HUMAN THERMOREGULATION IN THE HEAT : PREDICTIVE MODELS OF PHYSIOLOGICAL CONDUCTANCE AND SWEAT RATE

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DECLARATION

I, Marc Harry Cohen, declare that this dissertation is my own work, that its substance, neither in whole nor part, has been submitted to, or is to be submitted to, any other than the University of the Witwatersrand, Johannesburg, and that the information used in this dissertation has been obtained by me, while registered at the University of the Witwatersrand, as a candidate for the degree of Master of Science in Engineering. The work was carried out at the Chamber of Mines of South Africa Research Laboratories.

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ABSTRACT

The literature pertaining to models of human thermoregulation is critically reviewed. It is concluded that none of the models investigated can be used to predict the physiological response of acclimatized men required to work in the heat for extended periods of time, the reasons being: (i) physiological conductance (the lumped parameter describing internal heat transfer) has not been completely described in terms of all the variables effecting it (ii) the dynamic nature of the sweat rate response has never been mathematically described.

A composite block diagram model for human thermoregulation, based on a single cylinder core and shell model of the controlled system, is postulated as a feasible solution to the problem of predicting physiological responses to work in the heat. The controlling system, consisting of physiological conductance and sweat rate, is singled out for thorough investigation.

Detailed experimentation was carried out on a single nude acclimatized man over a wide range of environments (13,6°C dry-bulb, 9,2°C wet-bulb to 38,5°C dry-bulb, 36,5°C wet-bulb) and work rates (resting, 60 W/m^2 to exercising, 240 W/m^2). Each experiment lasted four hours. Physiological conductance (K) is expressed as a sigmoidal function of a weighted body temperature driving signal (T_{mb}) and metabolic rate (M), such that for the same T_{mb}, K increases with increasing M. The saturation level of K at low T_{mb} is expressed as a linear function of M, the saturation level of K at high T_{mb} is expressed as an exponential function of M. Because of the dynamic nature of the sweat rate response to a step change in environmental conditions and/or work rate, basic engineering control theory is used to formulate a block diagram model for thermoregulatory sweating. The model introduces a rational approach to combining T_{mb}, local effect of skin temperature, sweat gland fatigue, skin wettedness and their time histories.

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NOMENCLATURE

Upper Case

A	Surface area	m^2
A_d, A_w	Surface area of dry and wet patches of the skin respectively	m^2
A_1, A_2	Surface area of upper and lower cylinders respectively	m^2
C	Convective heat transfer	W/m^2
C_p	Specific heat of human tissue	kJ/kg °C
C_{cr}, C_s	Average specific heat of body core and skin respectively	kJ/kg °C
C_{pb}	Specific heat of the blood	kJ/kg °C
C_p^*	Apparent specific heat of moist air	kJ/kg °C
$C_n(,)$	Numerator coefficients in transfer functions	
$C_d(,)$	Denominator coefficients in transfer functions	
$C_1 \ldots C_9$	Parameters in empirical equations	
D	Dripped sweat	g/min
D_{sr}	Sweat rate drive	g/min
D_{srf}	Fatigued sweat rate drive	g/min
E	Evaporative heat transfer	W/m^2
E_{gm}	Evaporative heat transfer	g/min
E_{max}	Maximum evaporative capacity of the environment	W/m^2
E_{res}	Respiratory heat loss	W/m^2
K	Physiological conductance	W/m^2 °C
K_{drip}	Parameter in drippage equation	
K_{sr}	Parameter in wettedness effect equation	g/min
L	Parameter which is a function of the local skin temperature	
M	Rate of metabolic energy production	W/m^2

M^*	Rate of heat transfer from within the body to the skin surface	W/m^2
M_1, M_2	Rate of metabolic energy produced in the upper and lower cylinders respectively	W/m^2
P	Atmospheric pressure	kPa
Q	Volume of sweat accumulated on the skin	g
$\dot{Q}$	Flow rate of sweat onto the skin	g/min
Q_f	Parameter in drippage equation	g
R	Radiant heat transfer	W/m^2
S_r	Sweat rate	kg/s m^2
S_{rgm}	Sweat rate	g/min
S_t	Heat storage	W/m^2
T_b	Blood temperature	°C
T_{cr}	Body core temperature	°C
T_{db}	Dry-bulb temperature	°C
T_e	Oesophageal temperature	°C
T_{hy}	Hypothalmic temperature	°C
T_{mb}	Weighted body temperature driving signal	°C
T_m	Muscle temperature	°C
T_{mr}	Mean radiant temperature	°C
T_{re}	Rectal temperature	°C
$\bar{T}_s$	Mean skin temperature	°C
T_{set}	Set point temperature	°C
T_{sl}	Local skin temperature	°C
T_{wb}	Wet-bulb temperature	°C
T_{wo}	Expired air temperature	°C
V	Wind speed	m/s
W	Skin wettedness	ND
W_{ef}	Skin wettedness effect	ND

W_o	External mechanical work	W/m^2
X	Independent variable	
Y	Dependent variable	

Lower Case

d,g,h,i j,m,n,p, q,r	Parameters in the logistic function	
f_r	Radiant surface area as a function of total surface area	ND
h_c	Convective heat transfer coefficient	W/m^2 °C
h_e	Evaporative heat transfer coefficient	W/m^2 kPa
h_k	Conductivity of unperfused tissue	W/m °C
h_r	Radiative heat transfer coefficient	W/m^2 °C
h_t	Conductance of body tissue	W/m^2 °C
k_1, k_2, k_3	Parameters in Wyndham et al. (1966) sweat rate equation	
m	Body mass	kg
$\dot{m}_b$	Mass flow rate of the blood	kg/m^2s
m_{cr}, m_s	Core and shell mass per unit body surface area respectively	kg/m^2
p_a	Ambient water vapour pressure	kPa
p_s	Water vapour pressure at the body skin surface	kPa
t	Time	s
x_1, x_2	Shell thickness of upper and lower cylinders respectively	m

Greek Symbols

α, β, γ	Constants of proportionality used in various empirical equations	
λ	Latent heat of vaporization of sweat	kJ/kg °C
η_s	Ratio of sweat evaporated to sweat produced	ND

ϕ	Wettedness suppression factor	
ϕ_s	Relative humidity of the skin	
τ	Time constant	s

CHAPTER 1

INTRODUCTION

1.1 Origin of the Study

In the South African gold mining industry, the prevention of heat stroke and death from heat stroke is an extremely large scale problem. As many as 350 000 men are required to work every day in environments where the relative humidity usually exceeds 90 per cent and wet-bulb temperature lies between 25°C and 33°C. In order to ensure that the risk of heat stroke developing in man is negligible, it is necessary to be able to assess the heat stress of an environment.

The difficulty in assessing the level of heat stress of an environment is caused by the number of factors which must be taken into account:

(i) temperature of exposed rock surfaces,
(ii) dry-bulb temperature,
(iii) wet-bulb temperature,
(iv) wind velocity,
(v) barometric pressure,
(vi) clothing,
(vii) work rate,
(viii) degree of acclimatization,
(ix) state of hydration,
(x) duration of exposure.

Although many heat stress indices have attempted to combine in one number some or all of the abovementioned factors (Lee 1980 and Stewart 1981), the majority of indices lack a rational basis and their use beyond the conditions in which they were derived is uncertain.

In an extensive review of the problem of setting heat stress limits, Stewart (1981) concluded that the development of an analytical model of human thermoregulation is the only rational approach to the assessment of heat stress and provides a rational procedure for the setting of heat stress limits.

Such a model would have to rely on an accurate knowledge of

(i) heat transfer equations describing the heat transfer between man and environment,

(ii) equations describing the relationship between the body's cooling mechanisms (sweat rate and skin blood flow, as characterized by the parameter physiological conductance) and the physiological variables on which they depend.

Inherent in the analytical model would be the ability to relate heat stress (environment and work rate) to resulting physiological strain (rectal and skin temperature, physiological conductance and sweat rate), taking all the previously mentioned variables into consideration. Any combination of environment and work rate could be considered to impose the same heat stress if they resulted in the same degree of heat strain. Stewart (1981) has used rectal temperature as a measure of heat strain.

Stewart (1981) derived a simple mathematical model for predicting mean equilibrium rectal temperature and used this model as a rational basis for assessing heat stress and formulating heat stress limits for nude unacclimatized man. These limits apply only if the man has been exposed to the same environmental conditions and has been working at the same rate for four hours. His limits, expressed in the form of cooling power tables, are therefore applicable only to steady-state conditions. Cohen and Stewart (1982) have shown that it is potentially dangerous to apply time averaged values of conditions to the cooling power tables in order to assess heat stress when environmental conditions and/or work rates vary considerably during the course of a work shift.

A model capable of predicing transient pysiological responses would have a number of practical advantages in the assessmen of heat stress

(i) where the combination of environmental conditions and work rates could be dangerous, it would be possible to determine work-rest schedules such that the risk of heat stroke would be minimal. The use of work-rest schedules could represent the most economical method of achieving an acceptable level of heat exposure.

(ii) where it is necessary to perform work in exceptionally hot environments, maximum safe exposure times could be determined.

(iii) the effect of irregular work loads and/or varying environmental conditions on the performance of men could be calculated.

(iv) by recording the time history of rectal temperature of a worker and the environment, the model could be used to calculate his simultaneously varying work rate.

Experimental evaluations of the countless possibilities which exist in this regard would be impractical, whereas computer simulations of the model could be undertaken quickly, cheaply and with relative ease.

1.2 Background and Orientation

The first requirement of a model, namely the specification of heat transfer equations describing the heat transfer between man and environment, has been partially met. A considerable amount of attention has been devoted to the investigation of heat transfer between essentially nude man and the environment. (Mitchell 1972 and Stewart 1981). The specification of heat transfer coefficients for nude man is not a limiting factor when one considers that in hot conditions there is a natural tendency for men to wear as little clothing as possible, usually consisting of a pair of boots, short trousers and a safety helmet.

On the other hand, the second requirement of a model, namely the specification of the physiological responses of men, has not been adequately met. Stewart (1981) succeeded in specifying the fourth hour physiological conductance and sweat rate responses of nude unacclimatized man. Acclimatized and unacclimatized men exhibit different responses in the heat (Wyndham 1967, Mitchell et al. 1976 and Stewart 1982) and no similar "state of the art" equations exist for acclimatized man. In fact, it will be shown later, that the physiological conductance and sweat rate responses of nude acclimatized man have not been completely described in terms of all the factors which may influence them, a shortcoming of all existing models of human thermoregulatory reponse to the heat.

Physiological conductance and thermoregulatory sweating are identified as the two specific areas requiring attention and are therefore the major problems which are to be tackled in this dissertation.

1.3 Objectives of the Study

The scope of this study has been restricted to an investigation aimed at achieving the objectives given below.

(i) Review existing models of human thermoregulation with the aim of determining whether they can be used to predict rectal temperature and other physiological responses of semi-nude acclimatized men working in typical South African mining conditions.

(ii) By critical review of the literature, more specifically identify the work which needs to be done with the aim of deriving models or expressions for the physiological conductance and sweat rate responses.

(iii) Design and conduct experimentation to provide a basis from which to derive models or expressions for physiological conductance and thermoregulatory sweating.

To take the model to its logical end point, a full model would be too large an undertakeing. The present study seeks therefore to gain an understanding (quantitative, physical and physiological) of physiological conductance and thermoregulatory sweating and to show how they can be put together in a block diagram model of human thermoregulation.

1.4 Outline of the Dissertation

In order to achieve these objectives the work was carried out as a logical sequence of investigations outlined below.

Chapter 2

The concept of a thermoregulatory model is introduced. Existing thermoregulatory models are reviewed with the specific aim of pointing out why they cannot be used to predict the rectal temperature response of men subjected to heat stress. By means of an eclectic process a block diagram model of human thermoregulation in the heat is postulated. The controlled system is modelled as a single cylinder core and shell representation of the human body. The controlling system consists of two blocks representing physiological conductance and sweat rate. The physiological conductance and sweat rate responses of nude acclimatized men are singled out for thorough investigation. The different approaches adopted for quantifying physiological conductance and sweat rate are discussed.

Chapter 3

Chapter 3 deals with the physiological conductance experimentation. The experimental facility and instrumentation are described. The measurements taken and experimental procedures are explained. The environmental conditions and work rates used to ensure a wide range of response are tabulated.

Chapter 4

Two predictive models of physiological conductance are derived. The first expresses physiological conductance as separate functions of weighted body temperature driving signal for rest and for exercise. The second expresses physiological conductance as a function of both weighted body temperature driving signal and metabolic rate. The latter is shown to be a statistically better description of the experimental data as well as being the more physiologically tenable of the two.

Chapter 5

Information on sweat rate in the literature is combined with engineering control theory to formulate a block diagram model of the sweat rate response. In this way the interrelationships between variables are determined and the effect of time is introduced. The proposed model is simulated and the shape of response is close to that observed during the experimentation in Chapter 3. By optimizing the parameters in the block diagram model, accurate predictions of true response data from a few experiments can be made.

Chapter 6

The work is evaluated in terms of the objectives stated.