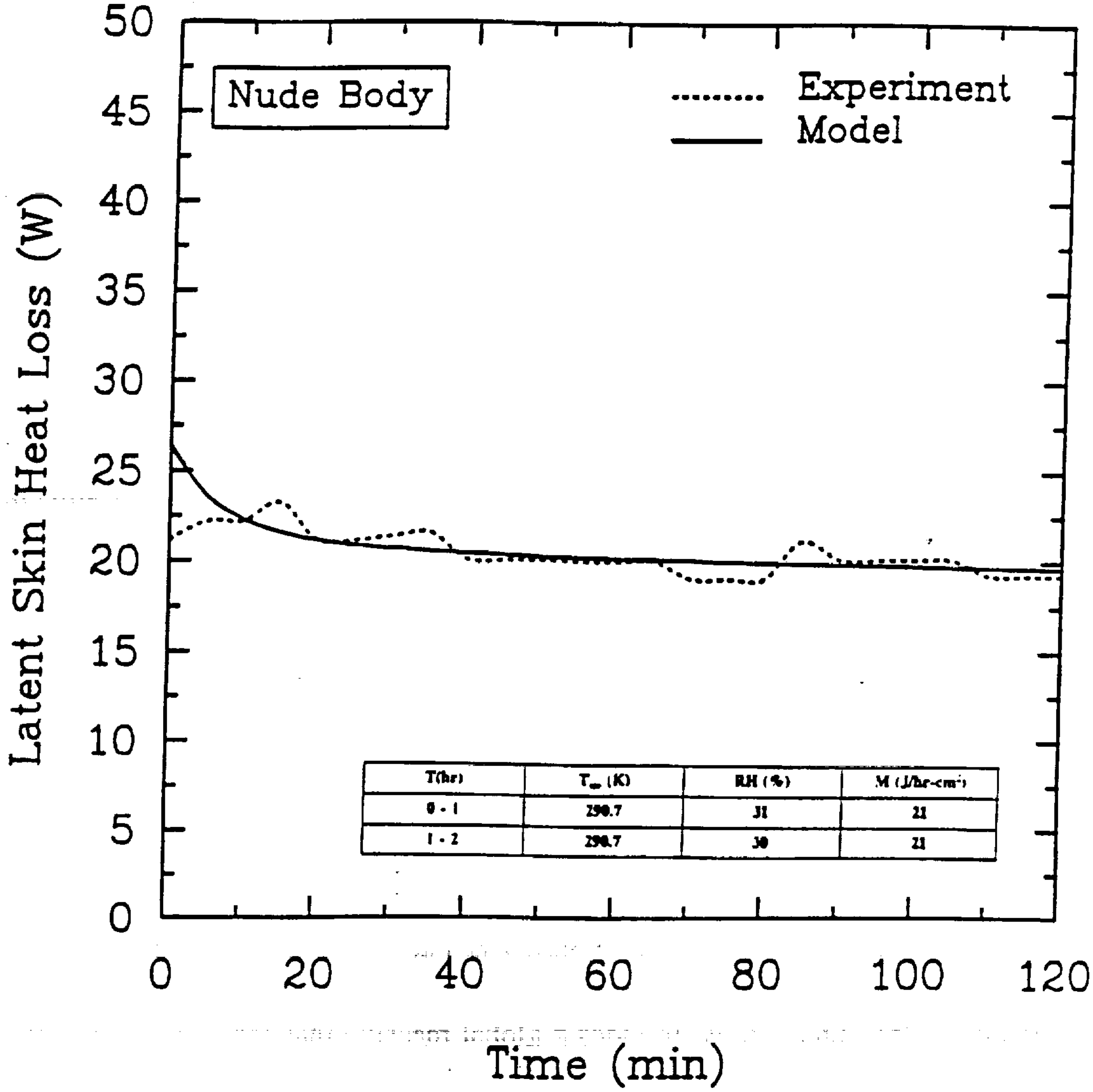


Figure 6.5 Mean Skin Temperature vs Time; Experimental Data from Hardy [72]



T(hr)	T_∞ (K)	RH (%)	M (J/hr-cm^2)
0 - 1	290.7	31	21
1 - 2	290.7	30	21

Figure 6.6 Latent Skin Heat Loss vs Time; Experimental Data from Hardy [72]

radii (or vasomotor responses), and entropy generation. The main reason for choosing to simulate mean skin temperature and skin blood vessel radii lies in the fact that skin temperature (ST) has been well established by Shusterman et al. [27] as an indicator of peripheral stress response. Skin temperature is an indirect measure of sympathetic nervous system. It has been found that skin temperature is related to peripheral blood flow as measured by plethysmography [20]. Thus, increases or decreases in skin temperature which is related to vasodilation or vasoconstriction of skin blood vessels respectively is demonstrated through computer simulation results. According to Cabanac [74], mean skin temperature is controlled by behavioral means in humans, and it has been considered as the basis for comfort. In a neutral thermal environment for a human being at rest, 33°C constant skin temperature is the result of a thermal equilibrium. It is thus quite remarkable that the skin temperature is not only a source of information, but also an interface between the environment and the thermal core temperatures resulting in thermal neutrality. Thus, simulation of both skin temperature and skin blood vessel radii (vasomotor response) would demonstrate quantitatively the relationship between behavioral and autonomic responses. Further, entropy generation, which is used as one of the responses, provides a global measure of chaos or thermal discomfort in the human body [9]. Thus, entropy generation in the human body provides a global measure that specifies the extent of chaotic motions and reactions occuring within the body [9]. Therefore, entropy generation is chosen as a global **Objective Thermal Stress Response (OTSR)** of the human body to the changes in environmental conditions, physical activity, and clothing types.

6.2.1 Environmental Conditions

The most important environmental variables which influence the condition of human thermal comfort are:

(i) Air temperature
(ii) Mean radiant temperature
(iii) Relative humidity
(iv) Air velocity

In this simulation to observe the effects of environmental variables on peripheral thermal stress responses, the environmental air temperatures ranged from 7°C to 37°C and the humidity conditions from 30% to 70%. The mean radiant temperature is approximated to be the same as the environmental air temperature [43, 44]. The air velocity is accounted for through the selection of values for convection heat transfer coefficient which are estimated to be 1.12 J/hr-cm^2-° C and 2.24 J/hr-cm^2-° C for 1.0 and 2.0 MET (1 MET = 58.2 W/m^2 of metabolic activity) respectively. However, the radiation heat transfer coefficient is approximated to be 1.7 J/hr-cm^2-° C [7]. As a result of approximation, the number of environmental variables are reduced from four to two which include air temperature and relative humidity.

(i) Air Temperature

Several physiological studies have established the fact that blood flow is one of the major fluid flow phenomena in the human body responsible for heat transfer from the body core to the peripheral skin [75]. Of the total amount of blood (the circulating blood volume) pumped by the heart, about 5 percent flows through the skin blood vessels. When the air temperature decreases from 310K to 280K, the temperature difference between the skin and the environment is increased; this causes an increased heat loss through conduction and radiation. A reduced heat flow to the skin results in a gradual lowering of the skin temperature as shown in Fig. 6.7. This results in a temperature gradient between the skin and the environment which eventually leads to vasoconstriction of the skin blood vessels causing a reduction in skin blood vessel radii and blood flow as demonstrated in Fig. 6.8. On the hotter side, when the air temperature increases from 280K to 310K, there is vasodilation of skin blood vessel radii as indicated in Fig. 6.8 causing an increased heat transfer from the core to the peripheral skin. This causes gradual increase in skin temperature as shown in Fig. 6.7. Thus, both Figs. 6.7 and 6.8 demonstrate the human peripheral stress response to changes in air temperature for a light clothing of thermal resistance (I_{cl} = 0.69 clo), relative humidity of 30% and physical activity corresponding to resting condition (M = 21 J/hr-cm^2-° C). Figure 6.9 shows the variation of entropy generation which indicates a lower value for higher air temperature (T_{air}=310K) and higher value for lower air temperature (T_{air}=280K) indicating an increase of heat production in the human body to balance the cooler environment. Further, it is observed that variation of entropy generation level is inversely proportional to that of skin temperature and blood vessel radii.

(ii) Relative Humidity

Some studies [76, 77] have shown that after a prolonged stay in an enclosure, the influence of temperature is not affected by the humidity of the air. The following combinations of air temperature and relative humidity produce the same level of thermal comfort in humans [18]:

70% RH and 20° C
50% RH and 20.5° C
30% RH and 21° C

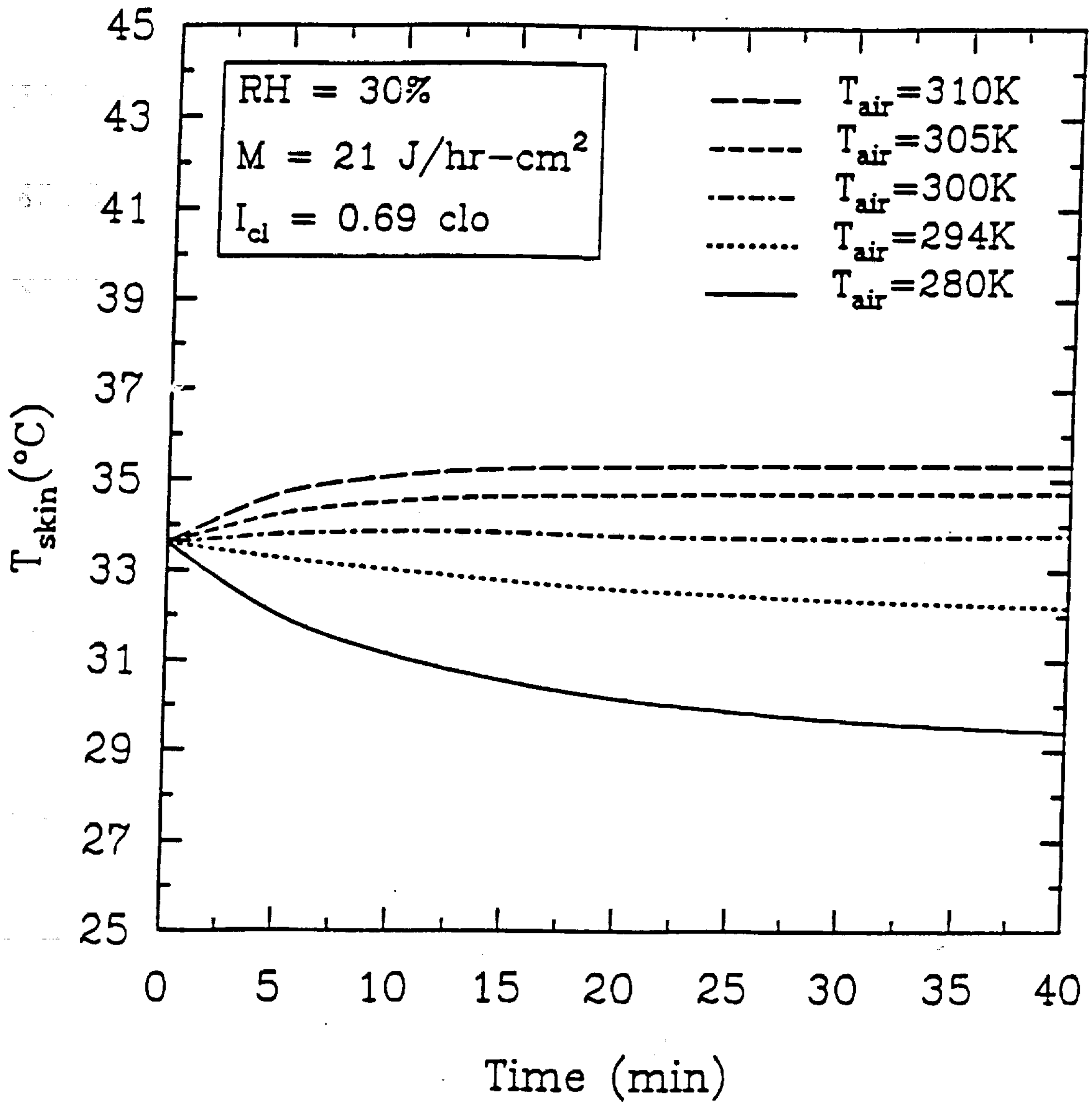


Figure 6.7 Effect of Air Temperature on Mean Skin Temperature

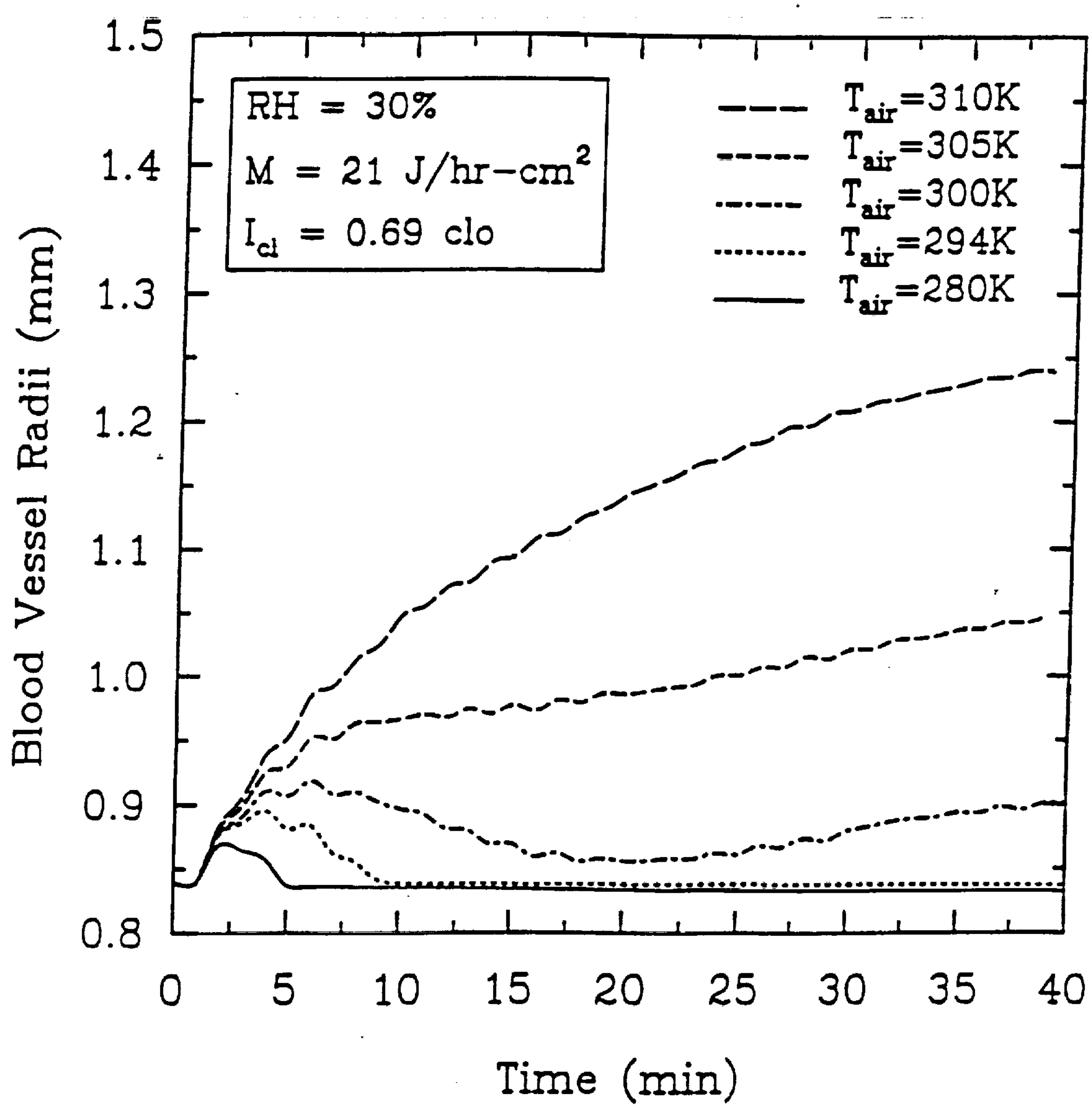


Figure 6.8 Effect of Air Temperature on Skin Blood Vessel Radi

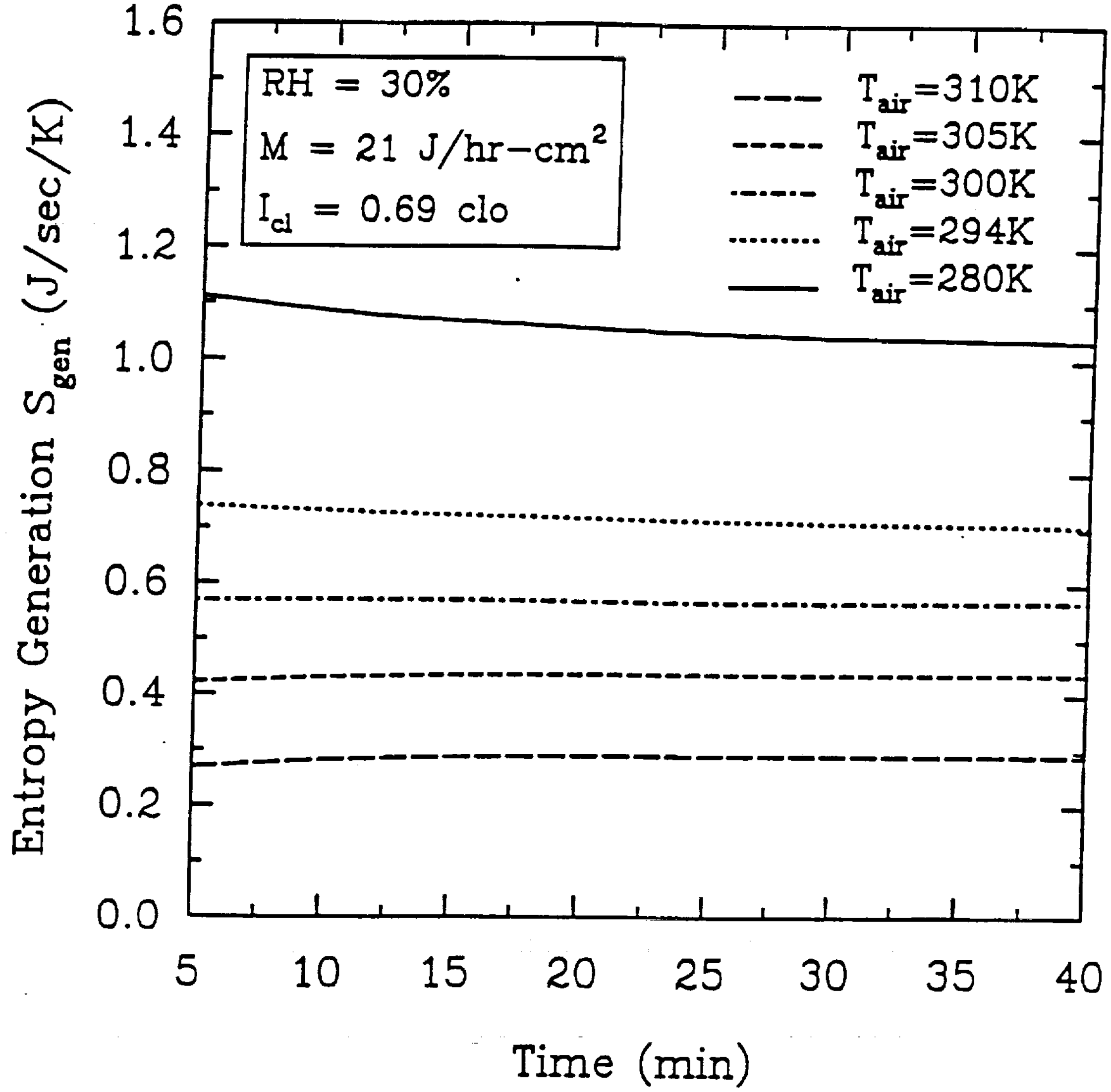


Figure 6.9 Effect of Air Temperature on Entropy Generation

Therefore, it is clear that within the range of 30-70%, the relative humidity has little influence on peripheral stress responses. As we observe from Figs. 6.10 and 6.11, there is not much significant deviation in mean skin temperature and skin blood vessel radii for varying relative humidity values ran from 30% to 70%. The other fixed conditions include light clothing of thermal resistance (I_{cl} = 0.69), air temperature of 294K and a resting condition which corresponds to a metabolic rate (M = 21 J/hr-cm^2). A sudden increase in the radii of skin blood vessels is observed during the intial ten-minute period which is attributed to the "fight-or-flight" autonomic thermal peripheral stress response. After this initial period of adjustment, the human thermal system attains the thermal neutrality. As mentioned in [11], it can be assumed that between 18 - 24 ° C the relative humidity can fluctuate between 30-70% without creating thermal discomfort. This is clearly demonstrated in Fig. 6.12 that the effect of changing relative humidity in the range of 30% to 70% on entropy generation is insignificant. However, the variation of entropy generation is proportional to that of skin temperature and blood vessel radii.

6.2.2 Physical Activity

The activity level of a human being is described quantitatively as the metabolic free energy production 'M' expressed per unit body surface area. Some of this energy may be used to perform external work, but most is lost as heat from the body. The metabolic rate is estimated by measuring the rate of oxygen consumption. A great deal of information is available in the literature on the metabolic rate associated with different physical activities [73]. Thermal comfort largely depends on the type and intensity of work performed [47]. Physical work in the cold may lead to increased heat production and hence to decreased

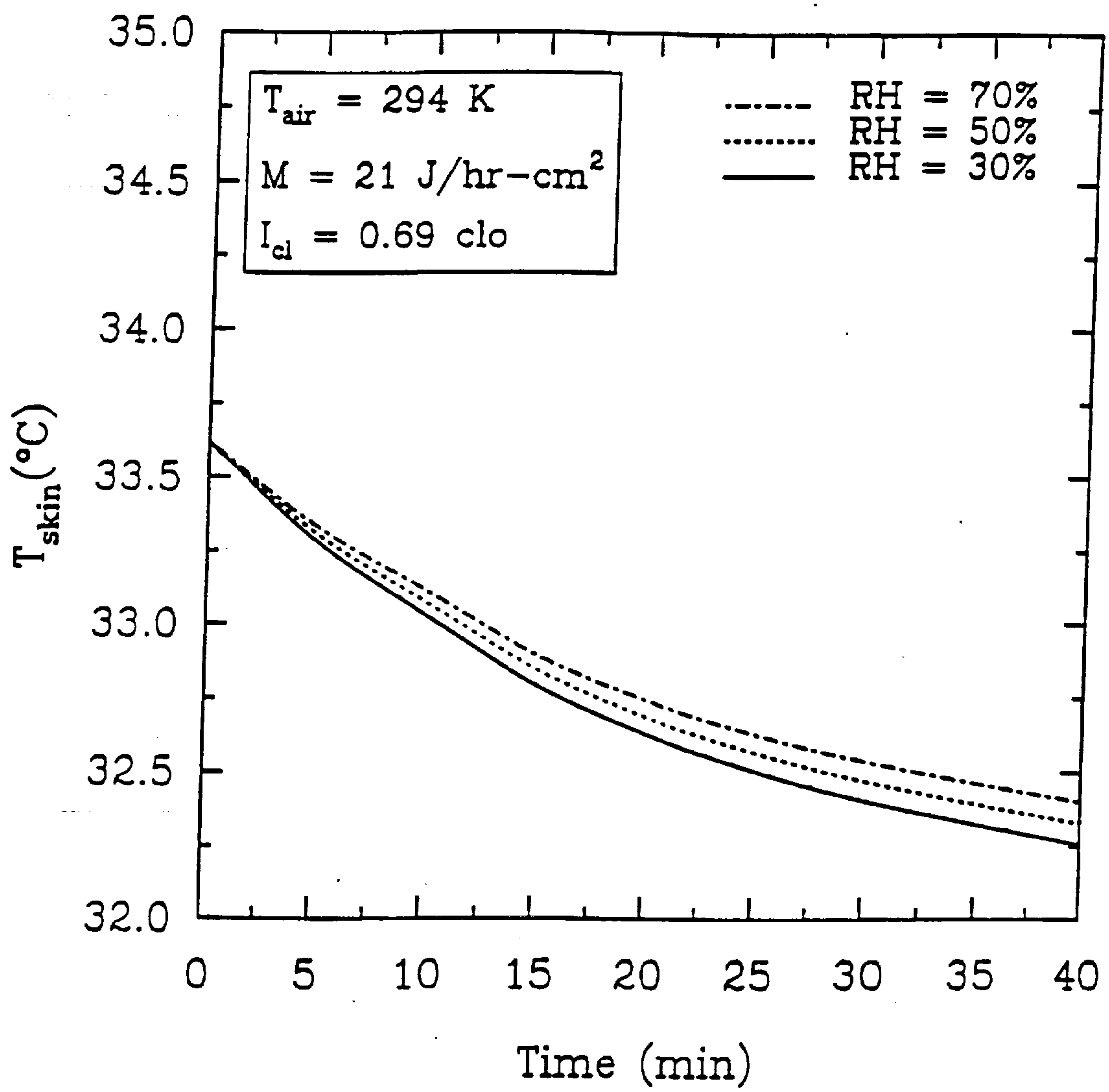


Figure 6.10 Effect of Relative Humidity on Mean Skin Temperature

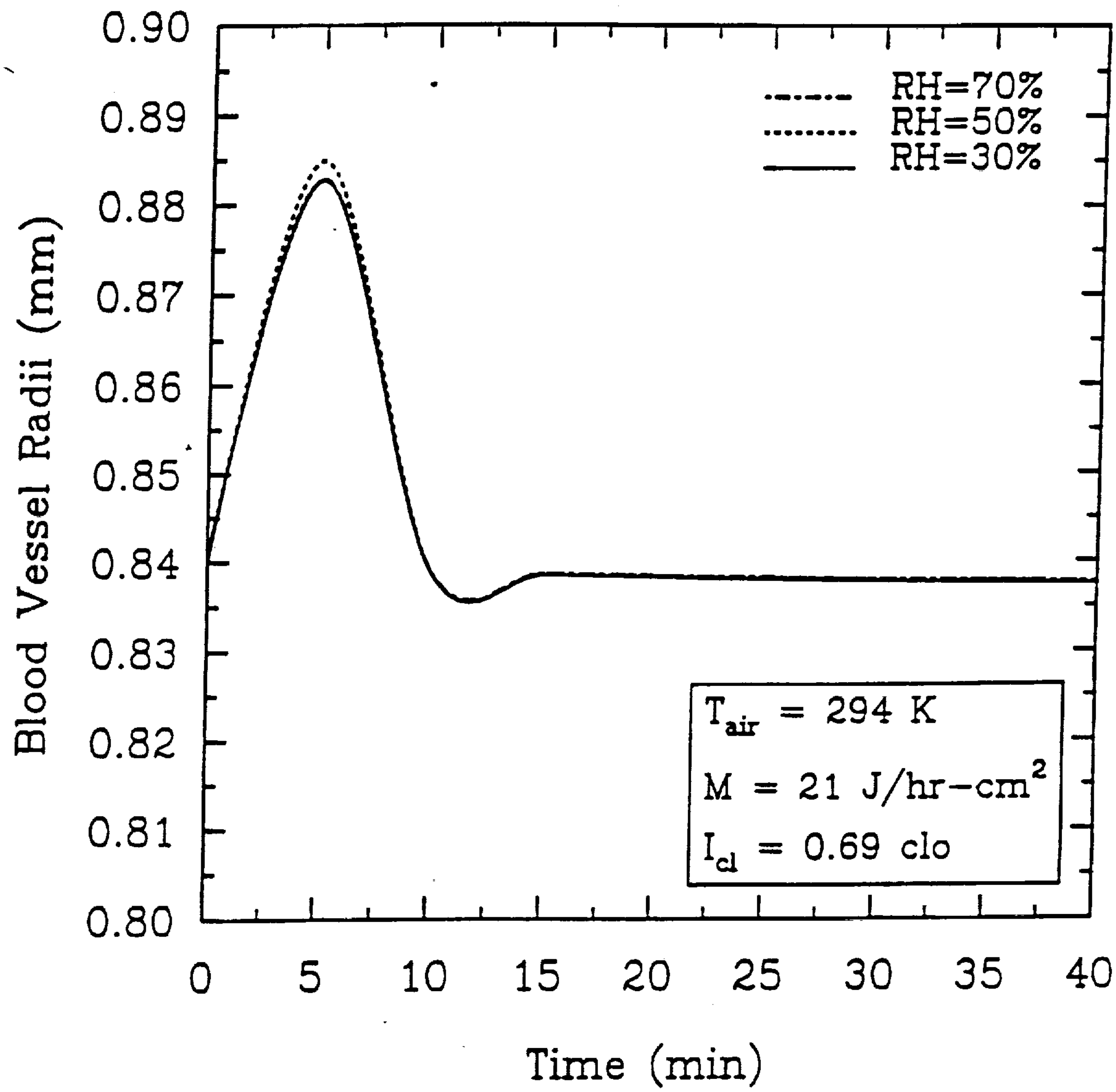


Figure 6.11 Effect of Relative Humidity on Skin Blood Vessel Radii

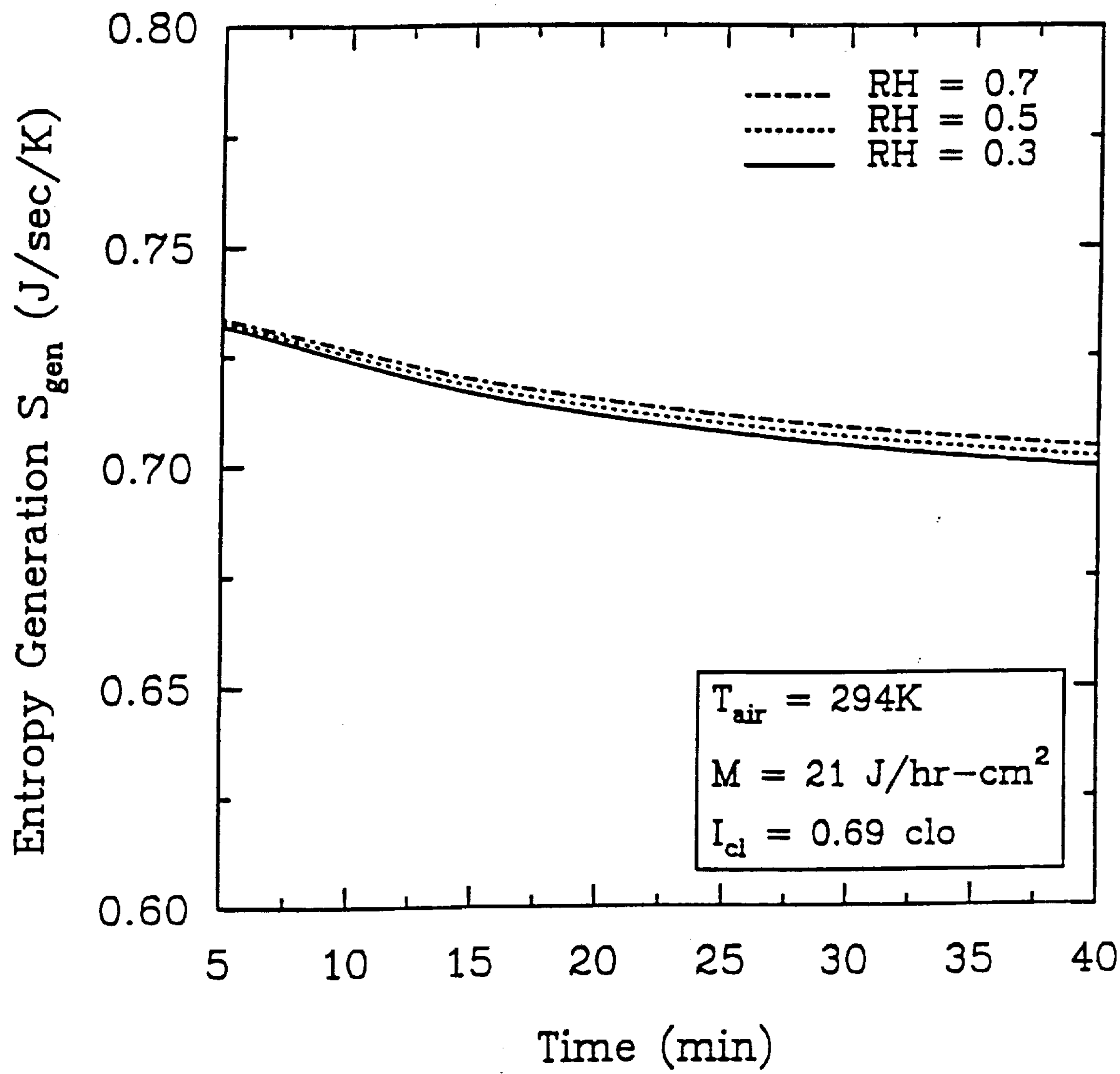


Figure 6.12 Effect of Relative Humidity on Entropy Generation

sensitivity to the cold environment, while in the heat, hard physical work could be highly detrimental to the attainment of energy balance which could lead to hyperthemia.

It has been stated in [78] that the average skin temperature in the relative steady state is a linear function of the ambient air temperature and is relatively independent of the level of exercise. The two major independent variables in evaluating the effect of exercise on temperature regulation are the air temperature and the level of metabolic rate. Thus, keeping the air temperature fixed at 294K, RH at 30% for light clothing with thermal resistance of $I_{cl} = 0.69$, it is observed from the Figs. 6.13 and 6.14 that there is not much significant effect on peripheral skin temperature and skin blood vessel radii. Also, in Fig. 6.14, the initial rapid increase in blood vessel radii is attributed to behavioral stress response due to exercise. It is concluded that for a given environmental condition and clothing type, the effect of physical activity on peripheral thermal stress responses is not significant. However, change in levels of physical activity has significant effect on the sensitivity of entropy generation as shown in Fig. 6.15. As metabolic rate increases from basal value, the relationship between mean skin temperature and entropy generation variation becomes inversely proportional.

6.2.3 Clothing

Humans wear clothes under normal conditions. The transfer of heat and mass (moisture) from the skin through the clothing to the environment is an important factor in thermal comfort. Clothing insulation is usually described as a single equivalent uniform layer over the whole body. Its insulating value is expressed in terms of "clo" units, defined as 1 clo = 0.155 $m^2 \cdot {}^\circ C/W$ [79]. The effect of clothing on thermal responses is investigated

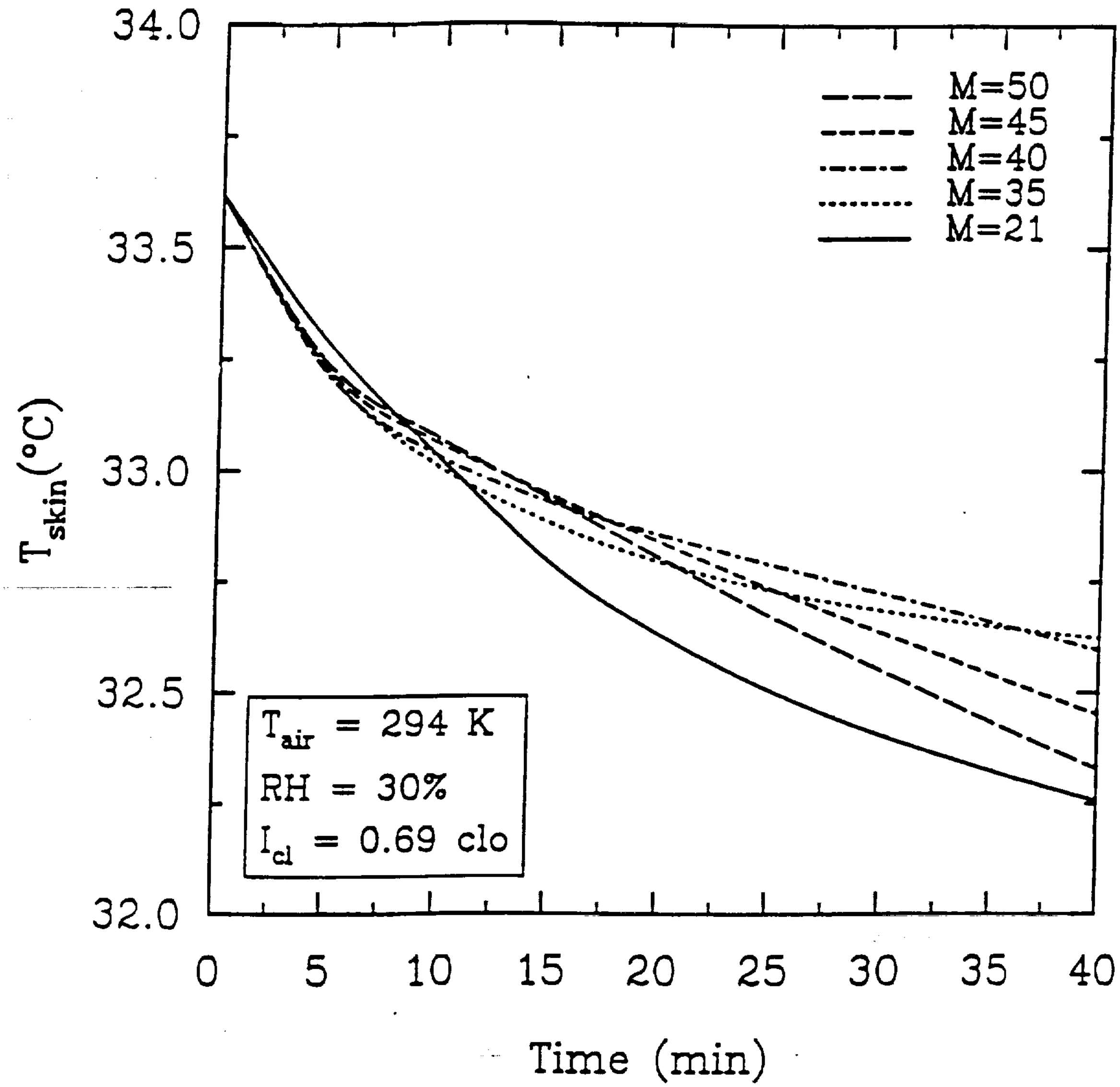


Figure 6.13 Effect of Physical Activity on Mean Skin Temperature

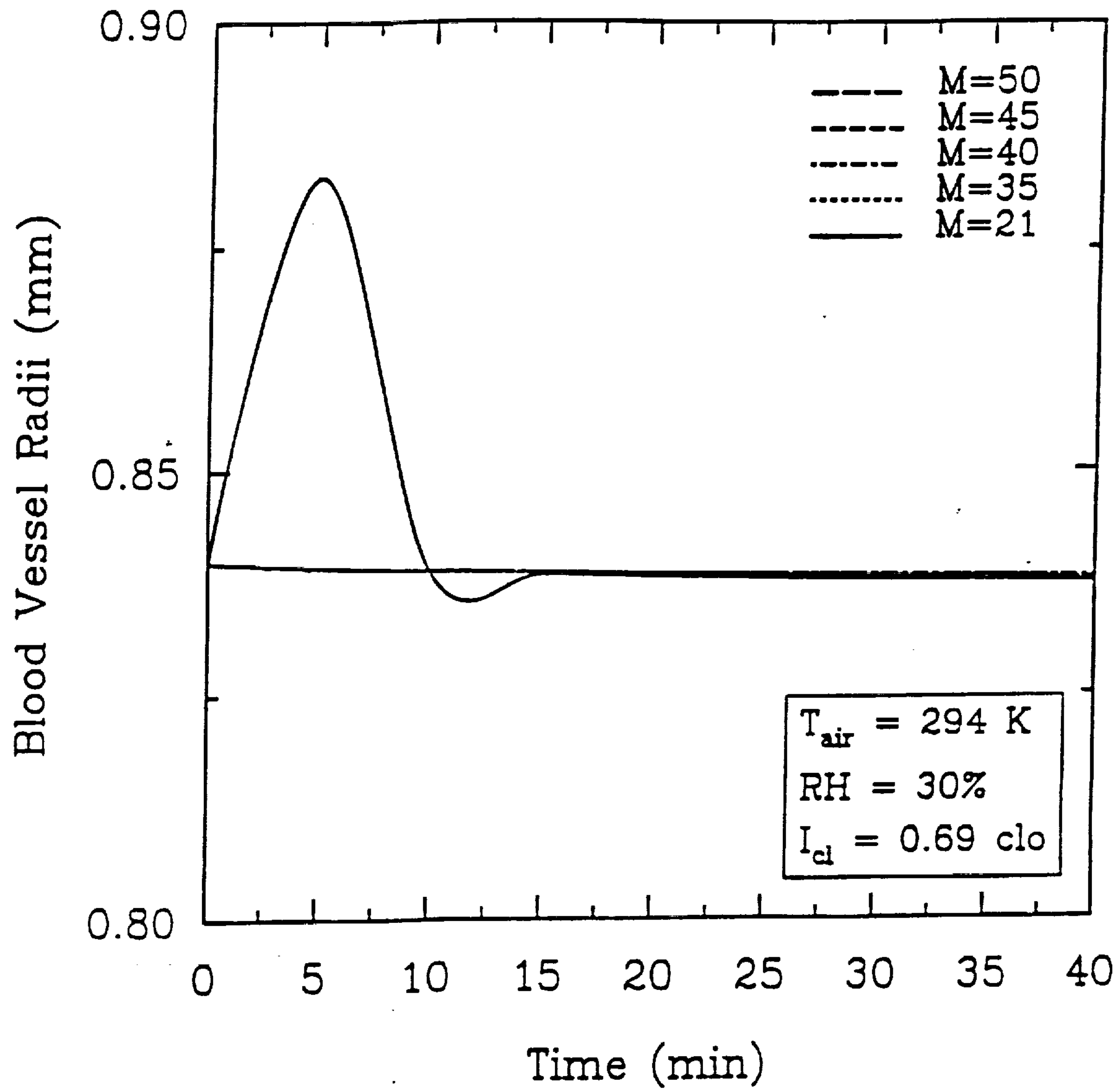


Figure 6.14 Effect of Physical Activity on Skin Blood Vessel Radii

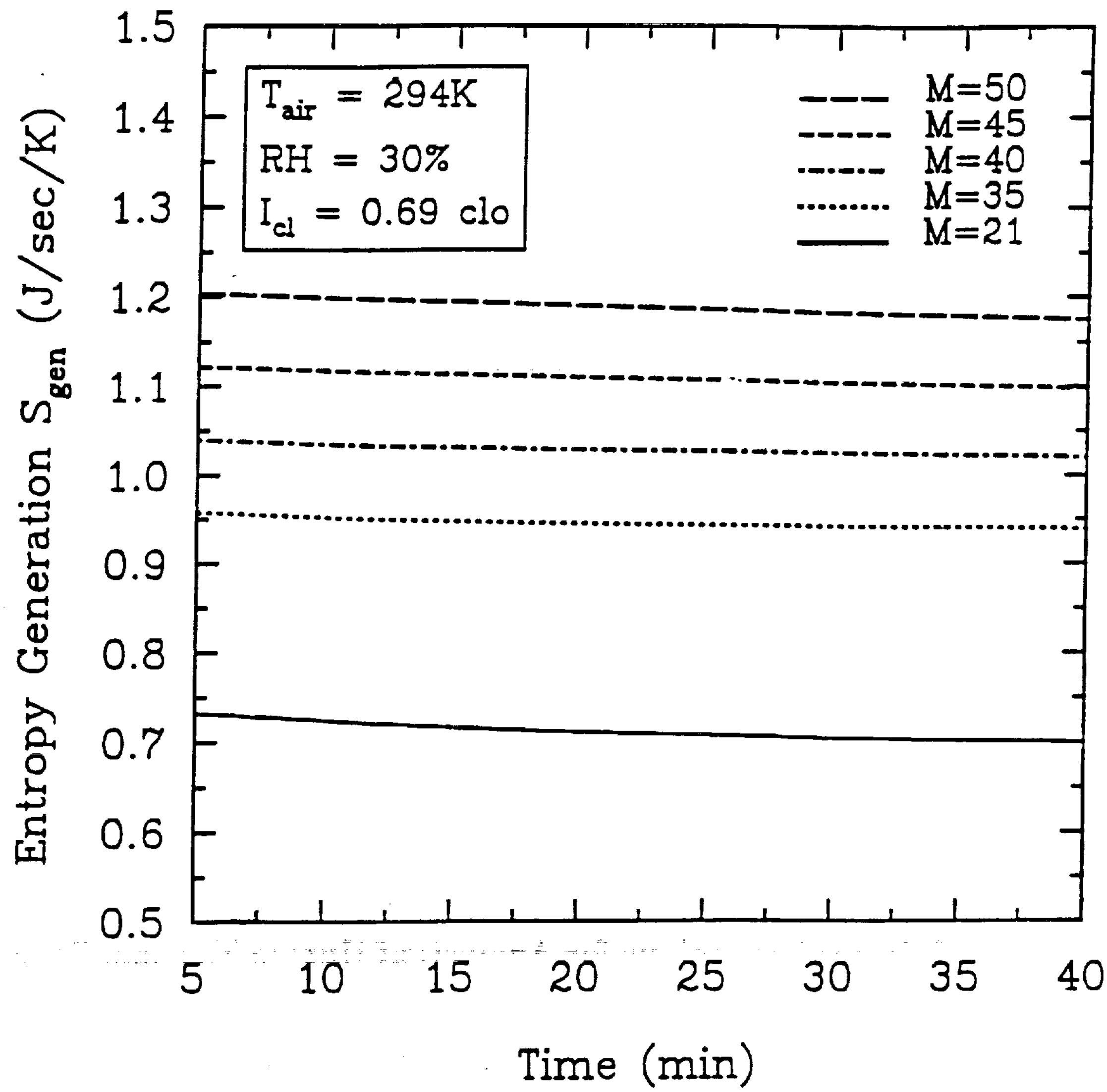


Figure 6.15 Effect of Physical Activity on Entropy Generation

using three kinds of clothing which include light clothing with a thermal resistance value of I_{cl} = 0.21 clo; medium clothing with I_{cl} = 0.69 clo; and heavy clothing with I_{cl} = 1.72 clo. The purpose of this simulation is to obtain quantitative data describing the dynamic nature of heat and moisture humans dissipate to their surroundings and to investigate the human comfort level for various types of clothing. The simulation was conducted for a period of forty minutes for constant environmental conditions of 294K air temperature, 30% relative humidity and a physical activity level corresponding to a resting condition (M = 21 J/hr-cm^2). It is observed from Figs. 6.16 and 6.17 that as the thermal resistance (clo value) increases from light (I_{cl} = 0.21) to heavy clothing (I_{cl} = 1.72), both mean skin temperature and skin blood vessel radii increase and remain at a relatively higher value throughout the 40-minute simulation period. It is concluded that for a given environmental condition and a level of physical activity, the impact of clothing types is quite significant on the peripheral thermal stress responses and thus affects the overall thermal comfort. Further, it is observed from Fig. 6.18 that entropy generation increases and its variation is directly proportional to that of skin temperature and blood vessel radii.

6.3 Hybrid Technique for Analysis of Human Thermal Behavior

The most important physical variables which influence the human thermal comfort level are air temperature (T_{air}) and relative humidity (RH) for a given clothing and physical activity. As this study is focussed mainly on the analysis of human behavior during coginitive tasks in aerospace or any industrial enclosures, the physical activity is assumed to be sedentary correspondng to the resting condition (Metabolic rate, M = 21 J/hr-cm^2). Also, clothing worn by humans during the performance of cognitive tasks is expected to

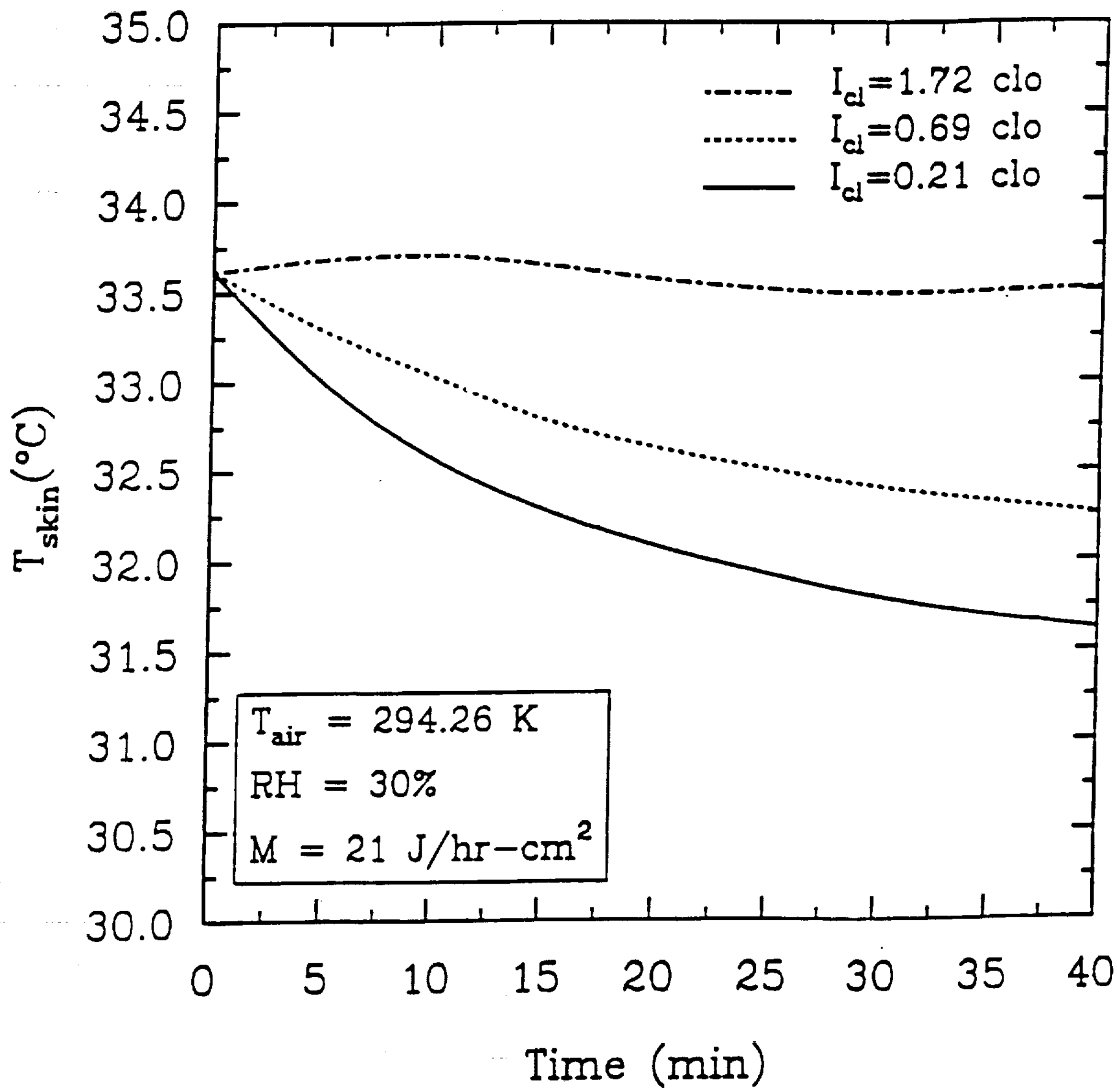


Figure 6.16 Effect of Clothing on Mean Skin Temperature

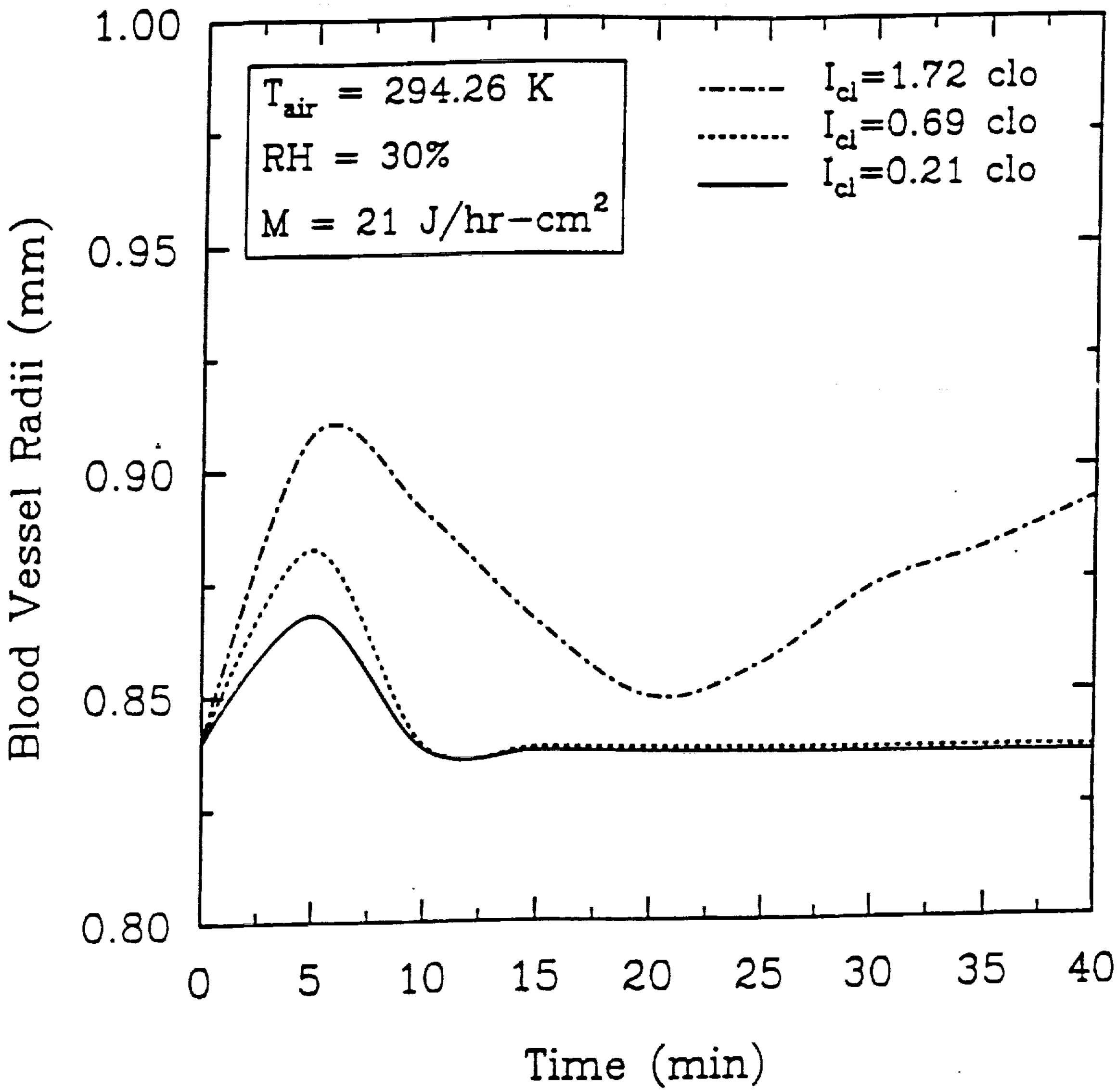


Figure 6.17 Effect of Clothing on Skin Blood Vessel Radii

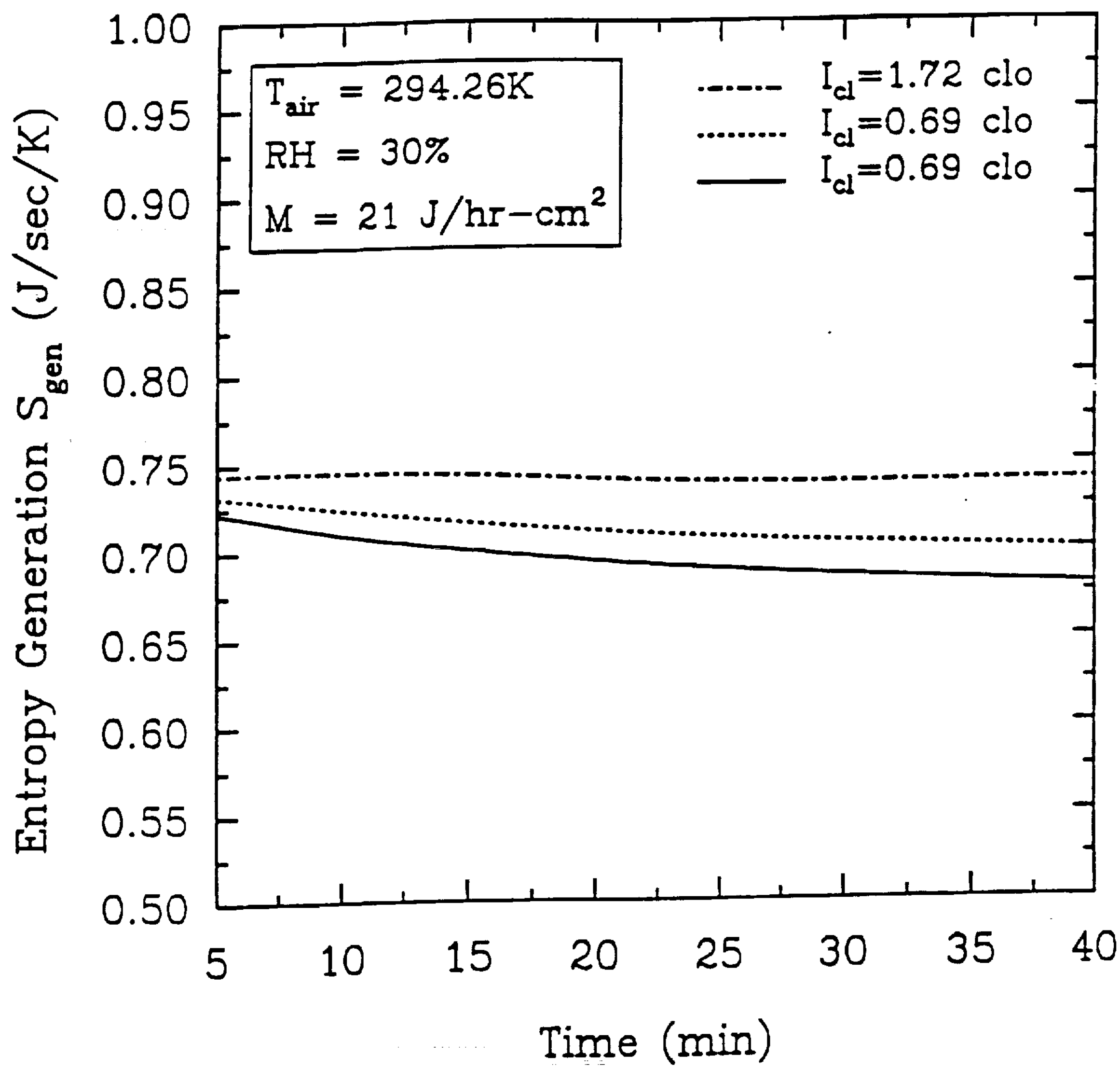


Figure 6.18 Effect of Clothing on Entropy Generation

be of medium thermal resistance which corresponds to a value of I_{cl} = 0.69 clo. Thus, only two environmental variables that will be affecting the human attention and vigilance capabilities during cognitive tasks are air temperature and relative humidity. The question is, what kind of human physiological response is most appropriate for analyzing the human behavior? Following the global approach, entropy generation is chosen as the response of the whole human body to the changes in environment. This is mainly due to the fact that entropy generation provides a global measure of activeness or chaos or stress level in the body as shown in a study by Boregowda et al. [9] and in the previous Sec. 6.2. Therefore, from now onwards in this chapter, entropy generation will be used as a parameter that quantifies thermal stress level and thus would be known as **Objective Thermal Stress Response (OTSR, J/sec/K)** according to Postulates IX and X.

Thermal comfort can be achieved by many different combinations of the environmental variables in technical systems. In any case, thermal comfort is the "product" which is produced and sold to the customers by the heating and air- conditioning industry. Therefore, it is very important to define and standardize the quality of this "product" called thermal comfort. In order to define and standardize this very subjective "product", there has to be an objective measure of human thermal stress that indicates the level of comfort or discomfort. At this point, the entropy generation in the human body is introduced as an objective measure of thermal stress based on the Unified Stress Response Theory (USRT) stated in Sec. 3.6. The entropy generation is a response of the whole human body to the environmental stimuli from a thermodynamic standpoint. With this approach, the ambiguity and uncertainty of the subjective analysis of thermal comfort is overcome. However, it is crucial to prove quantitatively that entropy generation is a valuable parameter that quantifies the level of thermal comfort which is presented in the next section, Sec. 6.4. Before the validation process, it is interesting to observe the cross effects of ambient temperature and humidity on the "objective" human thermal response which is entropy generation.

The technique of defining and investigating all possible conditions in an experiment involving multiple factors is known as the **design of experiments** [46]. This section is primarily devoted to demonstrate the integration of design of experiments approach developed by Fischer [45] and the entropy theory. The result of this integration is the synthesis of a **Hybrid Technique** to analyze human thermal behavior using the results of human thermal simulation. The hybrid technique is illustrated through five different cases of human thermal simulations conducted for different combinations of air temperature and relative humidity for the given conditions of physical activity and clothing.

Consider an Environmental Control Industry planning to design an optimal internal environment. The designers have standardized all other variables except the air temperature and relative humidity. The other fixed variables include moderate physical activity ($M = 21$ J/hr-cm^2) and clothing ($I_{cl} = 0.69$) for a human being performing a cognitive task. Two levels of air temperature, T_{air1} and T_{air2} and two levels of relative humidity, RH_1 and RH_2 are selected. (Subscripts 1 and 2, respectively refer to the low and high levels of each factor). Traditionally, in order to select the best combination of these factors or variables that meet the comfort level of most of the occupants in an enclosure, an experimental survey involving human subjects need to be conducted. This approach is statistically based and it takes into account the subjective sensations of the human subjects contrary to the objective analysis. In this regard, there is lot of ambiguity and uncertainty in the responses of the human subjects who would express their feelings of "warmth"or "cool" on a subjective scale. In order to overcome this fuzziness, a global measure of human response to environmental stimuli is constructed using the second law of thermodynamics as already explained in Sec. 5.2. In this context, entropy generation is the natural variable that gives the quantitative measure of thermal stress for each individual. It is this quantity which is used in the hybrid technique in the place of subjective responses.

Each one of the five different cases presented here is one of the simplest cases of design of experiments [46]. It involves two factors (air temperature and relative humidity) at two different levels (high and low) that affect the overall human thermal comfort level. Such an experiment is described as a 2x2 factorial experiment. There are four (2^2) possible treatments or combinations. For each one of these combinations of air temperature and relative humidity, a computer simulation is conducted, thus resulting in four simulations for each case and twenty simulations for the entire demonstration of hybrid technique. Each simulation was conducted for one hour for a moderate physical activity (M = 21J/hr-cm^2) and clothing (I_{cl} = 0.69). The steady-state response at the end of the simulation period (60th minute) were chosen for the calculation of entropy generation that provides the measure of thermal stress response. The steady-state responses include core and skin temperatures, heat losses, and heat production in the body. The thermal stress responses to two factors (RH and T_{air}) are given in Tables 6.1 - 6.5 and Figs. 6.19 - 6.23.

Case (i): Extreme Environmental Conditions

Examination of individual's thermal stress response (S_{gen}) shows a decrease in its value for the relative humidity level of 90% at the lower level of air temperature (260K).

Table 6.1 Objective Thermal Stress Responses (J/sec/K) to Extreme Environmental Conditions

	Relative Humidity Level			
Level of Air Temperature	RH_1 = 10%	RH_2 = 90%	Mean	Mean Response (Air Temp.) (T_{air1} - T_{air2})
T_{air1} = 260K	2.0497	1.1012	1.5755	1.0567
T_{air2} = 315K	0.4707	0.5668	0.5188	
Mean	1.2602	0.8340	Grand Mean 1.0471	
Mean Response (Relative Humidity) (RH_1 - RH_2)	0.4262			

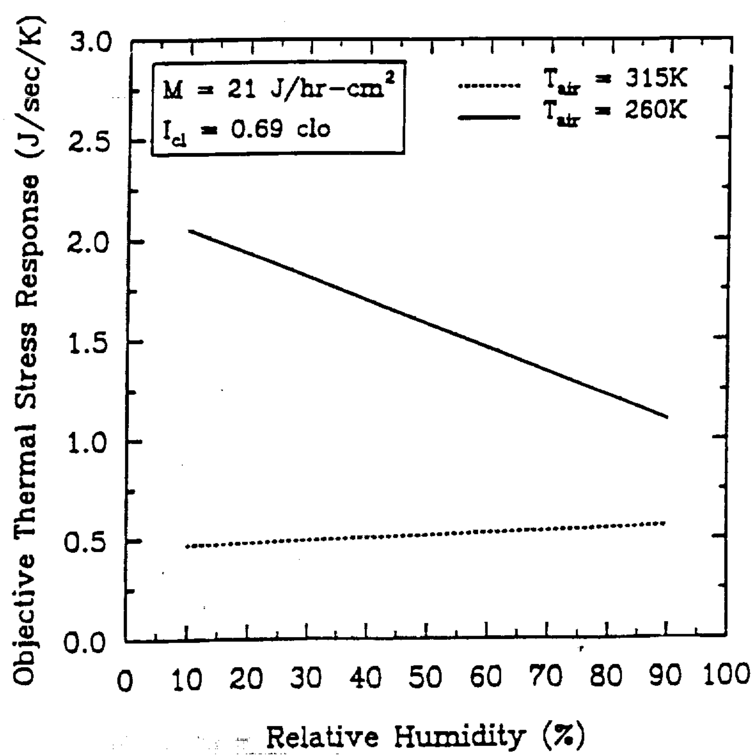


Figure 6.19 Extreme Environmental Conditions

Table 6.2 Objective Thermal Stress Responses (J/sec/K) to Threshold Environmental Conditions

Level of Air Temperature	Relative Humidity Level: $RH_1 = 20\%$	Relative Humidity Level: $RH_2 = 80\%$	Mean	Mean Response (Air Temperture) ($T_{air1} - T_{air2}$)
$T_{air1} = 280K$	1.2899	1.2875	1.2887	0.9854
$T_{air2} = 310K$	0.2883	0.3184	0.3033	
Mean	0.7891	0.8029	Grand Mean 0.7960	
Mean Response (Relative Humidity) ($RH_1 - RH_2$)	-0.0138			

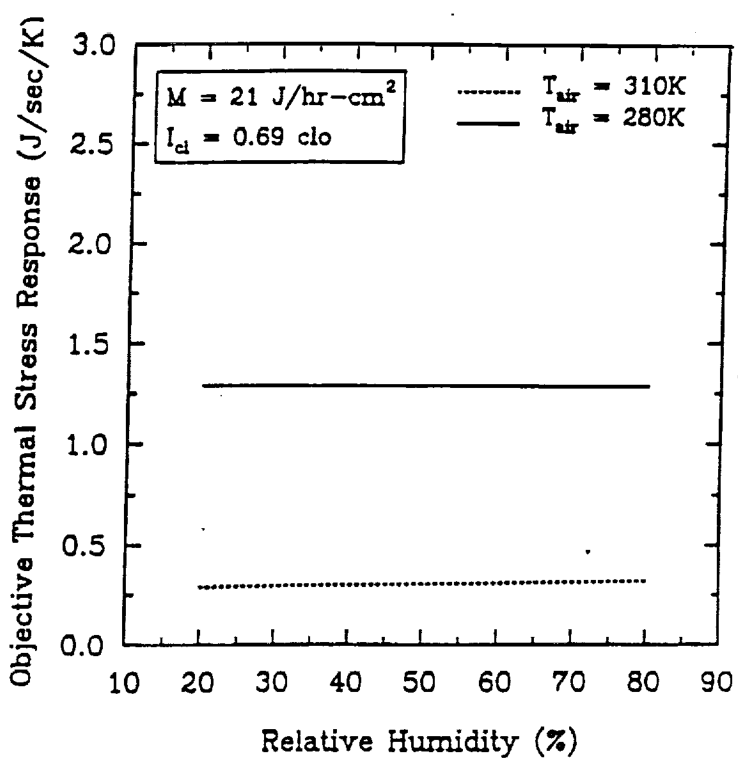


Figure 6.20 Threshold Environmental Conditions

Table 6.3 Objective Thermal Stress Responses (J/sec/K) to Mild Environmental Conditions

Level of Air Temperature	Relative Humidity Level		Mean	Mean Response (Air Temp.) (T_{air1} - T_{air2})
	RH_1 = 30%	RH_2 = 70%		
T_{air1} = 290K	0.9374	0.9333	0.9354	0.4968
T_{air2} = 305K	0.4361	0.4409	0.4385	
Mean	0.6868	0.6871	Grand Mean 0.6869	
Mean Response (Relative Humidity) (RH_1 - RH_2)	-0.0003			

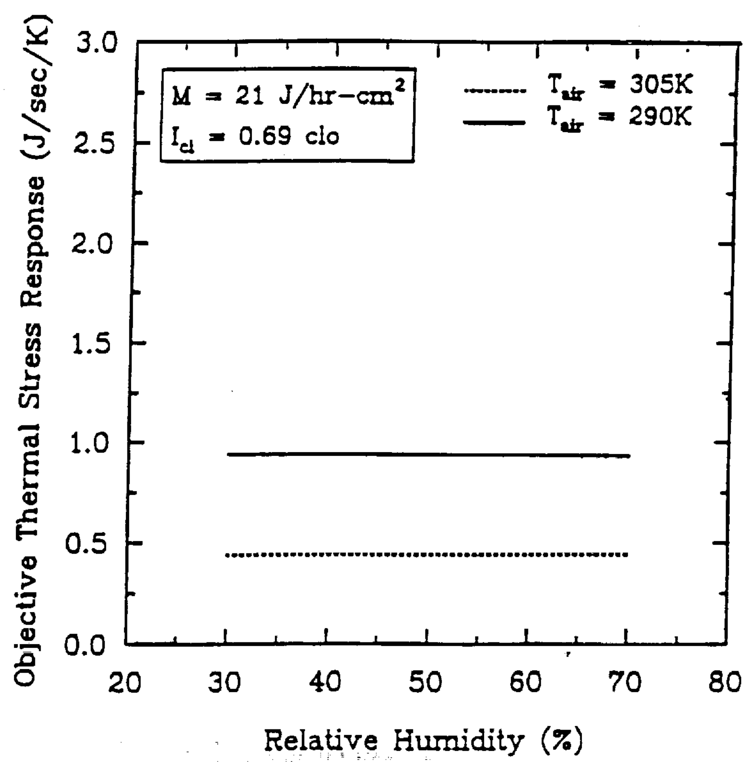


Figure 6.21 Mild Environmental Conditions

Table 6.4 Objective Thermal Stress Responses (J/sec/K) to Comfortable Environmental Conditions

	Relative Humidity Level			
Level of Air Temperature	$RH_1 = 40\%$	$RH_2 = 60\%$	Mean	Mean Response (Air Temp.) ($T_{air1} - T_{air2}$)
$T_{air1} = 294K$	0.7005	0.7029	0.7017	0.1246
$T_{air2} = 300K$	0.5756	0.5786	0.5771	
Mean	0.6380	0.6408	Grand Mean 0.6394	
Mean Response (Relative Humidity) ($RH_1 - RH_2$)	-0.0027			

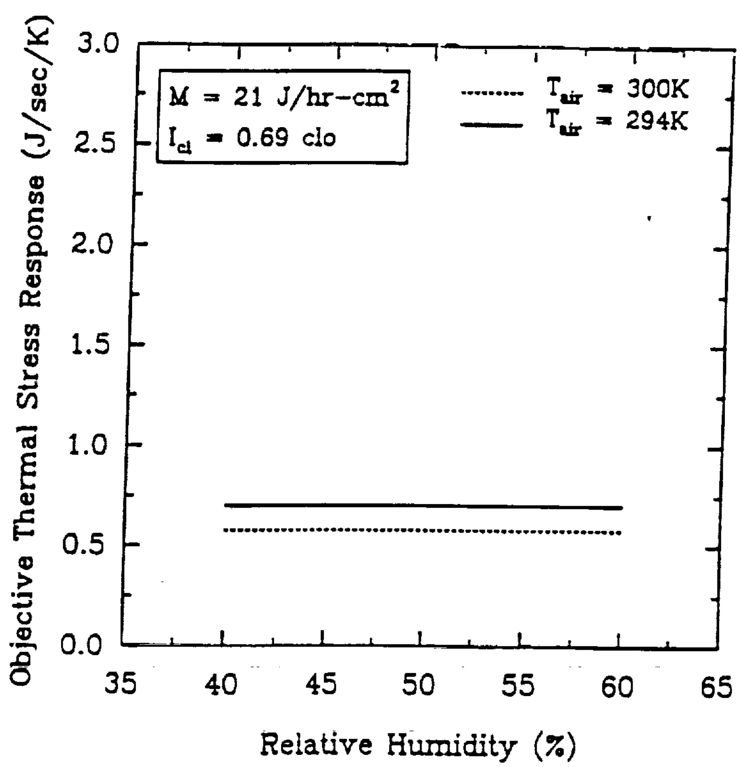


Figure 6.22 Comfortable Environmental Conditions

Table 6.5 Objective Thermal Stress Responses (J/sec/K) to Stuffy Environmental Conditions

Level of Air Temperature	Relative Humidity Level		Mean	Mean Response (Air Temp.) (T_{air1} - T_{air2})
	RH_1 = 60%	RH_2 = 80%		
T_{air1} = 291K	0.8865	0.8791	0.8828	0.2422
T_{air2} = 297K	0.6383	0.6430	0.6407	
Mean	0.7625	0.7611	Grand Mean 0.7618	
Mean Response (Relative Humidity) (RH_1 - RH_2)	0.0014			

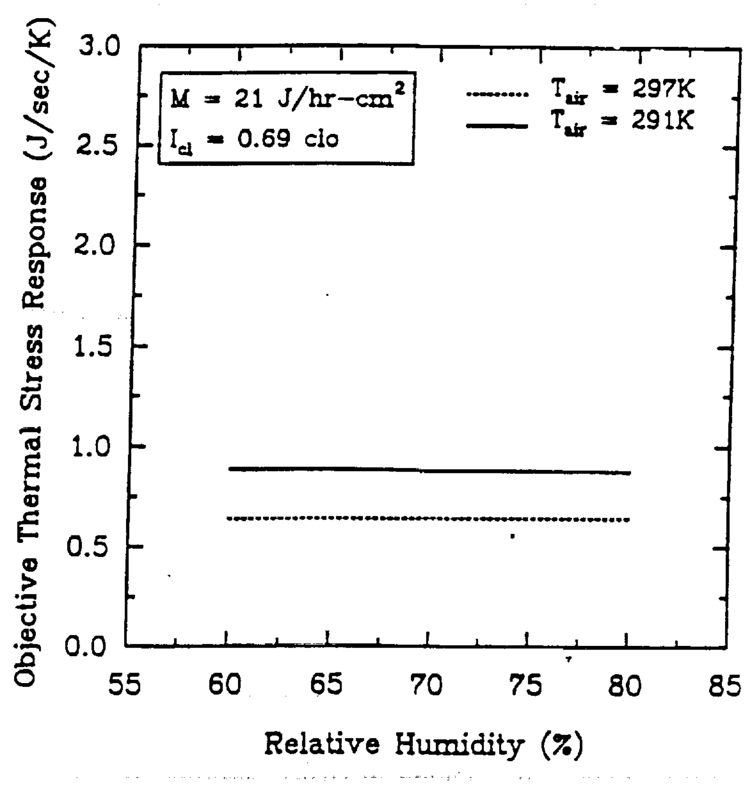


Figure 6.23 Stuffy Environmental Conditions

But the stress level increases when a higher level of air temperature (315K) is introduced. These increases are called the simple effect of relative humidity. On the other hand, for the higher air temperature, the stress level decreased from 2.0497 to 0.4707 J/sec/K at relative humidity level of 10% and it decreased from 1.1012 to a value of 0.5668 J/sec/K with the higher relative humidity of 90%. The mean response, i.e., the difference between the average effects at two levels of relative humidity (0.4262 J/sec/K), is called the main effect of relative humidity. Similarly, the main effect for air temperature is 1.0567 J/sec/K. The grand mean response which is average of all four stress responses is 1.0471 J/sec/K for extreme environmental conditions outside of comfort zone (see Table 6.1). The degree of interaction between two factors (air temperature and relative humidity) that affect the overall thermal stress responses is shown in Fig. 6.19. Figure 6.19 graphs the thermal stress response against one factor (relative humidity) for two levels of the second factor (air temperature). Nonparallel or skewed or intersecting lines would indicate some interaction between the two factors. Figure 6.19 indicates that there is interaction between air temperature and relative humidity that affects the thermal behavior or stress response in this case of extreme ambient conditions. However, the straight lines represent the relationship between the pairs of points and cannot be interpolated to obtain the OTSR.

Case (ii): Threshold Environmental Conditions

Table 6.2 shows the thermal stress response to threshold environmental conditions which lie within the comfort zone of the ASHRAE comfort chart [7]. A closer examination reveals that there is no change in stress response when relative humidity increases from 20% to 80% for an air temperature of 280K. While, there is a slight increase in stress response from 0.2883 to 0.3184 J/sec/K for an air temperature of 310K. On the other hand, for a relative humidity of 20%, the stress response decreases for increase in air temperature to 310K. The same trend is observed for a relative humidity of 80%. Regarding the main effects, the relative humidity has very little influence on individual stress response (-0.0138 J/sec/K) in the comfort zone. However, air temperature does show a significant effect on thermal stress response (0.9854 J/sec/K). The grand mean thermal stress response, which is the average of all four stress responses, decreases from 1.0471 in Case (i) to 0.7960 J/sec/K for this case. It is observed from Fig. 6.20 that the lines are almost parallel which indicates that there is not much interaction between the two factors (RH and T_{air}). Lack of interaction is attributed to the fact that the imposed environmental conditions are within the comfort zone.

Case (iii): Mild Environmental Conditions

When mild environmental conditions (30% and 290K; 70% and 305K) are introduced, the level of grand mean thermal stress response decreases from 0.7960 in Case (i) to 0.6869 J/sec/K for this case. Once again, it is observed that the main effect of the relative humidity is negligible (-0.0003 J/sec/K). However, air temperature still maintains its significant main effect with a value of 0.4968 J/sec/K, but lesser than those in Cases (i) and (ii). Table 6.3 and Fig. 6.21 show the human thermal response behavior. The interaction between the air temperature and relative humidity is found to be insignificant as shown by parallel lines in Fig. 6.21.

Case (iv): Comfortable Environmental Conditions

In the comfort zone, environmental conditions range from 40% to 60% RH and 294K to 300K air temperature. The grand mean thermal stress response reduces from 0.6869 in Case (iii) to 0.6394 J/sec/K for this case. The main effect of relative humidity is negligible, while that of air temperature decreases from 0.4968 in Case (iii) to 0.1246 J/sec/K. The thermal stress responses are shown in Table 6.4 and Fig. 6.22. From Fig. 6.22, it is clear that there is no interaction between the two environmental factors.

Case (v): Stuffy Environmental Conditions

According to Grandjean [18], the threshold at which the room begins to feel stuffy lies between the pairs of environmental factors, such as 80% RH at 291K and 60% RH at 297K. The simulations were conducted for these pairs of conditions. The results are shown in Table 6.5 and Fig. 6.23. The grand mean stress response increases from comfort value of 0.6394 in Case (iv) to 0.7618 J/sec/K for this case. The main effect of relative humidity is still insignificant, while that of air temperature shows a marked increase in its value from 0.1246 in Case (iv) to 0.2422 J/sec/K. From Fig. 6.23, slightly nonparallel lines indicate very little interaction between the environmental factors.

In order to observe the main effects of environmental factors and grand mean thermal stress responses, Fig. 6.24 is constructed for five different cases showing the overall trend in human thermal behavior for five different cases. On abscissa, five cases are numbered from one to five. The objective thermal stress responses to the main effects of environmental factors and grand mean response are marked on the ordinate. It is clear from Fig. 6.24, that the grand mean thermal stress response decreases in its value as the environmental factors (RH and T_{air}) gradually shift to the comfort zone as defined in ASHRAE comfort chart [7]. This gradual decrease occurs upto Case (iv), numbered 4 on abscissa. Then, there is slight increase in grand mean thermal stress response value for Case (v), number 5 on abscissa. The main effect of air temperature shows a clear trend with environmental conditions upto Case (iv) and increases slightly for Case (v), which represents

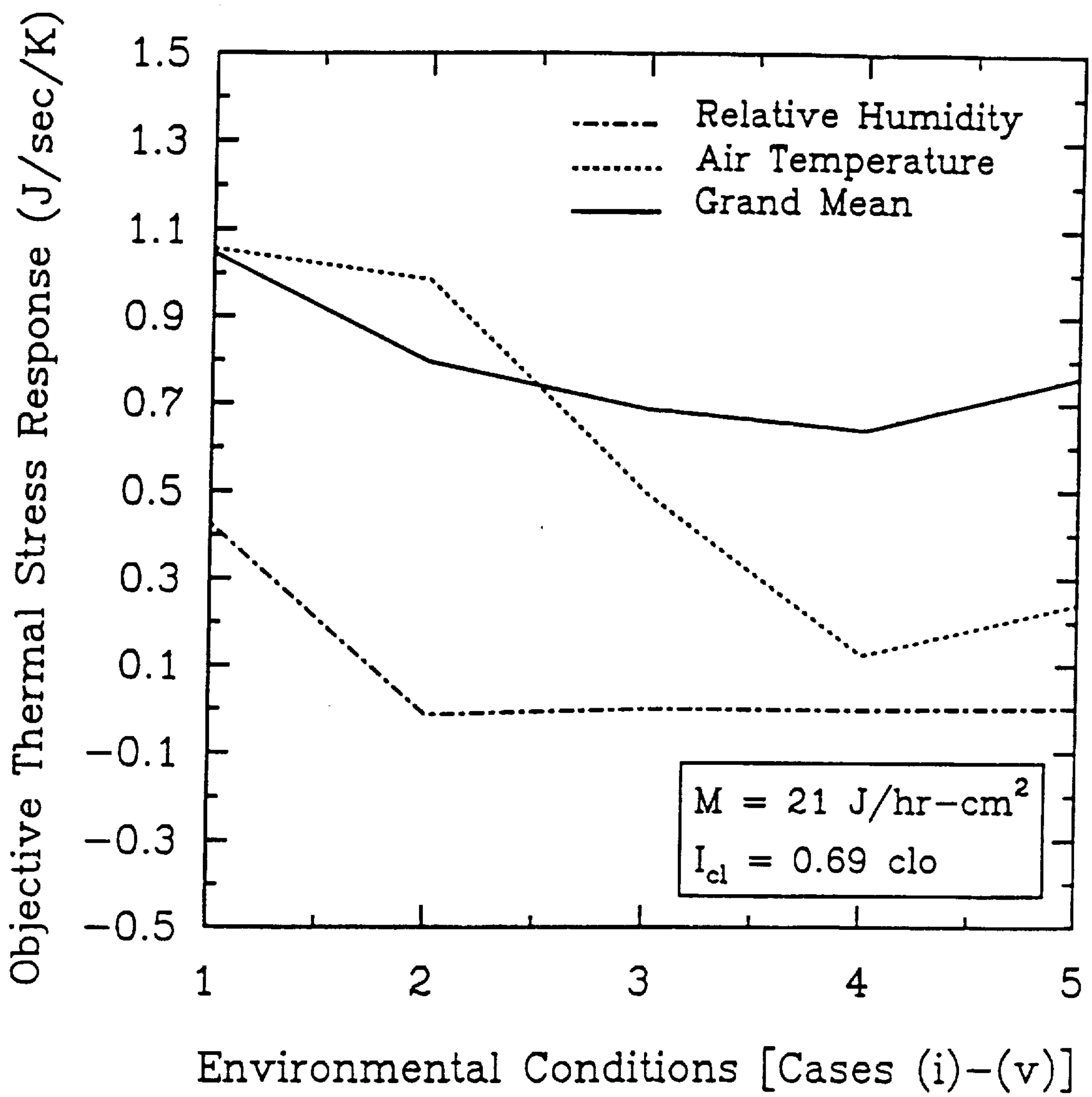


Figure 6.24 Objective Thermal Stress Responses versus Environmental Conditions

stuffy conditions. However, the relative humidity shows its significance in Case (i) which is an extreme environmental condition. Later, relative humidity becomes almost insignificant upto Case (v), indicating gradual transition to comfort zone.

So far, it has been observed that the thermal stress response value is quite sensitive to changes in environmental conditions. It provides a global measure of activeness or thermal discomfort in the body. Thus, it is a valuable parameter that could be used to obtain human thermal stress in the form of a single summative number. Now, the biggest challenge is to establish the value of thermal stress response for an optimum comfortable environmental condition. Once an optimum value of thermal stress corresponding to comfort level is established, then it becomes easier to demonstrate the deviation in comfort level from the equilibrium condition. This is demonstrated in Sec. 6.4 through the thermal stress level monitoring technique using an **Objective Thermal Stress Index (OTSI)** which is derived from Objective Thermal Stress Responses as illustrated in Sec. 5.2.

6.4 Thermal Stress Level Monitoring Using an Objective Thermal Stress Index (OTSI)

In this section, three different computer simulation studies are conducted to examine the pattern of human thermoregulatory behavior under different conditions. All three simulation studies cover the entire spectrum of environmental conditions ranging from most comfortable to extreme hot and cold. The feasibility of incorporating the concept of OTSI in human-machine systems for optimal human performance and safety is closely examined through the validation of Objective Thermal Stress Index. In order to establish the optimum comfort level or equilibrium condition, one-hour simulation is performed for a nude body at 50% RH and 75° F air temperature which corresponds to standard ASHRAE operating conditions [15]. In this comfort simulation, the steady-state response at the end of simulation is chosen as the Objective Thermal Stress Response (0.731841 J/sec/K) that corresponds to the thermal equilibrium or homeostasis in the human body. Further, all transient objective thermal stress responses obtained for other conditions are expressed as percentage deviations from this comfort or equilibrium value. The results from three different simulation studies are described in detail.

6.4.1 Effects of Relative Humidity and Clothing on Thermal Stress Level

In this study, all simulations conducted were of forty-minute period for a clothed human in comfortable conditions. The purpose of these simulations is to examine the effects of changing relative humidity and clothing on thermal stress. Figure 6.25 shows the influence of different relative humdities on variation of the OTSI which is a measure of thermal stress level. It has been observed that the relative humidity does not have significant effect on the human thermal stress response for a given air temperature of 294.26K, sedentary activity, and medium clothing of thermal resistance value 0.69 clo. It is concluded that the range of 30-70% RH lies in the comfort zone of ASHRAE comfort chart [15]. Thus, it is noted from Fig. 6.25 that there is negligible thermal discomfort in this range which is indicated by OTSI quantitatively approximately ranging from -1% to +7%.

Figure 6.26 shows the effect of different clothing types on variation of the OTSI for a given air temperature of 294.26K, 30% RH, and sedentary activity level of 21 J/hr-cm^2. The OTSI does indicate a small deviation from comfort level which is well within 10% for light (I_{cl} = 0.21 clo), medium (I_{cl} = 0.69 clo), and heavy (I_{cl} = 1.72 clo) clothing types.

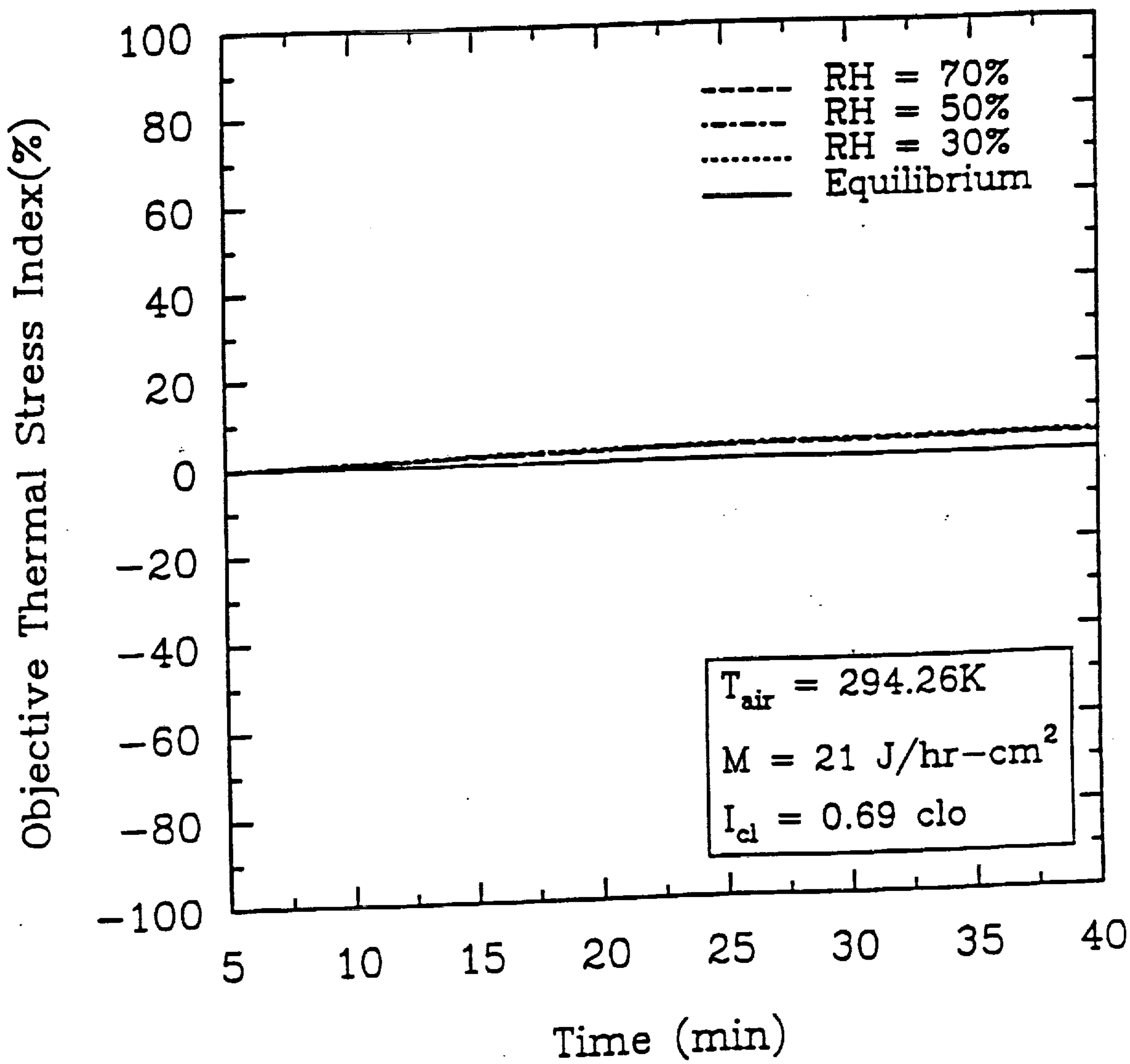


Figure 6.25 Effect of Relative Humidity on the Variation of OTSI

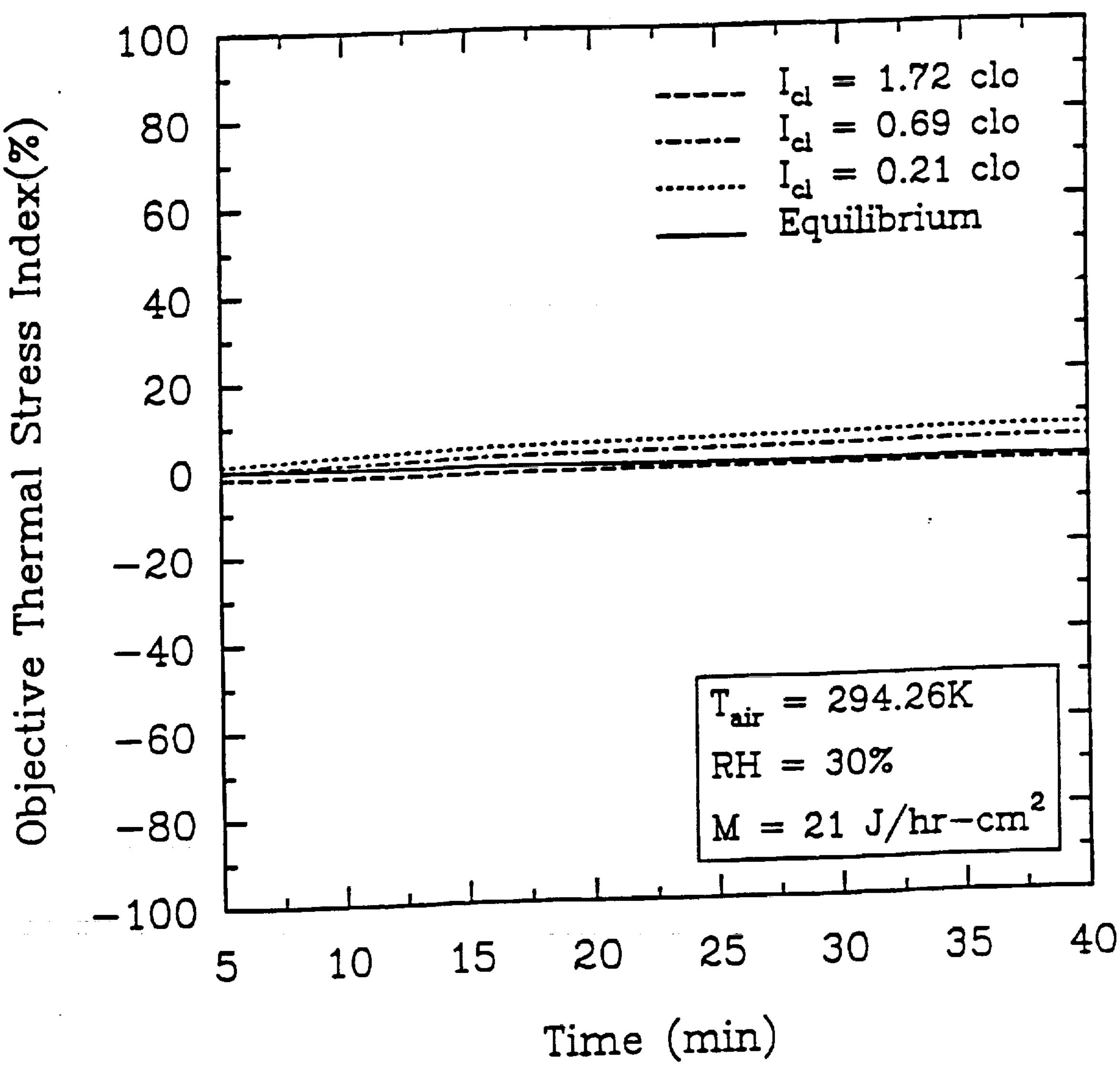


Figure 6.26 Effect of Clothing on the Variation of OTSI

It is concluded that for the given physical conditions (T_{air} = 294.26K, RH = 30%, and M = 21 J/hr-cm^2), the clothing does not cause any significant change in the value of OTSI and thus in thermal discomfort.

6.4.2 Thermal Stress Monitoring in Comfort Conditions

The computer simulations were conducted for a period of one hour for a clothed human in comfortable environmental conditions. The effects of varying air temperatures for different relative humidities on human thermal stress level are examined. Figure 6.27 shows the human thermal response in terms of OTSI to different air temperatures ranging from 286K to 308K for a given relative humidity of 30%, sedentary activty (M = 21 J/hr-cm^2), and medium clothing ensemble (I_{cl} = 0.69 clo). It is observed that there is significant deviation in human thermal stress response from the equilibrium or homeostasis condition. Cool air temperature (286K) produces deviation in the negative direction, starting from approximately - 30% to about -47% towards the end of the 60th minute.

As the air temperature is increased to 291K, the deviation from the equilibrium condition reduces starting from about -10% to -18%. As the air temperature continues to increase, thermal discomfort shifts from the equilibrium in the positive direction. It is concluded that warmer air temperatures produce deviations in positive direction, while the cooler air temperatures produce shifts in the negative direction from the thermal equilibrium of the body. Also, it is noticed that OTSI indicates a sudden change in thermal stress level at 25th and 45th minutes for air temperatures 286K and 291K, respectively. This is mainly attributed to the onset of heat production due to shivering which contributes to the increase of entropy generation.

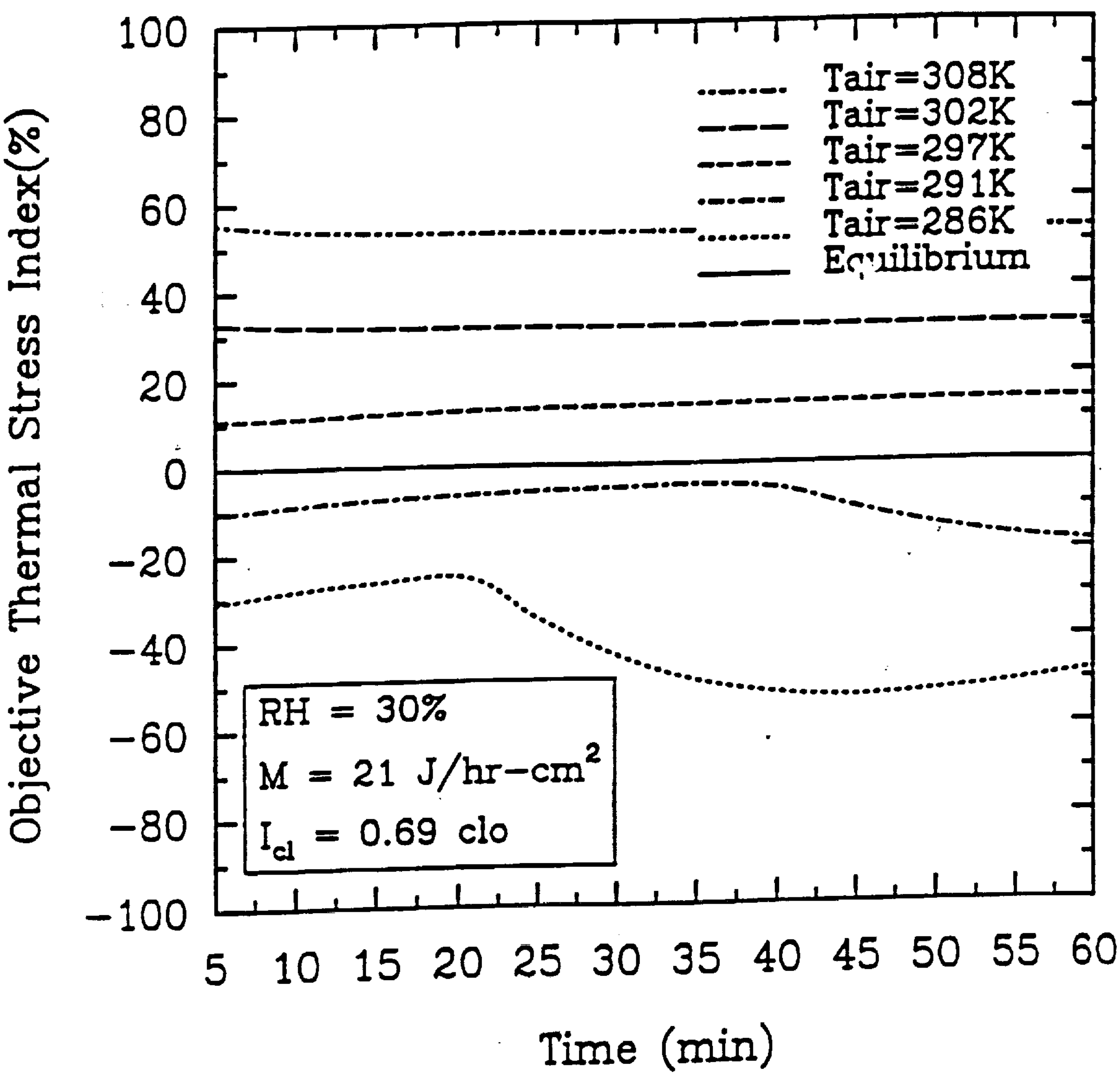


Figure 6.27 Effect of Air Temperatures on Thermal Stress Level for 30% RH

Figures 6.28 and 6.29 show a similar pattern of human thermoregulatory behavior for 50% and 70% relative humidities respectively. Thus, in the range of 30 to 70% relative humdity, it is established that the human body responds to environmental stressors in a regular pattern as demonstrated in Figs. 6.27 through 6.29. However, with regard to the effect of air temperature, the deviations represented by OTSI are quite significant. Thus, air temperature is a very important factor that influences the thermal stress or comfort.

6.4.3 Thermal Stress Monitoring in Extreme Hot and Cold Environments

Simulations were conducted for a period of one hour for a sedentary clothed human in extreme ambient conditions. The effects of cold (273.15K) and hot (316.48K) air temperatures for 10% and 90% relative humidities are examined. It is observed from Fig. 6.30 that for a 10% RH, the deviations from the thermal equilibrium are quite significant indicating cold and heat stress for 273.15K and 316.48K air temperature respectively. Figure 6.31 indicates a similar thermal response pattern for 90% RH, although there is a small change in the magnitude of deviation for heat stress. Further, it is noticed that there is an onset of shivering at the 10th minute which is seen in both Figs. 6.30 and 6.31 for 273.15K air temperature. Thus, OTSI can be used to quantify the effects of extreme heat and cold on mental workload.

6.4.4 Validation of Objective Thermal Stress Index (OTSI)

The Objective Thermal Stress Index (OTSI) is validated by comparing with subjective responses of the human subjects who were exposed to the similar environmental conditions. Large scale experimental studies conducted by Rohles and Nevins [16] and Rohles [17] on 1600 college-age students have revealed statistical correlations between comfort

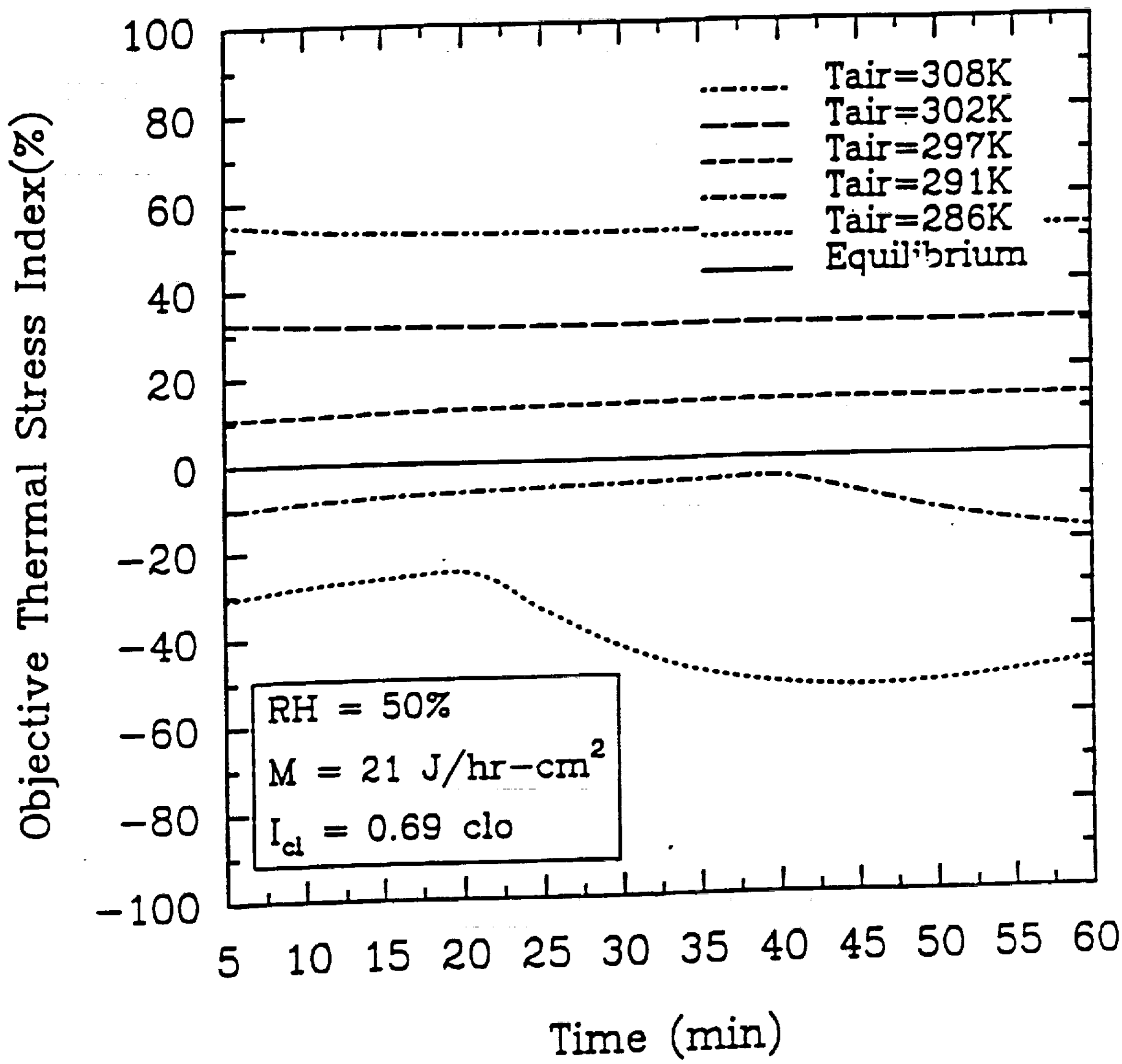


Figure 6.28 Effect of Air Temperatures on Thermal St ress Level for 50% RH

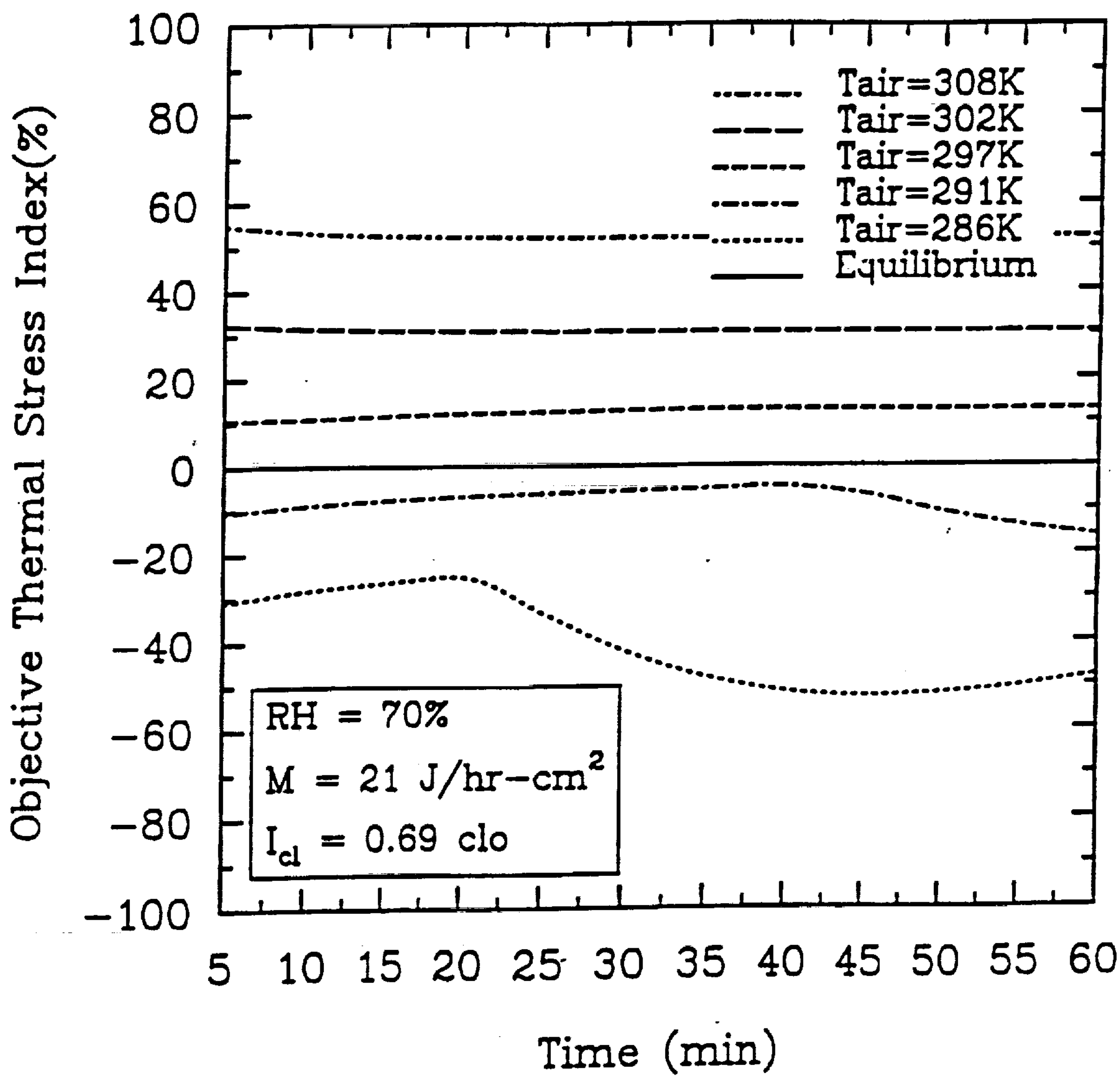


Figure 6.29 Effect of Air Temperatures on Thermal St ress Level for 70% RH

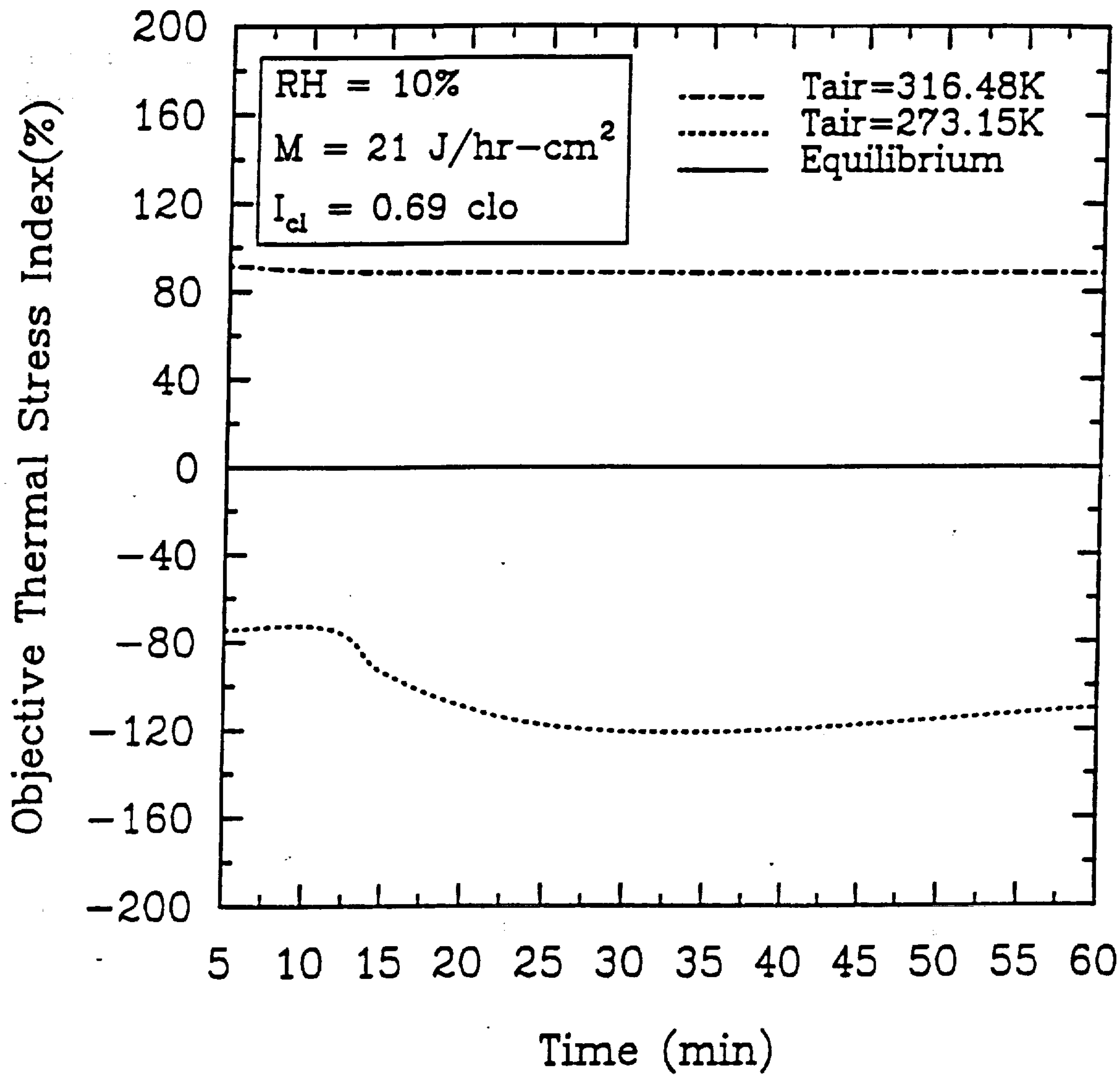


Figure 6.30 Thermal Stress Responses to Extreme Air Temperatures for 10% RH

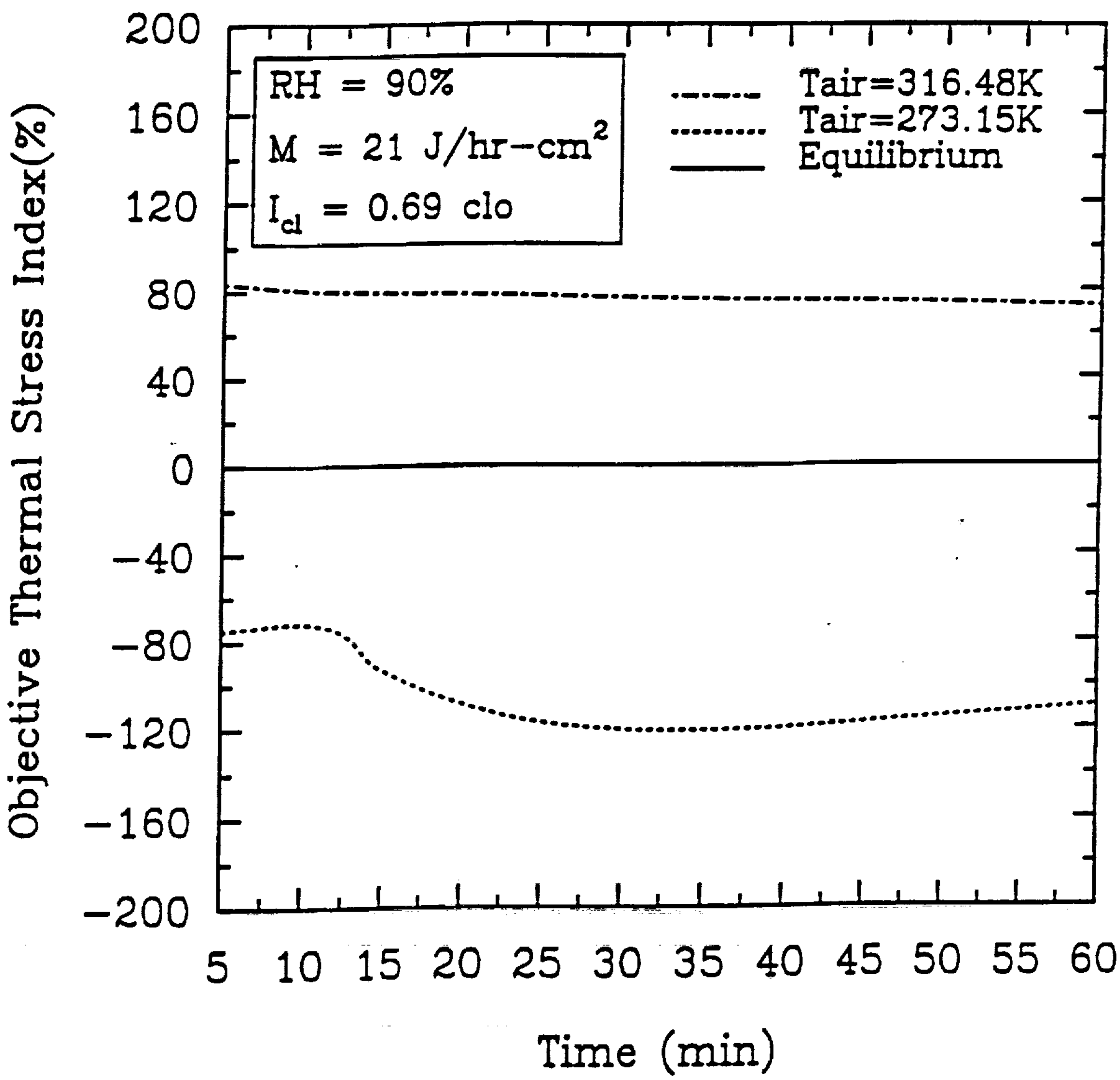


Figure 6.31 Thermal Stress Responses to Extreme Air Temperature for 90% RH

level, temperature humidity, sex, and length of exposure. The regression equation used in this validation is obtained from [7]. This equation is as follows:

$$PMV = 0.245\,(T_{air}) + 0.248\,(P_{vap}) - 6.475$$

Where, PMV = Predicted Mean Vote (on Thermal Sensation)
T_{air} = Air Temperature (° C) = Mean Radiant Temperature (T_{mrt})
P_{vap} = Vapor Pressure (kPa)

This equation is valid for both adult men and women subjects with sedentary activity ($M = 21$ J/hr-cm^2) and wearing medium clothing (approximately $I_{cl} = 0.50$ clo), and exposed for one hour to air velocities less than 0.2 m/sec. The thermal sensation scale used in this equation is referred to as the ASHRAE thermal sensation scale and is the same as the PMV scale developed by Fanger [2]. This scale is as follows:

+ 3 Hot
+ 2 Warm
+ 1 Slightly Warm
0 Neutral
- 1 Slightly Cool
- 2 Cool
- 3 Cold

In the actual experiments [7, 16, & 17], the subjects were asked to vote at every thirty-minute interval on their thermal sensation or comfort level and their mean votes were considered for assessing the thermal environment. In order to be consistent with the experimenatal studies, OTSI values at 30th and 60th minutes were chosen and their mean value was taken for comparison with the PMV obtained from the regression equation. Table 6.6 shows that there is a significant correlation between OTSI and PMV which is expressed quantitatively with the help of coefficient of correlation (or Pearson Correlation Coefficient). The values of coefficient of correlation were found to be equal to 0.9913, 0.9906, and 0.9900 for 30%, 50%, and 70% relative humditites respectively for air temperatures ranging from 286K to 308K. The value of correlation coefficient closer to +1 indicates that there is a linear variation between OTSI and PMV which is shown in Fig. 6.32 for comfort conditions. Further, Table 6.7 shows that the value of correlation coefficient equals +1.0 for both 10% and 90% relative humdities for 273.15K and 316.48K air temperatures respectively. The linear variation between OTSI and PMV for extreme environmental conditions is shown in Fig. 6.33. It is well established that there is a strong correlation between the OTSI and PMV which demonstrates that OTSI can be used as a valid parameter to quantify thermal stress or discomfort in the optimal design of human-environment systems. Finally, OTSI acts as an ecological parameter that quantifies the human-environment interaction.

6.4.5 Objective Thermal Sensation Scale (OTSS)

The OTSI combines the human thermal responses and environmental factors to express thermal stress in terms of a single summative number. Thus, by measuring the thermal stress, OTSI provides an objective measure of drain in attentional resources and reduction in vigilance capability, thus providing a quantitative methodology to prove the attentional theory of performance under stress developed by Hancock [51].

As a result of series of simulations that were conducted and shown in Figs. 6.25 through 6.31, an optimal functioning chart as shown in Fig. 6.34 is developed corresponding to the values of Objective Thermal Sensation Scale (OTSS) presented in Table 6.8. Figure 6.34 is developed on the basis of excellent correlation between objective and subjective scales demonstrated in the previous Sec. 6.4.4. This optimal functioning chart is

Table 6.6 Correlation between OTSI and PMV in Comfort Conditions

T_{air}(K)	RH = 30%		RH =50%		RH = 70%	
	OTSI (%)	PMV	OTSI (%)	PMV	OTSI (%)	PMV
285.93	-45.4990	-3.2328	-45.4374	-3.1587	-44.9166	-3.0847
291.48	-11.8702	-1.8259	-11.4687	-1.7204	-10.9505	-1.6149
297.04	13.7436	-0.3999	13.1414	-0.2518	12.6456	-0.1038
302.59	31.3358	1.0477	31.0026	1.2493	30.6569	1.4540
308.15	52.9799	2.5187	52.5688	2.7979	52.0788	3.0770
Coefficient of Correlation (ρ)	0.9913		0.9906		0.9900	

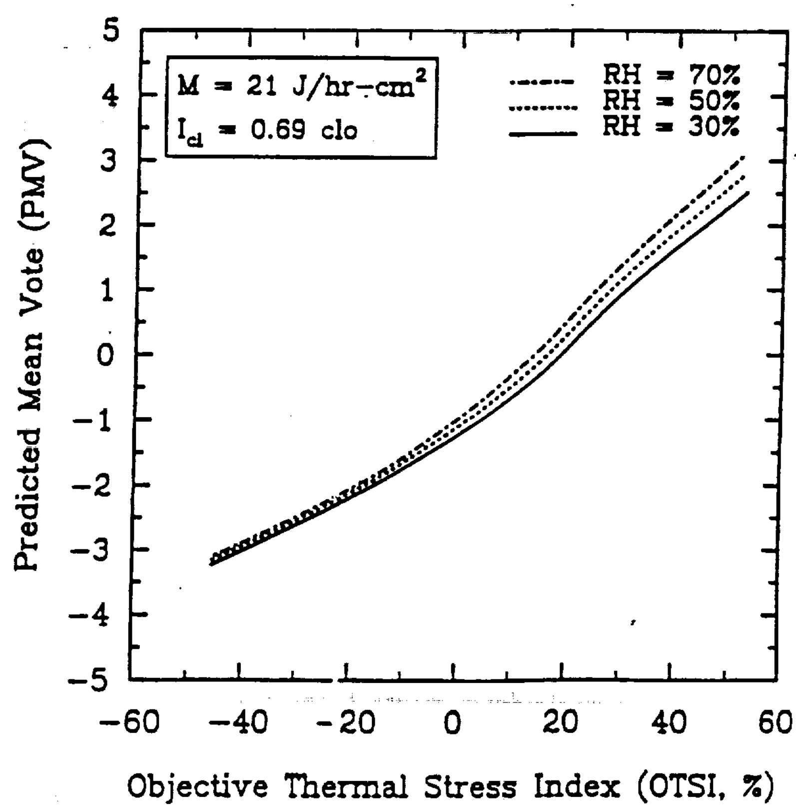


Figure 6.32 Variation between OTSI and PMV in Comfort Conditions

Table 6.7 Correlation between OTSI and PMV in Extreme Conditions

T_{air}(K)	RH = 10%		RH = 90%	
	OTSI (%)	PMV	OTSI	PMV
273.15	-115.3115	-6.4598	-114.9475	-6.3386
316.48	88.4137	4.3605	74.7081	6.1173
Coefficient of Correlation (ρ)	1.00		1.00	

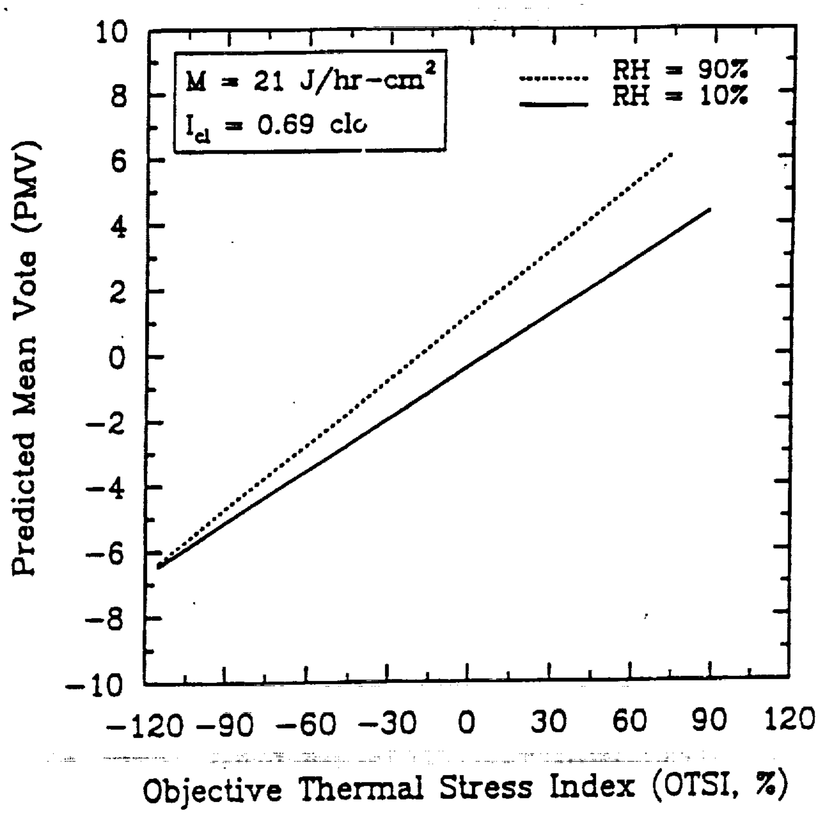


Figure 6.33 Variation between OTSI and PMV in Extreme Conditions

Table 6.8 Objective Thermal Sensation Scale (OTSS)

OTSI (%)	Thermal Sensation
+50 to +70	Hot
+30 to +50	Warm
+10 to +30	Slightly Warm
-10 to +10	Comfort Zone
-30 to -10	Slightly Cool
-50 to -30	Cool
-70 to -50	Cold

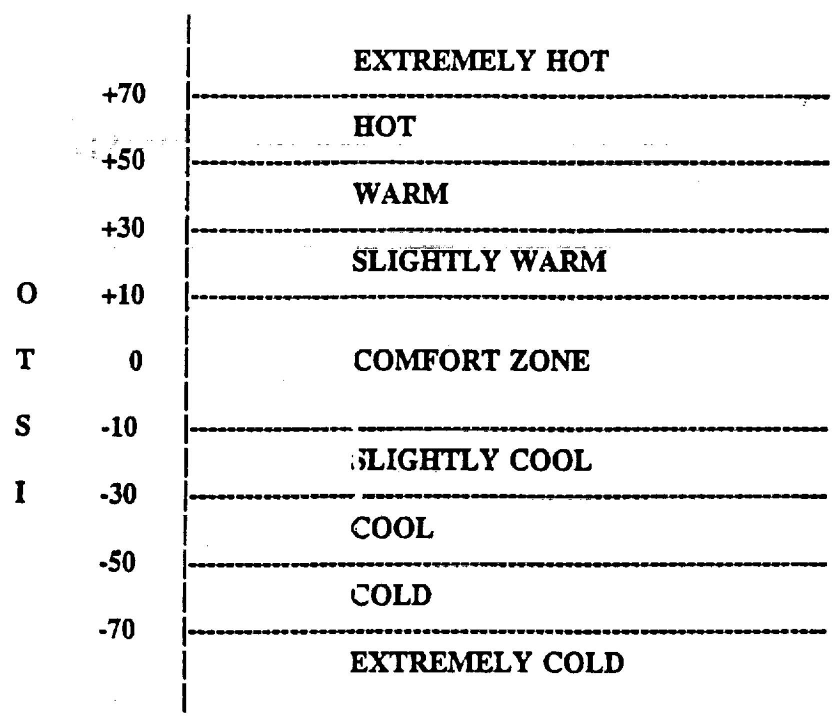


Figure 6.34 Optimal Functioning Chart

valid for a sedentary (M = 21 J/hr-cm^2) clothed (I_{cl} = 0.5 to 0.69 clo) human for relative humdities ranging from 10% to 90% and air temperatures from 273.15K to 316.48K. The OTSS is symmetrical around the zero point, so that a positive value corresponds to the warm side and a negative value to the cold side. However, any value beyond +70% or -70% means that the individual is experiencing severe discomfort due to extreme hot or cold environmental conditions and this zone must be avoided at all cost for human safety.

The optimal functioning chart provides the region of operation in the environmental control systems to keep the thermal stress in the comfort zone for optimal human performance and safety. This would facilitate to improve the attentional and vigilance capabilities of the human operators and thus contribute to the design and development of "human" centered environmental systems.

6.5 Mental Stress Level Monitoring Using an Objective Mental Stress Index (OMSI)

This section is mainly dedicated to examine the effects of mentally stressful and information processing vigilance tasks on physiological responses. In this regard, an Objective Mental Stress Index (OMSI) is derived from the Maxwell relations of thermodynamics which is discussed in detail in Sec. 5.4. This objective measure is used to indicate the level of mental stress as a function of physiological responses controlled by autonomic nervous system (ANS) such as blood pressure, heart rate, oral body temperature, and skin temperature. Further, the OMSI provides a thermodynamic and mathematical relationship between thermal responses (body and skin temperature) and cardiovascular responses (blood pressure and heart rate). In Sec 6.5.1, effects of a mentally stressful situation such as an examination on physiological responses of a group of students is investigated. Later, in Sec. 6.5.2, a moment-to-moment stress level monitoring technique during vigilance tasks is demonstrated. Finally, the OMSI is validated for its utility as a measure of clinical stress in Sec. 6.5.3.

6.5.1 Effect of Mentally Stressful Tasks on Physiological Responses

The effect of a mentally stressful situation such as a final examination on the physiological responses (blood pressure, heart rate, and oral body temperature) is examined. The Objective Mental Stress Index (OMSI) represented by Eq. (5.4) is used to indicate the objective measure of stress level experienced by individuals as a result of mental stress in terms of physiological responses. The purpose of this study is to investigate the pattern of these physiological responses and interrelationship using OMSI.

The data for verifying this biothermodynamic approach was obtained from an existing experimental study conducted by Mital and Mital [6]. In this study, fourteen male students of 18-21 years of age and 59-114 kg of body weight, and nine female students of 18-20 years of age and 50-68 kg of body weight voluntarily participated. All students were in one class under one instructor. The blood pressure, heart rate, and oral body temperature were measured three times. The first set of measurements were taken around midway in the semester (Condition 1 - Normal Condition). The second set of measurements were taken just prior to the final examination (Condition 2), and finally third set was taken immediately after the final examination (Condition 3). All measurements were made at approximately the same time of the day in an air-conditioned room under the same conditions. The air temperature and relative humidity were approximately 25 °C and 50%, respectively [80]. The subjects were allowed to relax in a chair for about fifteen minutes before any measurements were recorded.

The data were normalized by adjusting the physiological measurements under Condition 2 and Condition 3 by the amount recorded under Condition 1. The data collected under each condition were analyzed separately by performing an analysis of variance and multiple range test on the means. The data from the experimental study are summarized in Table 6.9. The numerical values of changes in physiological responses shown in Table 6.9 are used in Eq. (5.4) to obtain the value of OMSI under conditions 2 and 3. These OMSI values corresponding to systolic ($OMSI_{SBP}$) and diastolic ($OMSI_{DBP}$) for both males and females are provided in the Table 6.10. The changes in each of the physiological responses (systolic and diastolic blood pressure, heart rate, and oral body temperature) are also show in Figs. 6.35-6.38. It is only in Fig. 6.36 for changes in diastolic blood pressure, a significant difference between the response of males and females is observed. The variation in OMSI for both males and females is shown in Figs. 6.39 and 6.40 respectively. In both these figures, the shift from equilibrium condition is in the negative direction and this is attributed to decrease in oral body temperature from the normal as shown in Fig. 6.38. However, OMSI quantitatively indicates that the stress level has considerably decreased in reaching Condition 3 from 2. From Figs. 6.39 and 6.40, it is clear that female subjects experienced greater stress level than the male counterparts, but females were able to return much closer to the equilibrium than males with regard to both diastolic and systolic blood pressures. Also, residual stress was lower in females than males.

It is demonstrated that the amount of disorder or chaos in a human being reduces over a period of time after reaching a peak value depending on the nature of mental or physical

Table 6.9 Average Physiological Responses Due to Mental Stress: Experimental Data from Mital and Mital [6]

Responses	Sex	Condition	Average Change from the Normal	Significance (p)*
Systolic Blood Pressure (mm of Hg)	Male	2	+13.10	0.01
		3	+9.60	0.01
	Female	2	+11.70	0.01|
		3	+10.70	0.01|
Diastolic Blood Pressure (mm of Hg)	Male	2	+14.60	0.01|
		3	+11.20	0.01|
	Female	2	+6.70	0.01|
		3	+6.40	0.01|
Heart Rate (beats/min.)	Male	2	+16.80	0.01
		3	+5.50	**
	Female	2	18.70	0.01
		3	+3.70	**
Oral Body Temperature (°C)	Male	2	-0.45	0.05|
		3	-0.54	0.05|
	Female	2	-0.20	**
		3	-0.74	0.01

* Only Statistical significance indicated. Vertical line (|) indicates conditions not significantly different from each other ($p \geq 0.10$)
** Insignificant at $p \leq 0.10$

Table 6.10 Values of Objective Mental Stress Index (beats.mm Hg/min.° C)

Condition	Males		Females	
	$(OMSI)_{SBP}$	$(OMSI)_{DBP}$	$(OMSI)_{SBP}$	$(OMSI)_{DBP}$
2	-489.07	-545.06	-1093.95	-626.45
3	-275.55	-114.07	-53.50	-32.00

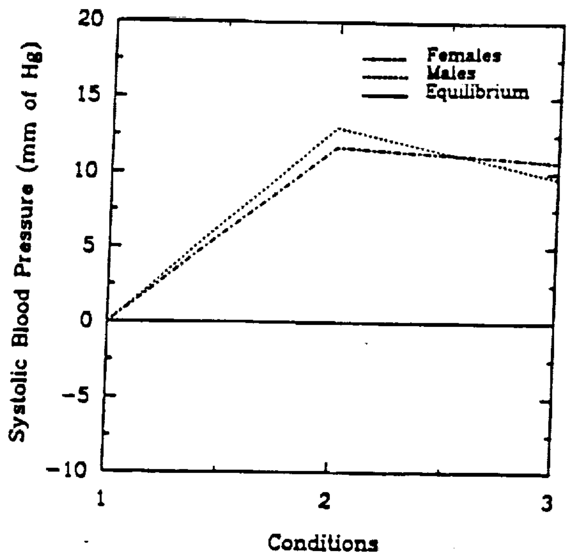


Figure 6.35 Changes in Systolic Blood Pressure

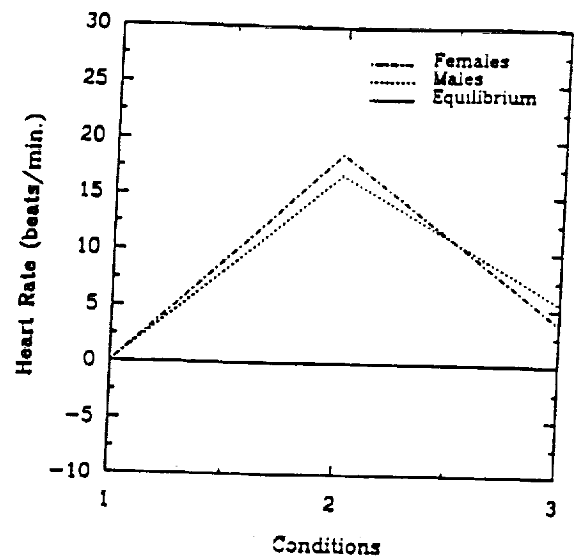


Figure 6.37 Changes in Heart Rate

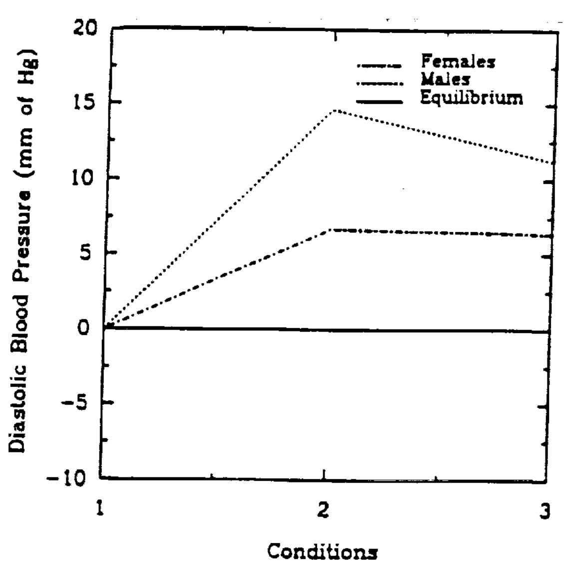


Figure 6.36 Changes in Diastolic Blood Pressure

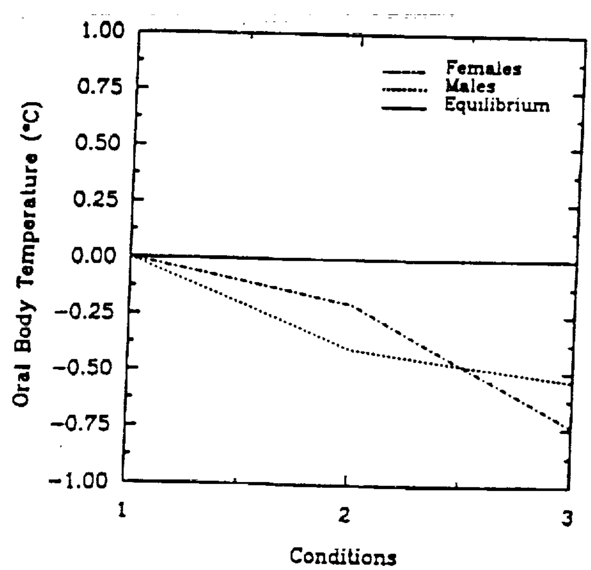


Figure 6.38 Changes in Oral Body Temp.

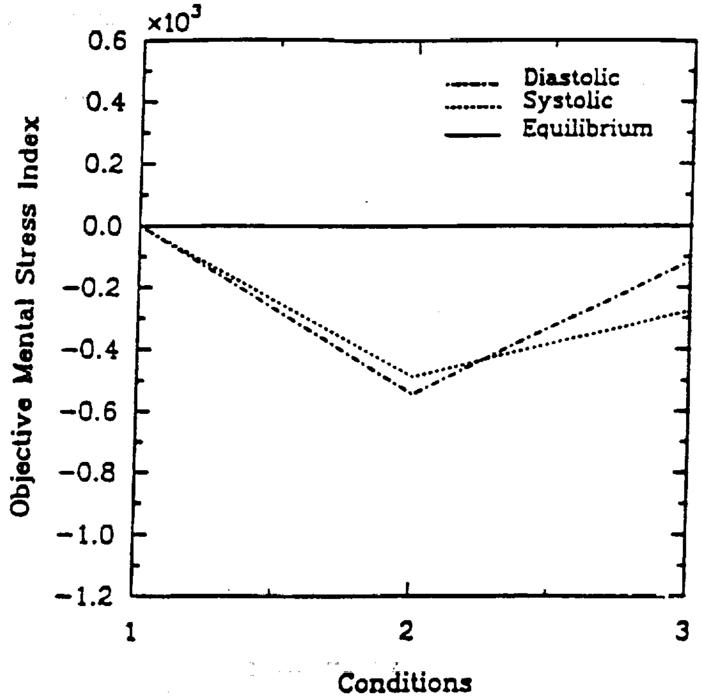


Figure 6.39 Objective Stress Responses of Males

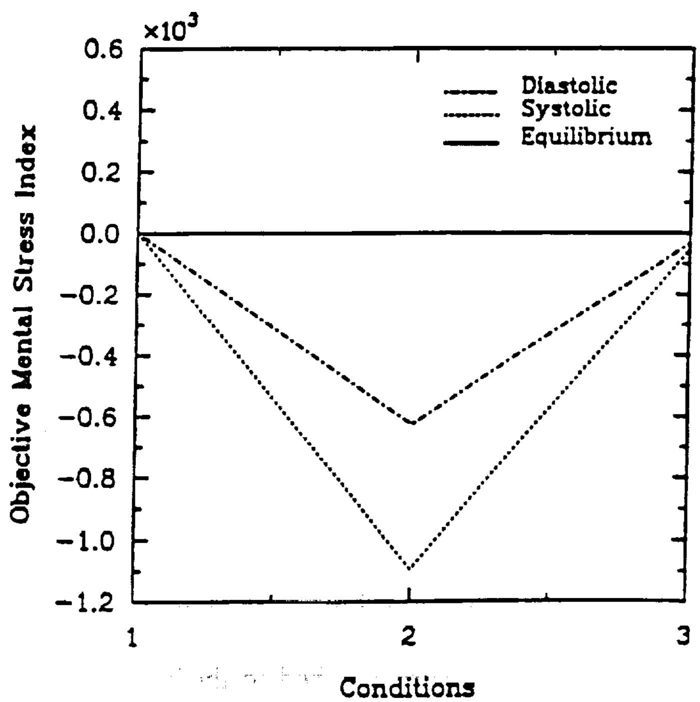


Figure 6.40 Objective Stress Responses of Females

task. According to the laws of thermodynamics, whenever a system is perturbed from its equilibrium position, it returns to equilibrium over a period of time. In a similar manner, human system regains its organic stability when it is perturbed from its normal state which is nothing but the phenomenon of **homeostasis**. In summary, Figs. 6.39 and 6.40 accurately demonstrate the phenomena of **thermal and cardiovascular homeostasis.**

6.5.2 Mental Stress Monitoring during Vigilance Tasks

The main purpose of this study was to demonstrate the technique of continuous moment-to-moment measurement and monitoring of mental stress during vigilance tasks. The data is obtained from a pilot study which was conducted at the simulation laboratory of NASA Langley Research Center. In this study, five male and three female subjects of 18-35 years of age participated. All subjects were students who were recruited from the local universities and colleges.

In this classic psychophysiological experiment, six measures such as Electroencephalogram (EEG), Electromyogram (EMG), Skin Conductance, Systolic Blood Pressure, Heart Rate, and Skin Temperature were recorded continuously using the LabVIEW data acquisition system. The sensors for measuring the physiological responses were mounted on the body surface of the subjects in a systematic manner. A sensor cap was placed on the head to permit recording of brain wave or EEG activity. Facial muscle activity or Frontalis EMG was measured from three sensors attached to the forehead. Skin conductance was measured from sensors attached to the pads of two fingers on the left hand. Heart rate was recorded from pulse sensors attached to the wrist and ankle. Skin temperature was measured from a small sensor taped to the back of the middle finger of the left hand. The Systolic blood pressure was measured continuously from the Pulse Wave

Velocity (PWV) technique, The PWV is the rate of travel of pressure pulse waves through the arterial system [20]. This measure does not use a cuff, but obtains a reading of time for the pulse to occur at two points along an artery. The resulting transit time (TT) is used as an indirect measure of blood pressure. However, it has been found that transit time is related to systolic but not to diastolic blood pressure. Also, other problems such as difficulty in calibration and sensitivity to movement artifacts limit the usefulness of this TT technique [20]. As a result of this difficulty in continuously measuring blood pressure, only the blood pressure data in three out of eight subjects in this study calibrated accurately against the standard cuff measurement data. Thus, the data from three subjects is chosen to demonstrate mental stress measurement and monitoring technique.

Besides all other laboratory procedures, the actual stress monitoring session lasted for 75 minutes. During this period, subjects were allowed to relax for first fifteen minutes while listening to a relaxation audio tape. Later, they were given a vigilance task on computer for 60 minutes with the interruption of a mental arithmetic task twice for 5 minutes each. The details of the stress monitoring under different conditions are provided in Table 6.11. In this section, some very important psychophysiological concepts (stimulus response specificity, individual response specificity, and autonomic balance) are demonstrated in Figs. 6.41 through 6.44.

The concept of **stimulus response (SR) specificity** refers to a patterning of physiological responses according to the particular stimulus situation [20]. The concept states that an individual's pattern of physiological response will be similar in a given situation, and that the pattern may vary when the situation is different. It is observed from Figs. 6.41-6.43 that during the relaxation period of first fifteen minutes, there are lot of changes that

Table 6.11 Mental Stress Monitoring Conditions

Time (minute)	Conditions
0 - 15	Baseline Recording during Relaxation
15 - 35	Vigilance Task (Dexter)
35 - 40	Mental Arithmetic Task
40 - 60	Vigilance Task (Dexter)
60 -65	Mental Arithmetic Task
65 - 75	Vigilance Task (Dexter)

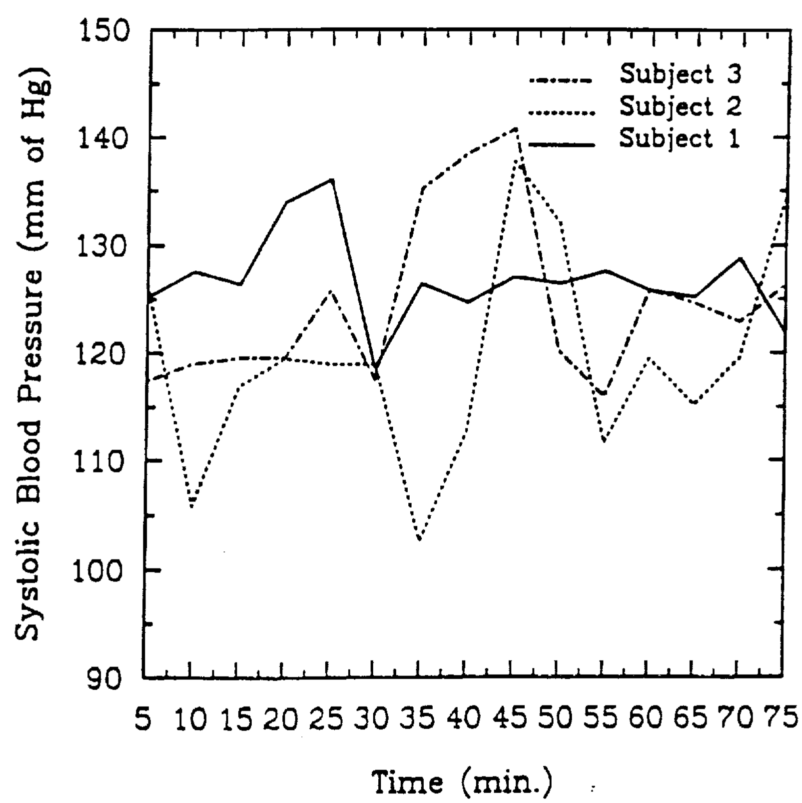


Figure 6.41 Continuous Monitoring of Systolic Blood Pressure (SBP)

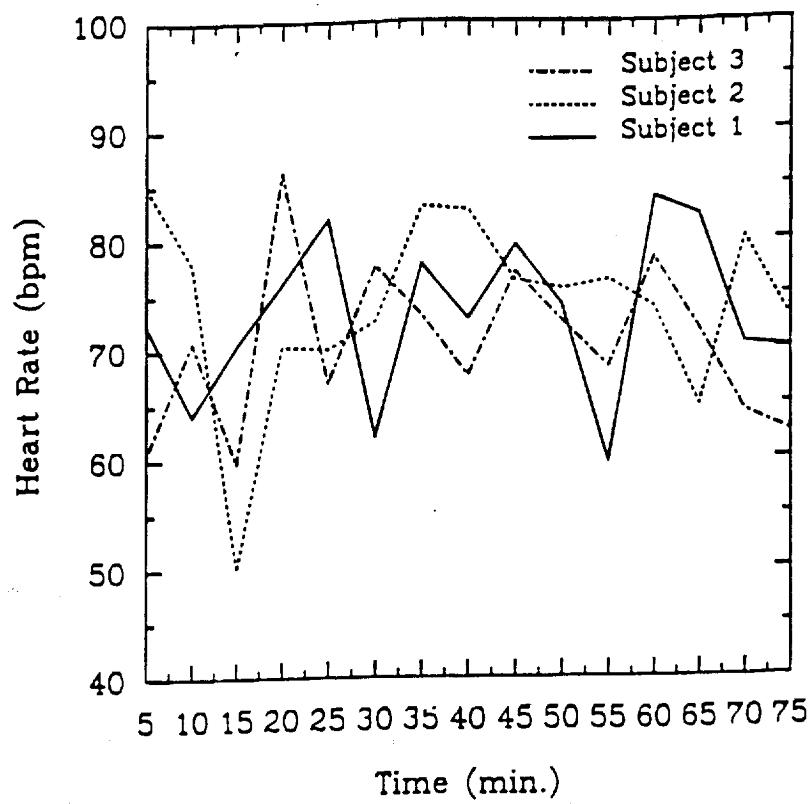


Figure 6.42 Continuous Monitoring of Heart Rate (HR)

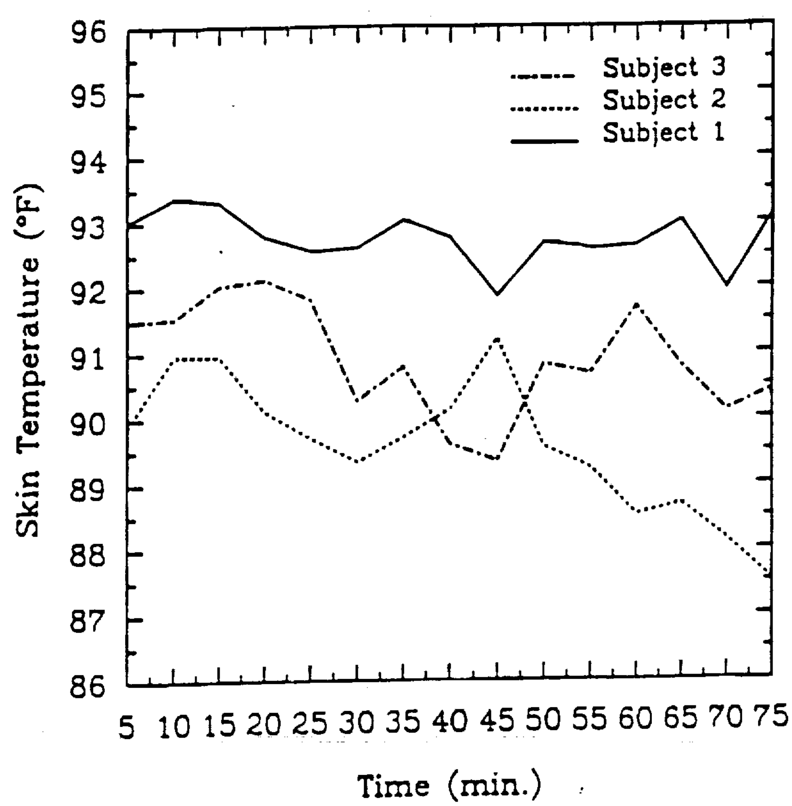


Figure 6.43 Continuous Monitoring of Skin Temperature (ST)

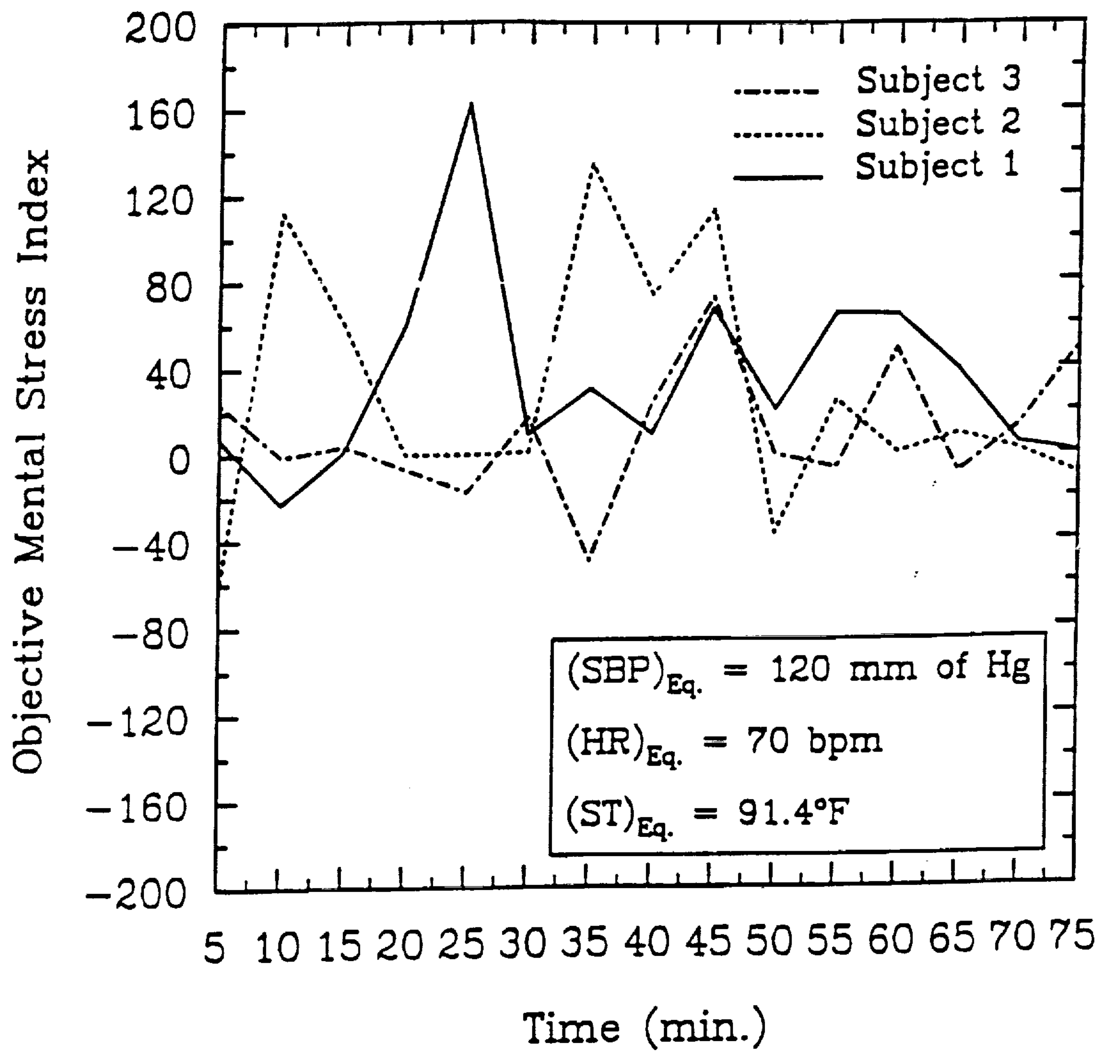


Figure 6.44 Continuous Monitoring of Mental Stress During Vigilance Task

take place in three different subjects. In Fig. 6.41, systolic blood pressure for subject #1 decreases towards the end of relaxation. For subject #2, the blood pressure decreases rapidly upto 10th minute and increases moderately towards the end of the 15th minute. Finally, for subject #3, blood pressure remains uniform during the relaxation period. In Fig. 6.42, there is a marked increase in heart rate for subjects # 2 and #3 during relaxation, while subject #1 shows a decrease upto 10th minute and a small increase at the 15th minute. With regard to skin temperature in Fig. 6.43, a steady increase is observed in all three subjects during the relaxation period indicating a relaxed state. During the rest of the monitoring session, the systolic blood pressure and heart rate fluctuate quite differently for different subjects. Also, in Fig. 6.43, it is very clear that all three subjects show different levels of skin temperature variation. This clearly demonstrates the **individual response (IR) specificity.** The concept of individual response specificity refers to the fact that each subject has characteristic responses to most stimuli. In other words, it involves consistency of an individual's response hierarchy in a variety of stimulus reactions.

It is known that the blood pressure and heart rate are controlled by parasympathetic nervous system (PNS) while the skin temperature is under the control of sympathetic nervous system (SNS). Both, PNS and SNS are subsystems of autonomic nervous system (ANS), the details of which are outlined in Chap. 3. The concept of **autonomic balance** examines human performance and behavior in the context of autonomic nervous system imbalance, that is, the extent to which SNS or PNS is dominant in an individual [20]. Wenger [81] proposed that, in a given individual, either SNS or the PNS may be dominant. An empirically determined weighted score called $\overline{A}$ (autonomic balance) was introduced [20]. The individual's $\overline{A}$ score is determined statistically from a number of autonomic responses. High $\overline{A}$ score means PNS dominance, whereas low $\overline{A}$ scores reflect relative SNS dominance. However, this is a statistical approach that is based on the data models. In this study, the Objective Mental Stress Index (OMSI) which is a **deterministically** developed model from the second law of thermodynamics provides the fundamental relationship between PNS (blood pressure and heart rate) and SNS (skin temperature) controlled autonomic responses. In other words, it is a better way to quantitatively represent the concept of **autonomic balance.** The universality of OMSI is clearly demonstrated in Fig. 6.44. It combines the three autonomic responses (blood pressure, heart rate, and skin temperature) to express the stress level in terms of a single summative number. This approach overcomes the ambiquity that arises between the concepts such as stimulus and individual response specificity. From Fig. 6.44, it is clear that subjects #1 and #3 reduced their stress level, while subject #2 responded in a reverse manner showing an increase in stress level. Subject #3 showed a steady and optimal stress level (between -49.45 and +49.06 beats-mm of Hg/min.° F) throughout the session. While subject #1 showed a rapid increase in stress level upto 162.81 beats-mm of Hg/min.° F at 25th minute and after that maintained a steady level of stress throughout the session. Finally, subject #2 reached the peak value of 135.19 beats-mm of Hg/min.° F at 35th minute and settles down after this. The equilibrium values corresponding to systolic blood pressure (SBP), heart rate (HR), and skin temperature (ST) were chosen to be equal to 120 mm of Hg, 70 bpm, and 91.4° F [20, 74]. The numerical change in responses from these equilibrium values were used in the OMSI equation, Eq. (5.4), to obtain the mental stress level. All three subjects tend to reach equilibrium condition after 45th minute as shown in Fig. 6.44. This is a clear representation of both **thermal and cardiovacular homeostasis**. Since, OMSI represents the processes controlled by the autonomic nervous system (ANS), it is concluded that OMSI quantitatively represents the phenomenon of **Autonomic Homeostasis**.

6.5.3 Validation of Objective Mental Stress Index (OMSI)

The objective of this study is to evaluate the feasibility of using OMSI as a measure to quantify the proneness of human beings to stress-related disorders. In order for the OMSI to be considered valid as a measure of stress and to be of any clinical significance, the index has to indicate a strong relationship with common physical stress symptoms. This study examined whether or not individual differences in the OMSI are related to the amount of physical stress symptoms. Also, it was investigated if OMSI provides a better reflection or measure of clinical stress compared to the most common single physiological parameters.

The data was obtained from a clinical study conducted by Palsson et al. [40] on a group of students. Thirty senior medical students and family medicine resident physicians (16 females and 14 males; mean age = 29.2 years) participated in the study. All of them completed a standard psychophysiological stress profile procedure routinely used for clinical assessment in the Behavioral Medicine Clinic at Eastern Virginia Medical School [40]. The participants were all healthy without any major health problems.

The physiological data was collected using a ProComp+ biofeedback system interfaced with Dell 166 MHz PC computer running a MultiTrace biofeedback software for data processing and analysis. In addition, a stand-alone Dinamap 1846 Vital Signs Monitor (Critikon Inc., Tampa, FL). Also, subjects completed the Stress-Related Physical Symptoms Inventory (SPSI).

The Psychophysiological Stress Profile is a 16-minute standard testing sequence, during which skin conductance, frontalis EMG, heart rate, blood volume pulse, and temperature from the palmar surface of the left hand little finger is collected continuously during five conditions for the subject listed clearly in Table 6.12. The blood pressure and heart rate were measured separately using Dinamap Vital Signs Monitor, with the help of mechanically inflated pressure cuff around the subject's right arm. These recordings are made three times: After Condition 2 (relaxing with eyes closed for 3 minutes), after Condition 3 (the stressor period), and following Condition 5 (that is, after the second post-stressor relaxation period).

The Stress-Related Physical Symptoms (SPSI) provided in Appendix C, is a paper-and-pencil self-report inventory where subjects are asked to indicate whether they have experienced each of 32 symptoms during the past one month. The symptoms listed are all bodily symptoms which are considered by many health professionals to be common physical manifestations of stress. The symptoms listed include stiff muscles, excessive sweating, dry mouth, chest pain, shortness of breath, and cold hands or feet. The instructions ask the subjects not to endorse any of the listed symptoms which are known to be related to a diagnosed organic illness or medications the person may be taking. The instructions on the SPSI also ask subjects to indicate how frequently they have experienced the endorsed symptoms, but the data from those frquency ratings were not used in the study.

The first two of three Dinamap blood pressure and heart rate measurements collected on each subject (first at the end of six minutes of relaxation and just before the 4-minute cognitive stress task, and then immediately following stress task) were used in conjunction with finger skin temperature recordings for the same time periods to calculate the Objective Mental Stress Index using Eq. (5.4) provided in Sec. 5.4.

Table 6.13 clearly shows that a significant Pearson correlation of 0.51 ($p = 0.004$) is between the OMSI and the number of stress-related symptoms on the SPSI. The three physiological parameters (diastolic blood pressure, heart rate, and finger skin temperature) used in the OMSI formula, as well as other physiological stress measures such as frontalis EMG, and Skin Conductance, were correlated with the SPSI. No statistically significant Pearson correlation coefficients were found between these five single physiological modalities and the amount of stress symptoms on the SPSI. The absence of significant correlations between any single parameter of stress reactivity and the amount of stress-related symptoms is in clear contrast with the above finding of a significant relationship between OMSI and SPSI. This leads to the conclusion that the OMSI is a better measure of clinical stress.

6.6 Link Between Thermal and Cardiovascular Systems

The previous sections, Sec. 6.4 and Sec. 6.5, addressed different aspects of thermal and mental stress separately. In this section, the dichotomy in the mathematical expressions for both thermal and mental stress is qualitatively explained. Although, Eq. (5.4) has been used to indicate the level of mental stress, it could also be used to examine the impact of environmental stressors on both thermal (core and skin temperatures) and cardiovascular (blood pressure and heart rate) responses. Due to limited resources, the Eqs. (5.3) and (5.4) are used under two different circumstances to address thermal and mental stresses separately. In any case, Eq. (5.4) takes into account the responses of both thermal and cardiovascular systems. Further, the Eq. (5.4) is quite profound and provides an interesting link between thermal and cardiovascular activities of the human body. In this regard, a large scale study needs to be designed to examine the simultaneous effects of both environmental and psychological stressors on physiological responses to gain maximum benefit from the use of objective measures of thermal and mental stress.

Table 6.12 Conditions for Psychophysiological Stress Profile

Time (minute)	Condition
0 - 3	Relax (eyes open)
3 - 6	Relax (eyes closed)
6 - 10	Stressor (Stroop Test and Mental Arithmetic Task)
10 - 13	Relax (eyes open)
13 -16	Relax (eyes closed)

Table 6.13 Comparison between OMSI and Other Single Physiologiical Parameters

Physiological Measures of Stress	Correlation with Amount of Physical Stress Symptoms	Significance (p)
$(OMSI)_{DBP}$	0.51	0.004
Diastolic Blood Pressure	-0.20	Not Significant (NS)
Heart Rate	0.07	NS
Finger Skin Temperature	0.25	NS
Skin Conductance	0.15	NS
Frontalis EMG	-0.18	NS

CHAPTER VII

CONCLUSIONS

A novel thermodynamic approach is developed to quantify human stress level in terms of a single summative number objectively. The two types of stress indices are developed. They are Objective Thermal Stress Index (OTSI) and Objective Mental Stress Index (OMSI). The OTSI quantifies thermal stress by determining the percentage deviation in entropy generation (S_{gen}) or Objective Thermal Stress Response (OTSR) from the equilibrium condition or homeostasis in human thermal system. It is based on the second law of thermodynamics as applied to analyze the human thermal system. The OMSI indicates the level of mental stress experienced by the individual as a result of mental workload or information processing. It provides a link between cardiovascular and thermal system as it involves blood pressure, heart rate, and skin or body temperature in its mathematical expression. The equation for OMSI is derived from the Maxwell relations of thermodynamics.

Thermal responses required to validate OTSI are obtained through computer simulation. The computer simulation is performed with the help of a human thermal model which is developed using finite element method. The model is validated against the experimental data and it is found that model accurately simulates several human thermal functions. A series of simulations are conducted to examine the human thermal behavior in different environmental conditions. The effects of varying air temperature, relative humidity, level of physical activity, and clothing on human thermal stress responses are examined. The human thermal behavior is quite accurately simulated and it conforms to the physiological and anatomical facts. A design of experiments philosophy is implemented to develop a hybrid technique to assess human thermal behavior. A hybrid technique is developed to analyze the interaction of two different levels of air temperature and relative humidity on human thermal stress responses. The thermal stress responses used in this situation are entropy generation or Objective Thermal Stress Response (OTSR). The synergy between the design of experiment approach and idea of using Objective Thermal Stress Responses in place of subjective responses provides a window of opportunities to design efficient human thermal experiments. The OTSI is validated against the values of Predicted Mean Vote (PMV) obtained from a regression equation which is developed using a large scale experimental data. It shows an excellent agreement with the experimental data and subjective responses with a Pearson coefficient value close to one. Also, a OTSI has been used to monitor thermal stress continuously; thus, showing the deviation in human thermal comfort on a moment-to-moment basis. This monitoring technique leads to the development a standard called Objective Thermal Sensation Scale (OTSS) and an Optimal Functioning Chart which draw parallel to PMV or ASHRAE Thermal Sensation Scale and ASHRAE Comfort Chart. The main advantage of using OTSI lies in its simplicity and objectivity backed by the strong basis of second law of thermodynamics.

The OTSI could be used in aerospace applications to enhance aviation safety. In this regard, it has been well established that attention and vigilance are related to changes in thermal environment. Based on these theories, the OTSI could be used to monitor the drain in attentional resource capacity and thus quantify reduction in vigilance capabilities. The other applications could be in HVAC industry and in the fields of medicine.

The human physiological data in response to a stressful cognitive or mental task is obtained from experimental studies which were conducted in both aerospace and medical settings. Initially, in order to test the OMSI, an existing data from an experimental study was taken. The OMSI clearly indicates the phenomena of homeostasis in both thermal and cardiovascular systems. This analysis established the potential to use OMSI in aviation and medical experiments. The continuous moment-to-moment monitoring of mental stress level is demonstrated. This technique quantitatively demonstrates some of the most important psychophysiological concepts such as autonomic balance, individual response specificity, and stimulus response specificity. Also, it could be used to examine the effects of information overloading on system operators, thus leading to the design of a "Human-Centered" flight deck for maximum safety and optimum performance. Finally, the OMSI is validated for potential clinical use as it shows a high correlation with stress related physical symptoms reported by normal subjects. Thus, large scale experimental studies are recommended to exploit the utility of OMSI for further use in aerospace or clinical or any other human factors applications.

The two indices (OTSI and OMSI) have been identified to have their roots in a common theory. This lead to the development of a Unified Stress Response Theory (USRT) which combines both thermal stress and mental stress depending on the nature of stressors. Further, the USRT finds its place in a new field of study called Engineering Psychophysiology which gets subdivided into two branches, Thermal Environmental Psychophysiology and Cognitive Psychophysiology. The new concepts and definitions are all summarized under twelve Postulates which constitute this new field of Engineering Psychophysiology and Unified Stress Response Theory (USRT).

REFERENCES

1. Anon., American Institute of Aeronautics and Astronautics (AIAA), Guide to Human Performance Measurements, American National Standard, ANSI/AIAA G-035-1992, AIAA, Washington, DC, July 1993.

2. Fanger, P. O., Thermal Comfort, 2nd Edition, McGraw-Hill Book Company, New York, September 1970.

3. Rodahl, K., The Physiology of Work, Taylor & Francis Ltd., London, 1989.

4. Hockey, G. R. J., Gaillard, A. W. K., and Coles, M. G. H., Energetics and Human Information Processing, Martinus Nijhoff Publishers, Dordrecht, Netherlands, 1986.

5. Hancock, P. A., Meshkati, N., and Robertson, M. M., "Physiological Reflections of Mental Workload," Aviation, Space, and Environmental Medicine, Vol. 56, No. 11, November 1985, pp. 1110-1114.

6. Mital, A., and Mital, C., "Mental Stress and Physiological Responses," In Mital, A. (Ed.), Trends in Ergonomics / Human Factors I, Elsevier Science Publishers Inc., New York, 1984, pp. 353-358.

7. Anon., ASHRAE, ASHRAE Handbook of Fundamentals, Chapter 8, Atlanta, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., 1993.

8. Talty, J. T., Industrial Hygiene Engineering, Second Edition, Noyes Data Corporation, New Jersey, 1988, pp. 326-369.

9. Boregowda, S. C., Tiwari, S. N., Chaturvedi, S. K., and Hou, G. J-W., "Thermodynamic Analysis of an Unsteady 3D Human Thermal Model," AIAA Paper No. 98-0841; Presented at the 36th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, January 12-15, 1998.

10. McCormick, E. J., and Sanders, M. S., Human Factors in Engineering and Design, McGraw-Hill Book Company, 5th Edition, New York, 1982, pp. 398-401.

11. Grandjean, E., Fitting the Task to the Man, Taylor & Francis Ltd., London, 1981, pp. 334-335.

12. Belding, H. S., and Hatch, T. F., 1955, "Index for Evaluating Heat Stress in Terms of Resulting Physiological Strains," Heating, Piping, and Air Conditioning, Vol. 207, August 1955, pp. 129-136.

13. Hatch, T. F., "Assessment of Heat Stress," In J. D. Hardy (Ed.), Temperature - Its Measurement and Control in Science and Industry, Vol. 3, Part 3, Reinhold, New York, 1963, pp. 307-318.

14. Hertig, B. A., and Belding, H. S., "Evaluation and Control of Heat Hazards," In J. D. Hardy (Ed.), Temperature - Its Measurement and Control in Science and Industry, Vol. 3, Part 3, Reinhold, New York, 1963, pp. 347-355.

15. Threlkeld, J. L., Thermal Environmental Engineering, 2nd Edition, Prentice-Hall Inc., New Jersey, 1970, pp. 370-373.

16. Rohles, F. H., Jr., and Nevins, R. G., "The Nature of Thermal Comfort for Sedentary Man," ASHRAE Transactions, Vol. 77, No. 1, 1971, pp. 239-251.

17. Rohles, F. H., Jr., "The Revised Modal Comfort Envelope," ASHRAE Transactions, Vol. 79, No. 2, 1973, pp. 52-60.

18. Aoki, I., "Entropy Flow and Production in the Human Body in Basal Conditions," Journal of Theoretical Biology, Vol. 141, June 1989, pp. 11-21.

19. Aoki, I., "Effects of Exercise and Chills on Entropy Production in Human Body," Journal of Theoretical Biology, Vol. 145, January 1990, pp. 421-428.

20. Andreassi, J. L., Psychophysiology: Human Behavior and Physiological Responses, Lawrence Erlbaum Associates Publishers, Hillsdale, NJ, 1989.

21. Barnard, R. J., and Duncan, H. W., "Heart Rate and ECG Responses of Fire Fighters," Journal of Occupational Medicine, Vol. 17, No. 1, 1985, pp. 247-250.

22. Zwaga, H. J. C., "Psychophysiological Reactions to Neural Tasks: Effort or Stress," Ergonomics, Vol. 16, No. 1, January 1973, pp. 61-67.

23. Grandjean, E. P., Wotzka, G., Schaad, R., and Gilgen, A., "Fatigue and Stress in Air Traffic Controllers," Ergonomics, Vol. 14, No. 1, January 1971, pp. 159-165.

24. Kasl, S. V., and Cobb, S., "Blood Pressure Changes in Men Undergoing Job Loss," A Preliminary Report, Psychosomatic Medicine, Vol. 32, No. 1, Jan.-Feb. 1970, pp. 19-38.

25. Renbourn, E. T., "Psycho-Physiological Stress and the Soldier, with a Review of the Literature," Clothing and Equipment Physiological Research Establishment, Report No. 118, May 1961.

26. Hampton, I. F. G., and Lewis, H. E., "Psychological and Physiological Responses to Raised Body Temperature," Journal of Applied Physiology, Vol. 19, No. 2, March 1964, pp. 287-291.

27. Shusterman, V., and Barnea, O., "Spectral Characteristics of Skin Temperature Indicate Peripheral Stress-Response," Biofeedback and Self-Regulation, Vol. 20, No. 4, 1995, pp. 357-367.

28. Freedman, R. R., "Physiological Mechanisms of Temperature Biofeedback," Biofeedback and Self-Regulation, Vol. 16, No. 2, 1991, pp. 95-115.

29. Ettema, J. H., and Zielhus, R. L., "Physiological Parameters of Mental Load," Ergonomics, Vol. 14, No. 1, January 1971, pp. 137-144.

30. McCubbin, J. A., Richardson, J. E., Langaer, A. W., Kizer, J. S., and Obrist, P. A., "Sympathetic Neuron Function and Left Ventricular Performance during Behavioral Stress in Humans: The Relationship between Plasma Catecholamines and Systolic Time Intervals," Psychophysiology, Vol. 20, No. 1, January 1983, pp. 102-110.

31. Levi, L., Stress: Sources, Management, and Prevention, Liveright Publishing Corporation, New York, 1967.

32. McLean, A., Occupational Stress, Charles C. Thomas Publishers, Springfield, IL, 1974.

33. Eaton, M. T., "Detective Executive Stress in Time," Industrial Medicine and Surgery, Vol. 35, No. 1, 1967, pp. 115-118.

34. Horowitz, M., Schaefer, C., Hirotu, D., Wilner, N., and Levin, B., "Life Event Questionnaires for Measuring Presumptive Stress," Psychosomatic Medicine, Vol. 39, No. 6, Nov.-Dec. 1977, pp. 413-431.

35. Takakuwa, E., "Maintaining Concentration (TAF) as a Measure of Mental Stress," Ergonomics, Vol. 14, No. 1, January 1971, pp. 145-158.

36. Boregowda, S. C., Palsson, O. S., Tiwari, S. N., and Bartolome-Rull, D. S., "Thermodynamic Approach to Quantify and Measure Human Stress Level," Proceedings of 29th Annual Association for Applied Psychophysiology and Biofeedback (AAPB) Conference, Orlando, Florida, April 1-5, 1998, pp. 20-23.

37. Boregowda, S. C., Tiwari, S. N., Chaturvedi, S. K., and Palsson, O. S., "An Innovative Approach to Measure and Monitor Human Stress Level in Man/Machine Interactions," Proceedings of 18th Annual American Society of Engineering Management (ASEM) National Conference, Virginia Beach, Virginia, October 1997, pp. 5-13.

38. Boregowda, S. C., and Tiwari, S. N., "Human Stress Level Measurement Using a Engineering Approach," In Eanes, I. A., Boregowda, S. C., and Tiwari, S. N. (Eds.), ISET Review of NASA/ODU/EVMS Symposium on Technology for the Treatment of ADHD, Technical Report No. NAS1-19858-68, NASA CR-198068, July 1997.

39. Boregowda, S. C., Tiwari, S. N., Chaturvedi, S. K., and Redondo, D. R., "Analysis and Quantification of Mental Stress and Fatigue Using Maxwell Relations from Thermodynamics," Journal of Human Ergology, Vol. 26, No. 1, Center for Academic Publications, University of Tokyo, Tokyo, Japan, June 1997 (In Press).

40. Palsson, O. S., Boregowda, S. C., and Downing, B. K., "The Relationship between an Objective Stress Index (OSI) and Stress-Related Physical Symptoms," Proceedings of 29th Annual AAPB Conference, Orlando, Florida, April 1-5, 1998, pp. 70-72.

41. Gagge, A. P., "Rational Temperature Indices of Thermal Comfort," In Cena, K., and Clark, J. A. (Eds.), Bioengineering, Thermal Physiology and Comfort, Elsevier Scientific Publishing Company, Amsterdam, 1981, pp. 79-98.

42. Selye, H., The Stress of Life, Revised Edition, The McGraw-Hill Companies, Inc., 1956.

43. Smith, C. E., "A Transient Three-Dimensional Model of the Human Thermal System," Ph.D. Thesis, Kansas State University, Manhattan, Kansas, May 1991.

44. Fu, G., "A Transient, Three-Dimensional Mathematical Thermal Model for Clothed Human," Ph.D. Thesis, Kansas State University, Manhattan, Kansas, May 1995.

45. Fisher, R. A., Design of Experiments, Oliver & Boyd, Edinburgh, 1951.

46. Roy, R., A Primer on the Taguchi Method, Von Nostrand Reinhold, New York, 1990.

47. Kroemer, K. H. E, Kroemer, H. B., and Kroemer-Elbert, K. E., Ergonomics: How to Design for Ease and Efficiency, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1994.

48. Leibowitz, H. W., Owens, D. A., and Helmreich, R. L., "Transportation," In Nickerson, R. S. (Ed.), Emerging Needs and Opportunities for Human Factors Research, National Academy Press, Washington, DC, 1995, pp. 241-261.

49. Pope, A. T., Bogart, E. H., and Bartolome, D. S., "Biocybernetic System Evaluates Indices of Operator Engagement in Automated Task," Biological Psychology, Vol. 40, No. 1, 1995, pp. 187-195.

50. Hancock, P. A., "Sustained Attention Under Thermal Stress," Psychological Bulletin, Vol. 99, No. 2, March 1986, pp. 263-281.

51. Hancock, P. A., and Pierce, J. O., "Toward an Attentional Theory of Performance Under Stress: Evidence from Studies of Vigilance in Heat and Cold," In Mital, A., (Ed.), Trends in Ergonomics/Human Factors I, Elsevier Science Publishers, Inc., New York, 1984, pp. 353-358.

52. Wickramasekara, I. E., Clinical Behavioral Medicine, Plenum Press, New York, 1988.

53. Boregowda, S. C., and Tiwari, S. N., "A Test Plan for the Investigation of Human Thermoregulation in Microgravity Environment," AIAA Paper No. 98-0460; Presented at the 36th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 1998.

54. Lehrer, P. M., and Woolfolk, R. L., Principles and Practice of Stress Management, Second Edition, The Guilford Press, New York, 1993.

55. Green, E., and Green, A., Beyond Biofeedback, Delacorte Press Seymour Lawrence, 1977.

56. Parks, P., "Psychophysiologic Self-Awareness Training: Integration of Scientific and Humanistic Principles," Journal of Humanistic Psychology, Vol. 37, No. 2, 1997, pp. 67-113.

57. Flach, J., Hancock, P., Caird, J., and Vicente, K., Global Perspectives on the Ecology of Human-Machine Systems, Vol. 1, Lawrence Erlbaum Associates, Publishers, Hillsdale, NJ, 1995.

58. Lacey, J. I., "Somatic Response Patterning and Stress: Some Revisions of Activation Theory," In Coles, M. G. H., Jennings, J. R., and Stern, J. A., (Eds.), Psychophysiological Perspectives, Van Nostrand Reinhold Company, New York, 1984, pp. 42-70.

59. Burchfield, S. R., Stress: Psychological and Physiological Interactions, Hemisphere Publishing Corporation, New York, 1985.

60. Hancock, P. A., and Warm, J. S., "A Dynamic Model of Stress and Sustained Attention," Human Factors, Vol. 31, No. 5, October 1989, pp. 519-537.

61. Swan, H., Thermoregulation and Bioenergetics, American Elsevier Publishing Company, Inc., New York, 1974.

62. Callen, H. B., Thermodynamics and An Introduction to Thermostatics, Second Edition, John Wiley & Sons, New York, 1985.

63. Nicolis, G., and Prigogine, I., Self-Organization in Nonequilibrium Systems, John Wiley & Sons, New York, 1977.

64. Cooney, D. O., Biomedical Engineering Principles, Marcel Dekker, Inc., New York, 1976.

65. Guyton, A. C., Textbook of Medical Physiology, 6th Edition, W. B. Saunders Company, Philadelphia, 1981.

66. Gordon, R. G., "The Response of a Human Temperature Regulatory System Model in the Cold," Ph.D. Thesis, University of California, Santa Barbara, California, May 1974.

67. Shitzer, A., and Eberhart, R. C., Heat Transfer in Medicine and Biology: Analysis and Applications, Vol. 2, Plenum Press, New York, 1985.

68. Wissler, E. H., "The Use of Finite Difference Techniques in Simulating the Human Thermal System," In Hardy, J. D., Gagge, A. P., and Stolwijk, J. A. J. (Eds.), Physiological and Temperature Regulation, Charles C. Thomas Publishing Company, Springfield, pp. 367-388.

69. Segerlind, L. J., Applied Finite Element Analysis, 2nd Edition, John Wiley & Sons, New York, 1984.

70. Flach, J. M., and Warren, R., "Active Psychophysics: The Relation Between Mind and What Matters," In Flach, J. M., Hancock, P. A., Caird, J., and Vicente, K. J. (Eds.), Global Perspectives on the Ecology of Human-Machine Systems, Vol. 1, Lawrence Erlbaum Associates, Publishers, Hillsdale, NJ, 1995, pp. 189-209.

71. Fechner, G., Elements of Psychophysics, Holt, Rinehart, and Winston, New York, 1966.

72. Hardy, J. D., and Stolwijk, J. A. J., "Partitional Calorimetric Studies of Man During Exposures to Thermal Transients," Journal of Applied Physiology, Vol. 31, No. 6, April 1966, pp. 1799-1806.

73. McIntyre, D. A., "Design Requirements for a Comfortable Environment," In Cena, K., and Clark, J. A. (Eds.), Bioengineering, Thermal Physiology and Comfort, Elsevier Scientific Publishing Company, New York, 1981, pp. 195-220.

74. Cabanac, M., "Physiological Signals for Thermal Comfort," In Cena, K., and Clark, J. A. (Eds.), Bioengineering, Thermal Physiology and Comfort, Elsevier Scientific Publishing Company, New York, 1981, pp. 181-192.

75. Astrand, P., and Rodahl, K., Textbook of Work Physiology, McGraw-Hill Book Company, New York, 1970.

76. Koch, K. W., Jennings, B. H., and Humphreys, C. H., "Is Humidity Important in the Temperature Comfort Range?," ASHRAE Transactions Vol. 66, No. 1, 1960, pp. 63-68.

77. Nevins, R. G., Rohles, F. H., Springer, W., and Feyerherm, A. M., "A Temperature Humidity Chart of Thermal Comfort of Seated Person," ASHRAE Journal, Vol. 8, No. 4, April 1966, pp. 55-61.

78. Hardy, J. D., Stolwijk, J. A. J., and Gagge, A. P., "Man," In Whittow, G. C. (Ed.), Comparitive Physiology of Thermoregulation, Academic Press, New York, 1971, pp. 327-380.

79. Gagge, A. P., Burton, A. C., and Bazett, H. D., "A Practical System of Units for the Description of Heat Exchange of Man with his Environment," Science, Vol. 5, No. 94, 1941, pp. 428-430.

80. McQuiston, F. C., and Parker, J. D., Heating, Ventilation, and Air-Conditioning, John Wiley & Sons, New York, 1984.

81. Wenger, M. A., "Studies of Autonomic Balance: A Summary," Psychophysiology, Vol. 3, No. 2, 1966, pp. 173-176.

APPENDIX A

DERIVATION OF OBJECTIVE THERMAL STRESS INDEX (OTSI)

Living organisms including human beings belong to the class of open systems. This is due to the fact that they have to continuously exchange energy and matter with the surroundings in order to maintain homeostasis which is essential for the existence and support of life. Prigogine [63] formulated an extended version of the second law of thermodynamics applicable to both closed and open systems.

Consider the entropy change dS during a time interval dt. The entropy change dS is decomposed into the sum of two contributions (See Fig. A.1).

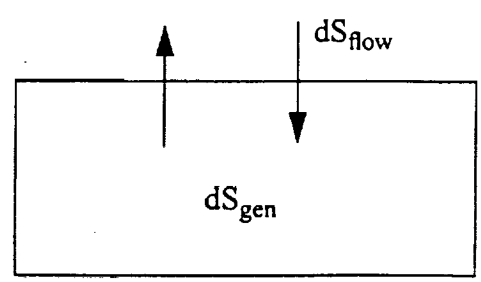


Figure A.1 Entropy Flow and Entropy Production in an Open System

$$dS = dS_{flow} + dS_{gen} \tag{A.1}$$

where dS_{flow} = entropy flow or flux due to heat exchanges with the environment. dS_{gen} = entropy generation due to the irreversible processes inside the system, such as diffusion, heat conduction, and chemical reactions

The second law implies:

$$dS_{gen} \geq 0 \;\; (= 0 \text{ at equilibrium}) \tag{A.2}$$

For an isolated system, $dS_{flow} = 0$, and Eq. (A.1) yields,

$$dS = dS_{gen} \geq 0 \tag{A.3}$$

In summary, open systems differ from isolated systems by the presence of flow terms, dS_{flow}, in the entropy change. Contrary to dS_{gen} which can never be negative, these terms do not have a definite sign. As a result, one may imagine evolutions where the system attains a state of lower entropy than the initial one, i.e.,

$$\Delta S = \int_{path} dS < 0 \tag{A.4}$$

This state, which from the point of view of the equilibrium would be highly improbable, and be maintained indefinitely provided the system is allowed to attain a steady state such that $dS = 0$ or

$$dS_{flow} = -dS_{gen} \tag{A.5}$$

In principle, if the system is given a sufficient amount of negative entropy flow to enable it to maintain an ordered configuration. As Eq. (A.5) shows, this supply must occur under nonequilibrium conditions, otherwise both dS_{gen} and dS_{flow} would vanish. This leads to the possibility of a new nonequilibrium order principle. More precisely, nonequilibrium may be a source of order. This is of obvious interest for living systems; the biosphere as a whole is a nonequilibrium system, as it is subject to the flow of solar energy. It is enough to establish that the second law ($dS_{gen} \geq 0$) is compatible with a decrease of overall entropy ($dS < 0$), but also to indicate the mechanisms responsible for the emergence and maintenance of coherent states.

There are systems which exhibit two types of behavior: (a) a tendency to a disordered state under certain conditions; (b) a tendency to a coherent behavior under certain conditions. The destruction of order prevails in the neighborhood of thermodynamic equilibrium. Creation of order may occur far from equilibrium provided the system obeys nonlinear laws of some type. In this case, the spontaneous appearance of order is accompanied by an instability of the states showing the usual thermodynamic (i.e., disordered) behavior. Traditionally, classical thermodynamics is limited to equilibrium or near equilibrium and could only treat the first type of behavior which is the emphasis of present study.

In the present study, Eq. (A.1) is modified as shown by Aoki [18, 19] as

$$\Delta S = S_{flow} + S_{gen} \tag{A.6}$$

where

ΔS = total entropy change

S_{flow} = net entropy flow

S_{gen} = entropy generation

From Eq. (A.6), the entropy generation in the human body is given by

$$S_{gen} = \Delta S - S_{flow} \tag{A.7}$$

where $\Delta S = \Delta Q / T_{core}$

$$S_{flow} = S_{in} - \{S_{out} + S_{CNV} + S_{EVAP} + S_{RAD} + S_{CNV\_RES} + S_{EVAP\_RES}\} \tag{A.8}$$

The terms S_{in} and S_{out} on the right hand side of Eq. (A.8) are given as follows [18, 19]:

$$S_{in} = 2.05\ \sigma\ (T_{air})^3 \tag{A.9a}$$

$$S_{out} = 2.05.\ \sigma\ (T_{skin})^3 \tag{A.9b}$$

where σ = Stefan-Boltzmann constant = 5.67×10^{-8} J. m^{-2} sec^{-1} K^{-4} .The other terms in Eq. (A.8) related to heat losses are given as follows:

$$S_{CNV} = E_{CNV} / T_{skin} \tag{A.10a}$$

$$S_{RAD} = E_{RAD} / T_{skin} \tag{A.10b}$$

$$S_{EVAP} = E_{EVAP} / T_{core} \tag{A.10c}$$

$$S_{CNV\_RES} = E_{CNV\_RES} / T_{core} \tag{A.10d}$$

$$S_{EVAP\_RES} = E_{EVAP\_RES} / T_{core} \tag{A.10e}$$

According to Postulate IX, the Eq. (A.7) is rewritten as

$$OTSR = \Delta S - S_{flow} \tag{A.11}$$

where OTSR = Objective Thermal Stress Response (J/sec/K).

The Objective Thermal Stress Response (OTSR) is calculated at the equilibrium or comfort condition at 50% RH and 75 ° F air temperature for nude body. Thus, any percentage deviation from the equilibrium or comfort OTSR value indicates the amount of stress or disorder. In other words, it is the deviation from thermal homeostasis. Thus, OTSI is defined as

$$OTSI = \{1.0 - (OTSR)_{act} / (OTSR)_{com}\} x100 \qquad (A.12)$$

where subscripts "act" and "com" refer to actual and comfort or equilibrium conditions. Equation (A.12) is the primary equation used in the monitoring of thermal stress level.

APPENDIX B

DERIVATION OF OBJECTIVE MENTAL STRESS INDEX (OMSI)

(i) Exactness Condition

Consider a variable z that is a continuous function of x and y,

$$Z = f(x, y) \tag{B.1}$$

$$dz = \left(\frac{\partial z}{\partial x}\right)_y dx + \left(\frac{\partial z}{\partial y}\right)_x dy \tag{B.2}$$

It is convenient to write the above equation in the following form:

$$dz = M(dx + Ndy) \tag{B.3}$$

where,

$$M = \left(\frac{\partial z}{\partial x}\right)_y, \quad N = \left(\frac{\partial z}{\partial y}\right)_x$$

If in Eq. (B.1), x, y, and z are all point functions (i.e., quantities that depend only on the state and are independent of the path), then the differentials are exact differentials. Therefore, in order for Eq. (B.1) to be EXACT differential equation, the following condition must be satisfied:

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y \tag{B.4}$$

Equation (B.4) is called the "EXACTNESS CONDITION".

(ii) Maxwell Relations

Maxwell relations are derived from the property relations of thermodynamic potentials by involving the exactness conditions. For any system, there are four thermodynamic potentials

U = Internal Energy

H = Enthalpy

A = Helmoltz function

G = Gibbs function

Property Relations for Thermodynamic Potentials

I. First Property Relation

This is obtained from the first law of thermodynamics as,

$$dU = \delta Q - \delta W = TdS - pdV \tag{B.5}$$

II. Second Property Relations

This is obtained by using the definition of enthalpy, H, i.e.,

$$H = U + PV$$

$$dH = dU + pdV + vdp$$

Using relation (B.5), this is expressed as

$$dH = TdS + Vdp \tag{B.6}$$

III. Third Property Relation

This is obtained by using the definition of Helmholtz function A,

$$A = U - TS$$

$$dA = dU - TdS - SdT$$

$$dA = -PdV - SdT \tag{B.7}$$

IV. Fourth Property Relation

This is obtained by using the definition of Gibbs function G,

$$G = H - TS$$

$$dG = dH - TdS - SdT$$

$$dT = VdP - SdT \tag{B.8}$$

The following Maxwell relations are obtained by invoking the exactness condition (B.4) to property relations (B.5)-(B.8):

I. $$\left(\frac{\partial T}{\partial V}\right)_s = -\left(\frac{\partial P}{\partial S}\right) \tag{B.9}$$

II. $$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P \tag{B.10}$$

III. $$\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T \tag{B.11}$$

IV. $$\left(\frac{\partial V}{\partial T}\right)_P = -\left(\frac{\partial S}{\partial P}\right)_T \tag{B.12}$$

The partial derivatives in Eqs. (B.9)-(B.12) were approximated to form a modified set of Maxwell relations that were used in the present study, i.e.,

I. $$\left(\frac{\Delta T}{\Delta V}\right)_S = -\left(\frac{\Delta P}{\Delta S}\right)_V \tag{B.13}$$

II. $$\left(\frac{\Delta T}{\Delta P}\right)_S = \left(\frac{\Delta V}{\Delta S}\right)_P \tag{B.14}$$

III. $$\left(\frac{\Delta P}{\Delta T}\right)_V = \left(\frac{\Delta S}{\Delta V}\right)_T \tag{B.15}$$

IV. $$\left(\frac{\Delta V}{\Delta T}\right)_P = -\left(\frac{\Delta S}{\Delta P}\right)_T \tag{B.16}$$

Any of these relations, (B.13)-(B.16), could be used to quantify the mental stress. The analogy between human and mechanical systems is drawn and Eq. (B.13) is shown arbitrarily to indicate the mental stress level. The variables pertaining to mechanical system like changes in pressure, volume, and temperature correspond to physiological variables such as changes in blood pressure (both systolic and diastolic), heart rate, and skin temperature (or body temperature) respectively. It is very important to note that sign preceding the entropy change (Δ S) is ignored. It is the magnitude of the entropy departure value that determines the level of stress. This derivation may be on the positive or negative side of equilibrium entropy value depending on the imposed conditions.

In accordance with the postulate XII from Sec. 5.4, the Objective Mental Stress Index (OMSI) is mathematically defined as

$$\text{OMSI} = \frac{(\Delta \text{BP}) \times (\Delta \text{HR})}{(\Delta \text{T})} \tag{B.17}$$

where

OMSI = Objective Mental Stress Index (beats mm of Hg/min °C)

Δ BP = Change in Blood Pressure (mm of Hg) from the baseline value

Δ HR = Change in Heart Rate (bpm) from the baseline value

Δ T = Change in Oral Body of Skin Temperature (°C) from the baseline value

Besides quantifying mental stress, OMSI provides a link or relationship between human thermal and cardiovascular systems. Finally, the OMSI acts as a parameter that quantifies the mind-body interaction from a thermodynamic viewpoint.

APPENDIX C

STRESS-RELATED PHYSICAL SYMPTOMS INVENTORY (SPSI)

Please indicate by circling one number how often you have had each symptom DURING THE LAST MONTH.

Important: DO NOT include symptoms which are caused by diagnosed organic (physical) illness or caused by medications you are taking.

		Never	Once	Occasionally	Often	Most of the time or always
1.	Cold hands or feet	0	1	2	3	4
2.	Stiff muscles	0	1	2	3	4
3.	Headache	0	1	2	3	4
4.	Back pain	0	1	2	3	4
5.	Chest pain	0	1	2	3	4
6.	Abdominal pain	0	1	2	3	4
7.	Jaw pain (or TMJ)	0	1	2	3	4
8.	Pain other than 3-7 above (do not include menstrual pain)	0	1	2	3	4
9.	Sleep difficulties	0	1	2	3	4
10.	Dizziness	0	1	2	3	4
11.	Diarrhea	0	1	2	3	4
12.	Physical fatigue	0	1	2	3	4
13.	Excessive sweating	0	1	2	3	4
14.	Fast (racing) or pounding heart beat	0	1	2	3	4
15.	Shortness of breath	0	1	2	3	4
16.	Eye twitching	0	1	2	3	4

		Never	Once	Occasionally	Often	Most of the time or always
17	Asthma attacks	0	1	2	3	4
18.	Allergic reactions (do not include drug allergies)	0	1	2	3	4
19.	Constipation	0	1	2	3	4
20.	Dry mouth	0	1	2	3	4
21.	Nausea or vomiting	0	1	2	3	4
22.	Teeth grinding (or bruxism)	0	1	2	3	4
23.	Poor appetite	0	1	2	3	4
24.	Sexual difficulties	0	1	2	3	4
25.	Restlessness (difficulty being still or at ease when sitting or standing)	0	1	2	3	4
26.	Unexplained skin rash (if not included under allergic reactions above)	0	1	2	3	4
27.	Trembling hands	0	1	2	3	4
28.	Blurred vision	0	1	2	3	4
29.	Weak or wobbly legs	0	1	2	3	4
30.	Easily startled (jumpy)	0	1	2	3	4
31	Flushing of the face	0	1	2	3	4
32	Difficulty swallowing (lump in throat)	0	1	2	3	4

SCORING: A. _____ = TOTAL # OF NON-ZERO RESPONSES

B. _____ = TOTAL SUM OF CIRCLED NUMBERS