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MODELING HEAT EXCHANGE CHARACTERISTICS OF LONG TERM SPACE OPERATIONS: ROLE OF SKIN WETTEDNESS AND EXERCISE

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ABSTRACT

The problems of heat exchange during rest and exercise during long term space operations are covered in this report. Particular attention is given to the modeling and description of the consequences of requirements to exercise in a zero-g atmosphere during Space Shuttle flights, especially long term ones. In space environments, there exists no free convection therefore only forced convection occurring by movement, such as pedalling on a cycle ergometer, augments required heat dissipation necessary to regulate body temperature. The requirement to exercise at discrete periods of the day is a good practice in order to resist the deleterious consequences of zero-gravity problems and improve distribution of body fluids. However, during exercise (ca. 180 to 250W), in zero-g environments, the mass of eccrine sweating rests as sheets on the skin surface and the sweat cannot evaporate readily. The use of exercise suits with fabrics that have hydrophobic or outwicking properties somewhat distributes the mass of sweat to a larger surface from which to evaporate. However, with no free convection, increased skin wettedness throughout the body surface induces increasing thermal discomfort, particularly during continuous exercise. This report presents several alternatives to aid in this problem: use of intermittent exercise, methods to quantify local skin wettedness, and introduction of a new effective temperature that integrates thermal stress and heat exchange avenues in a zero-g atmosphere.

INTRODUCTION

The general heat balance equation (in W• m^{-2}) associated with physiological responses to any thermal environment, including Space Shuttle astronauts and those exercising in zero gravity, can be expressed by

$$S = M - W - E - (R + C) \qquad (1)$$

where:

S = the time rate of change of body heat

M = the rate on metabolic heat production

W = the rate of accomplished mechanical work

E = the rate of evaporative heat loss via sweating from eccrine sweat glands, diffusion, and respiration

C = the rate of convective heat loss from the total body surface and respiration

R = the rate of radiant heat loss (or gain from) the surrounding surfaces

Radiation Exchange:

In any space environment, a linear radiation transfer coefficient may be derived (6, 9) by

$$h_r = 4 \bullet (0.72) \bullet (5.67 \times 10^{-8}) [(T_o + Tsurf) / 2 + 273.15]^3 \quad ,W \bullet m^{-2} \bullet C^{-1} \qquad (2)$$

where the factor 0.72 represents the ratio of the effective radiating area of the human body to the total body surface area, as measured by the Dubois surface area formula. The interior environmental temperature is composed of a average of the operative temperature + all the surface temperatures (Tsurf); the constant (5.67×10^{-8}, in $W \bullet m^{-2} \bullet K^{-4}$) is the Stefan-Boltzmann constant.

Convective exchange:

Under zero gravity, as present in a Space Shuttle flight, there is no free convection and the only means of generating a forced convection is by increased metabolic activity or increased room air movement artificially (1, 11). Two equations for estimating the convective heat transfer coefficient have been formulated based on a composite of free and forced convection (9). For still room air in which the convective heat exchange is generated mainly by increased metabolic activity

$$h_c = 1.2 [(M - 50) (P_B/760)]^{0.39} \quad ,W \bullet m^{-2} \bullet °C^{-1} \qquad (3)$$

where M is the metabolic activity in watts/sq. m and P_B is the barometric pressure in Torr. Alternatively, h_c for fan generated forced convection, in which ambient air movement (V, $m \bullet s^{-1}$) is the main factor affecting convective heat exchange can be expressed by either (h_c in $W \bullet m^{-2} \bullet °C^{-1}$)

$$h_c = 8.6 [V \bullet P_B/760]^{0.53} \qquad (4)$$

when persons are dressed in shorts and T-shirts or by

$$h_c = 12.7 [V \bullet P_B/760]^{0.50} \qquad (4')$$

when persons are clothed in general purpose work clothing (9).

THERMAL ENVIRONMENT OF A SPACE SHUTTLE

The heat balance in a Space Shuttle may be described in a graphical format in terms of two independent gradients : Operative temperature (T_o) in the interior space and ambient water vapor pressure (P_a) requiring only an adequate calculation of convective, radiative (h') and evaporative heat transfer coefficients (h'_e) affected by clothing factors, the Lewis relation, and knowledge of net heat flux (H_{sk}) through the skin surface (3,6,8,9). H_{sk} may be determined from metabolism (M), less work level (Wk), less respired, evaporative (E_{res}) and convective (C_{res}) heat losses, and any incurred heat storage (S) (all in $W \bullet m^{-2}$).

This relationship is shown in eq (1) for thermal equilibrium conditions in exercising persons as:

$$(P_a - P_{s,sk}) = -\ h'/(wh'_e) \bullet\ [T_o - (\bar{T}_{sk} - H_{sk}/\ h'\ )] \qquad [\text{Torr}] \qquad (5\ )$$

The ratio h'/h'_e or Ψ is the effective combined physical heat transfer characteristic of the Space Shuttle environment that incorporates all sensible and insensible heat exchange coefficients (9,11). $P_{s,sk}$ is the skin saturation vapor pressure (Torr) and w is the skin wettedness, the fraction of the skin surface that is enveloped by a layer of thermoregulatory sweat. Skin wettedness has been classically described by Gagge (5) as being equivalent to the ratio of evaporative heat loss (E_{sk}) to maximum evaporation possible (E_{max}).

CHALLENGE TO THE HEAT BALANCE EQUATION

The theoretical bases of the above heat balance can be characterized on a psychrometric chart in which ambient water vapor pressure is depicted on the y-axis and dry bulb temperature is on the x-axis. The use of a graphical description allows facile assessment of thermal limits for a given work level that a astronaut might employ during his/her daily exercise within the interior of a shuttle craft. Any of the dependent physiological variables affected by or governing heat exchange such as skin temperature ($\bar{T}_{sk}$), skin wettedness (w) due to regulatory sweating, internal body temperature or skin blood flow (SkBF) can be displayed (3,8).

The critical parameter, ($\bar{T}_{sk}$- H_{sk}/h'), present in eq (5) can be further described in terms of a transient factor, T_{act} , (°C) which accounts for the magnitude and level of rate of heat storage as sweat glands are impeded by continual level of hypo-hydration.
Equation 5 could also be expressed by

$$-\frac{\Psi}{w} = \frac{\Phi_a P_t - P_{ssk}}{T_o - T_{act}} \qquad (5')$$

where $\Phi a P_t$ is the ambient relative humidity (as a fraction) times the saturation pressure of the ambient temperature.

Figure 1 illustrates these concepts further. In this figure, a given environmental condition (e.g. the operating point, OP) is composed of a distinct dry bulb temperature and relative humidity (Φa) or ambient water vapor pressure (P_a). A common point, CP is always formulated by a distinct locus on the x-axis composed of Tact and the y-axis, composed of Ps,sk. The slope of the line connecting OP and CP has the value of the ratio - $h'/(wh'_e)$ or $-\Psi/w$ (in°C/Torr) which represents a unique parameter of the sensible to evaporative heat exchange coefficients of the Space Shuttle environment. T_{act} is a derived, theoretical temperature at which all heat dissipation would occur by dry (sensible) heat exchange alone. The term, H_{sk}, is that component of the final sensible and insensible heat flux arriving at the skin surface that must be dissipated to the environment.

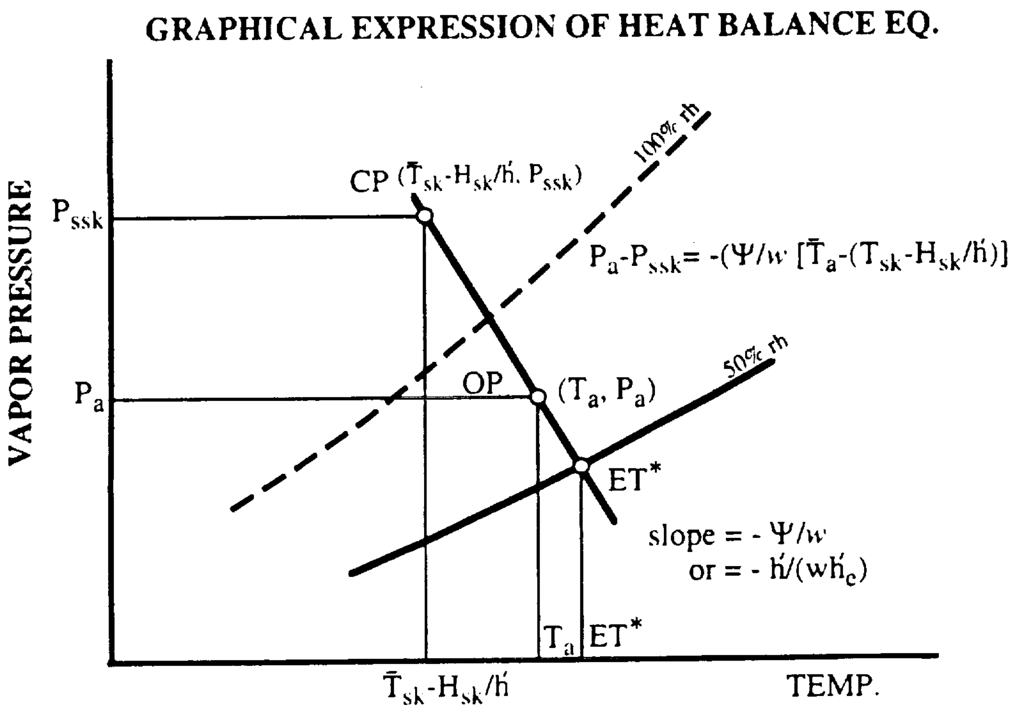

Figure 1. Graphical description of heat balance equation and ET* in a Space Shuttle environment.

The intersection of the CP-OP lines along the 100% saturation line (100% rh) of the psychrometric chart represents the humid operative temperature (T_{oh}).

Since humans recognize the effect of a humidity on perceived thermal discomfort, a new Effective Temperature (ET*) described by dry bulb temperature in which the intersection of the CP-OP line intersects the 50 % rh line (Figure 1) has better meaning by which to integrate heat stress of the environment to physiological responses. This ET* (°C) may be determined analytically by

$$ET* = T_o - \frac{(P_a - 0.5P_{ET}*)}{(-\Psi/w)} \quad (6)$$

This displacement of heat balance can readily be expressed graphically on a psychrometric chart or illustrated graphically in real time (e.g. on a PC-VDT of a shuttle craft) in which P_a is placed on the y-axis and operative temperature (e.g. $T_o \approx T_a = T_{wall}$ of the shuttle) is shown on the x-axis. Towards the right x-axis of operative temperature, level of heat storage, if any, is expressed by Gain = $(T_{act}+\Delta T_{stor})$ and may be also quantified by

$$\Delta T_{stor}=(\Delta\bar{T}_b/\Delta t)\bullet[(0.97\bullet m_b)/A_D] / h' \qquad ,°C \quad (7)$$

where $(\Delta\bar{T}_b/\Delta t)$ is the rate of change of core and skin temperatures (weighted as a mean body temperature, $\bar{T}_b$ per time in hours), 0.97 is the body specific heat constant $(W\bullet h\bullet kg^{-1} \bullet °C^{-1})$ and m_b is *sea-level* body weight (kg), and A_D is Dubois surface area (m^2). This Gain concept has been used adequately before to express effects of atropine treatment during exercise in warm environments by Kolka et.al. (8).

EXERCISE IN A SPACE SHUTTLE

Table I is a simulation of the probable heat balance in an environment of 27 °C and P_a= 21 Torr (80 F/ 70 % rh) that would be the anticipated maximum for any Space Shuttle environment (1, 11). In this simulation a typical 60 min bout of exercise at 180 watts ($\dot{V}_{O2}\approx$ 2.6 L/min) was considered.

Table I. Typical Space Shuttle Exercise Bout.

Exercise	% VO2 Max	M (1)	Wk (2)	T_a (°C)	P_a (Torr)	T_{es}	$\bar{T}_{sk}$	$\dot{m}_{sw}$ (3)	skin wettedness (%)	ET* (°C)
A	65	480	96.4	27	21	38.0	32	15.45	>100	42
B	32	240	40.0	27	21	37.3	33	8.12	88	36

Simulation assumes an Astronaut has a $\dot{V}_{O2}$ max = 4.0 L/min; A_D= 1.9 m^2; shorts + T shirt; forced convection with h_c = 5.5 $W\bullet m^{-2}\bullet °C^{-1}$ using equation 4. Units for : 1) & 2) in $W\bullet m^{-2}$; 3) in g/min.

As shown in Table I (A), assuming that this astronaut exhibits a maximum aerobic power of 4.0 L/min and a 1.9 m2 surface area, the intensity is about 65 % $\dot{V}_{O2}$max or around 8 met (1 met= 100 watts). Table I assumes that the rate of heat storage S at most is no greater than 10% of M. The essential part of the simulation is that the rate of body weight loss due to thermoregulatory sweating of some 15.45 g/min would be developed in this environment in the which the maximum evaporative capacity of the Space Shuttle is 174 $W \bullet m^{-2}$. In these circumstances, the predicted skin wettedness would become greater than 100%. Under zero-g at the ambient water vapor pressure given above, such an amount of sweating will likely create a sheeting layer appearing on the skin surface as documented by many astronauts (Dr James Bagian, personal communication 1992).

Alternatively, a simulation based on one-half the work intensity as shown in Table I (B), or roughly 32 % $\dot{V}_{O2}$ max indicates that the rate of body weight loss due to sweating would be about 8 g/min with a likely skin wettedness of some 80%. In the zero-g of the Shuttle, this amount of sweat would probably create a thinner sheeting layer appearing on the skin surface and would be more acceptable to crewmembers. Based on the formulation of ET* described in this report, the simulation also predicts that the ET* during exercise bout (A) would be about 42 °C whereas during exercise (B), the ET* would be about 36 °C, or result in a 6 °C downward shift in overall thermal strain.

Obviously, any relief in zero-g atmospheres when there exists anterior fluid displacements and congestion of the head during various sojourns in Space Shuttle flights can be facilitated by exercise which has been documented repeatedly (11). However, there should be an optimum exercise intensity to prevent salt and fluid imbalance leading to hypo-hydration (see paper by Sawka et. al. in this symposium). Perhaps intermittent work at 3 min of 65 % $\dot{V}_{O2}$ max coupled with 3 min of free pedalling would be a more suitable option instead of continuous exercise for 60 minutes.

LOCAL SKIN WETTEDNESS IN SPACE SHUTTLE

One parameter that has never been fully experimented upon is the actual measurement of local skin wettedness during space flight. The above simulation only covered effects due to total body skin wettedness. However, it is known that the level of skin evaporation often remains constant as ambient water vapor rises (3). Local skin wettedness, alternatively, at various skin sites undoubtedly increases in a less regular manner since the skin dew point temperature and convective heat transfer are variable throughout the human body sites (2). The result is that the skin surface wetted area may become increasingly larger than predicted from estimates of whole body E_{sk}/E_{max} to facilitate evaporation of water. The development of a small resistance type dew point sensor (7) allows the direct measurement of skin relative humidity. This has permitted the combining of theoretical concepts by which calculation of local regional water loss ($\dot{m}_{sw}$, $mg \bullet cm^{-2} \bullet min^{-1}$) from specific skin areas may be quantified. There is evidence that local skin wettedness is physiologically adjusted as a efferent drive from the central nervous system to provide the required rate of evaporation (6, 8). How all these physiological and physical factors inter-relate in the absence of gravity environments is not known at present and should prove a fruitful source of research.

CONCLUSION

An effective temperature index (ET*), which assesses both dry heat stress and humid heat stress in terms of observed heat exchange may be derived for any given exercise intensity. This ET* is defined as the dry bulb temperature (T_a) at 50% rh in which total heat exchange from the skin surface is the same as in the actual indoor Space Shuttle environment, described by T_a and P_a and movement by the individual. A means to characterize the thermal environment in a Space Shuttle by use of a rational effective temperature (ET*) may therefore allow a better integration of human heat balance, rate of heat storage, and local and total skin wettedness during exercise at zero-g environments.

DISCLAIMER

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