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RATIONALIZATION OF THE EFFECTIVE TEMPERATURE ET*, AS A MEASURE OF THE ENTHALPY OF THE HUMAN INDOOR ENVIRONMENT

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ABSTRACT

The ASHRAE Effective Temperature (ET*) describes the temperature of a standard environment at 50% relative humidity in which the total skin heat exchange (dry and latent) is equal to that in the real environment. The significance of ET* is reexamined here in terms of basic thermodynamics and transport theory. Dry-bulb (DBT) and wet-bulb (WBT) temperatures measure the potential of the environment to exchange dry heat and total heat with wet surfaces through convection. The Lewis Relation links the coefficients of heat and mass transport. By analogy, operative temperature (t_o) and ET* measure the potential for dry heat and total heat exchange by convection and radiation with a human whose skin is partially wet and protected by clothing. Here, the Lewis Relation must be modified by the nondimensional factor i_m, a function of the air layer and clothing transfer coefficients. This analogy substantiates the use of ET* as a more accurate index of the energy transfer potential and enthalpy for the total environment surrounding the skin than either t_o or WBT.

INTRODUCTION

The term "Effective Temperature" was introduced more than fifty years ago by Houghten and Yaglou (1923). Their empirically derived ET index combined the effects of DBT and WBT (dry-bulb and wet-bulb temperatures). It represented the first integrated index of the human response to a humid indoor environment. The ET index received both criticism and praise, which have been documented extensively in the ASHRAE Transactions and Handbooks. The more recent Effective Temperature (ET*) used by ASHRAE derives from the energy balance between the human and his thermal environment. The use of ET* as a temperature index of the indoor environment is well substantiated by its physiological and psychophysical bases. A comprehensive summary paper on ET* was presented recently (Gagge et al. 1986).

The purpose of the present paper is to reexamine the psychrometric origin of ET* in terms of classical thermodynamics and transport theory. More specifically, the question addressed here is: Can the basic theory of energy transfer from a wet surface through convection be applied to the energy balance of a partially wet skin covered with clothing?

For clarity, "total heat" or "energy" is used for the combined dry and latent heat. WBT and DBT always refer to the thermodynamic wet-bulb and air temperatures.

Energy exchange due to the combined convective heat and mass transfer between a wet surface and the surrounding flow of air may be expressed in terms of the enthalpy difference of humid air. This difference is measured between the free flow (i.e., outside of the boundary layer) and the wet surface. The Lewis Relation links the convective transfer coefficients for heat and mass (i.e., water vapor). Since constant wet-bulb temperature lines on a psychrometric chart closely approximate lines of constant enthalpy, wet- bulb temperature has often been used as a measure of the energy transfer potential of a given environment.

There are three factors that affect the analogy between a totally wet surface and a sweating skin and limit the application of wet-bulb temperature to the energy transfer to or

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from a clothed human: (1) the skin surface is often not completely wet with a film of perspiration; (2) heat is exchanged between the skin and the environment by radiation and convection, while wet- bulb temperature applies only to convective transfer; and (3) clothing, when worn, imposes different resistances to heat and mass transfer than an air layer.

SIMILITUDE BETWEEN MOMENTUM, HEAT, AND MASS TRANSFER

Before studying in detail the energy exchange from the skin surface, the fundamental case of a completely wet surface in pure convection is reviewed. The fluxes of momentum, heat, and mass from a wet surface to the surrounding flow of air through convection are expressed in analogous forms, e.g., as a diffusion coefficient times the slope of the driving force profile (velocity, temperature, and concentration) evaluated at the wet surface. Since derivatives are almost impossible to measure experimentally, flux is usually defined in terms of the potential across the whole boundary layer. In dimensionless form, heat and mass transfers are expressed in terms of the classic Nusselt (Nu_L) and Sherwood (Sh_L) numbers. These dimensionless numbers are defined as the ratio of the actual flux to a flux that would take place under the same potential if molecular diffusion was the only transfer mechanism. The product of the Reynolds number (Re_L) and one-half of the skin friction factor (C_f) is the analog dimensionless number for momentum transport.

In the case where momentum, thermal, and mass diffusivities are equal, the boundary layers for momentum, heat, and mass transfer have equal thicknesses and identical nondimensional driving force profiles. Then, the dimensionless fluxes are equal:

$$(C_f/2).Re_L = Nu_L = Sh_L \qquad \text{(N.D.)} \qquad (1)$$

The left-hand equality between heat and momentum transfer is known as the Reynolds analogy and is extended to mass transfer. The subscript L indicates that the dimensionless numbers are averaged over the length of the surface.

The often used Chilton-Colburn analogy (also known as the j-factor analogy) makes the following corrections when the Prandtl (Pr) and Schmidt (Sc) numbers are not equal to 1:

$$j_h = St_h.Pr^{2/3} = C_f/2 \;; \qquad St_h = Nu/(Re.Pr) \qquad \text{(N.D.)} \qquad (2)$$

$$j_m = St_m.Sc^{2/3} = C_f/2 \;; \qquad St_m = Sh/(Re.Sc) \qquad \text{(N.D.)} \qquad (2')$$

where the subscripts h and m indicate heat and mass transfer, respectively.

THE LEWIS RELATION

Similarity between heat and mass transfer translates into the equality of the Chilton-Colburn j-factors for heat and mass. The ratio of heat to mass transfer coefficients is derived from Equations 2 and 2' and is given by the following equation known as the Lewis Relation:

$$(h_c/h_m)(1/\rho.c_p) = P_{AM}.(\alpha/D)^{2/3} \qquad \text{(N.D.)} \qquad (3)$$

When the flow next to the wet surface is turbulent, mechanisms of heat and mass transport are due to large scale flow structures, and molecular diffusion mechanisms may not play a significant role. As a consequence, the effective diffusion coefficients α and D are equal (turbulent or eddy diffusion). Therefore, it may be argued that the α/D correction should be ignored ($1/Le = \alpha/D = Sc/Pr = 0.60/0.72$). However, next to a surface, there always exists a laminar sublayer where molecular transport is not negligible. Since transfer is proportional to the slope of the driving force evaluated at the surface, the Chilton-Colburn analogy remains valid in turbulent flow conditions.

The correction factor, P_{AM}, stems from the fact that, similar to the water vapor partial pressure gradient, there exists a dry air partial pressure gradient resulting in dry air diffusion toward the surface. The correction factor evaluated for 35°C surface temperature and air conditions of 25°C, 50% relative humidity, is 1.04 (ASHRAE Fundamentals, Chapter 5, Example 1, 1985). Substituting this value in Equation 3 gives a value of 0.92 for the right- hand side of the Lewis Relation.

A detailed derivation of the above results is found in chapters 2, 3, 5, and 6 of ASHRAE Fundamentals (1985) and in a variety of textbooks. Rosner's recent textbook on transport processes (1986) was used extensively for the preparation of this section. Review articles by Rapp (1970) and Sibbons (1970) also present excellent theoretical information on the limitations and applications of these analogies between transport processes, specifically as they apply to human skin surface.

INTERPRETATION OF WET-BULB TEMPERATURE AND LINES OF CONSTANT ENTHALPY

The convective dry (sensible) heat and mass fluxes between a wet surface and its surrounding airflow are written as:

$$\mathring{q}_{h,conv} = h_c.(t_s - t_a) \qquad (W/m^2) \qquad (4)$$

$$\mathring{m} = h_m.(\rho_s - \rho_a) = \rho.h_m.(W_s - W_a) \qquad (kg/m^2.s) \qquad (4')$$

The expression for the heat flux associated with evaporation and subsequent transport from the surface is derived from the mass flux equation by making use of the perfect gas relationship for water vapor and of the Lewis Relation. The enthalpy differences due to temperature changes in liquid and gaseous phases are negligible compared to the latent heat of evaporation, H_{fg}. It follows:

$$\mathring{q}_{m,conv} = H_{fg}\ [h_c/(\rho\ c_p\ 0.92)]\ [M_w/(R_u\ T)]\ (p_s - p_a) \qquad (W/m^2) \qquad (5)$$

Defining:

$$LR = [H_{fg}/(\rho\ c_p\ 0.92)]\ [M_w/(R_u\ T)] \qquad (K/kPa) \qquad (5')$$

Equation 5 becomes:

$$\mathring{q}_{m,conv} = LR\ h_c\ (p_s - p_a) \qquad (W/m^2) \qquad (5'')$$

where ρ, c_p, and T are evaluated at mean film conditions, e.g., average between surface and flow conditions. LR as defined in Equation 5' will be referred to as the Lewis Relation Coefficient.

For example, if one takes 25°C, 50% rh as a typical mean film condition, then H_{fg} = 2450 kJ/kg, ρ = 1.16 kg/m^3, $c_p = (c_{pa} + W.c_{pw})/(1 + W)$ = 1.013 kJ/kg.K. From Equation 5', the value of LR is 16.5 K/kPa, in agreement with values ranging from 16.2 to 16.6 reported by Rapp. At 30°C, LR is equal to 16.4 K/kPa. Since the coefficients in the expression for LR are themselves functions of the psychrometric conditions, LR is a complex function of surface temperature, air temperature, relative humidity, and pressures of water vapor and dry air. Among these factors, average film temperature and density are the most sensitive to changing psychrometric conditions. In Equation 5', changes in temperature, T, and density, ρ, balance each other when skin or air temperature varies. As a result, over the narrow range of temperatures (20°C to 40°C) and humidities (0.5 kPa to 5 kPa) of interest for temperature regulation by sweating, the value of the Lewis Relation Coefficient (LR) can be considered constant at 16.5 K/kPa.

In Equation 5, the flux of water vapor (mass) is described in terms of the heat transfer resulting from evaporation (latent or evaporative heat transfer). The sensible and latent heat fluxes may be combined into a total energy flux: making use of the Lewis Relation and of the definition of enthalpy for a perfect gas, the total energy transfer is given by (ASHRAE Fundamentals, Chapter 5, 1985):

$$\dot{q}_{conv} = \dot{q}_{h,conv} + \dot{q}_{m,conv} \qquad (W/m^2) \qquad (6)$$

$$= \rho.h_m.(H_s - H_a) \qquad (W/m^2) \qquad (6')$$

where the following approximations are made: (1) in the Lewis Relation, the corrections for Lewis number ($Le = D/\alpha$) and P_{AM} are ignored (the right-hand side of Equation 3 is set equal to one), and (2) the expression of air enthalpy assumes that perfect gas laws apply and that latent heat of vaporization of water is independent of temperature.

It follows from the thermodynamic properties of humid air that constant wet-bulb temperature lines closely approximate lines of constant enthalpy; hence, they represent lines of constant energy (sensible and latent heat) for the transfer between a humid air environment and a given, completely wet, surface. In other words, two environments with the same wet-bulb temperature will exchange the same energy with a given wet surface, even though the balance between dry and latent heat transfer may shift. As a consequence, given a wet surface and a flow condition (in terms of a Nu_L-Re_L relationship, for example), the wet-bulb temperature of the humid air environment completely characterizes the total convective energy balance for the surface.

HEAT AND MASS TRANSFER BETWEEN HUMANS AND THEIR ENVIRONMENTS

The next question is how the energy transfer from the human skin, through a layer of air captured by clothing and through clothing itself, can be related theoretically to the equations derived above. For the present, attention is restricted to energy transfer between the skin surface and the environment. For a square meter of cylindrical skin surface, the following assumptions are made: (1) distribution of clothing is uniform over the skin area; (2) the area of the clothing interface with the environment is increased by a factor f_{cl}; (3) clothing insulation, as reported in the literature (ASHRAE Fundamentals, Chapter 8, 1985), includes the insulation of the air trapped between the skin and the clothing layer; (4) evaporation of sweat takes place at the skin surface, and water vapor diffuses through clothing after evaporation; and (5) there is neither heat nor water vapor accumulation in clothing.

The energy transfer equations for sensible heat will be examined first. Based on Figure 1a, the equations describing (1) the heat transfer from the skin to the outer surface of clothing, and (2) the heat transfer from the outer surface of clothing to the environment, are (Nishi 1969):

$$DRY = h_{cl}.(t_{sk} - t_{cl}) \qquad (W/m^2) \qquad (7)$$

$$DRY = f_{cl}.h_c.(t_{cl} - t_a) + f_{cl}.h_r.(t_{cl} - t_r) \qquad (W/m^2) \qquad (7')$$

where t_{cl} can be eliminated from the two equalities. The result is a simple first degree equation for DRY:

$$DRY = h_{cl}.f_{cl}.[h_c.(t_{sk} - t_a) + h_r.(t_{sk} - t_r)]/[f_{cl}.(h_c + h_r) + h_{cl}] \quad (W/m^2) \qquad (8)$$

Equation 8 may be rewritten in a form analogous to that of Equation 4:

$$DRY = h'.(t_{sk} - t_o) \qquad (W/m^2) \qquad (9)$$

where

$$h' = f_{cl}.(h_c + h_r).\{h_{cl}/[f_{cl}.(h_c + h_r) + h_{cl}]\} \qquad (W/m^2.K) \qquad (10)$$

and $t_o = (h_c . t_a + h_r . t_r)/(h_c + h_r)$, (^oC) (11)

The operative temperature (t_o) is a weighted average of dry-bulb and mean radiant temperatures. The coefficient $\{h_{cl}/[f_{cl} . (h_c + h_r) + h_{cl}]\}$ in Equation 10 is known as Burton's thermal efficiency factor for clothing (F_{cl}). The coefficient h', defined in Equation 10 as a combination of the fundamental heat transfer coefficients, h_{cl}, h_c, and h_r, is the effective sensible heat transfer coefficient. The prime is used to differentiate effective from fundamental variables. The fundamental coefficients for radiation and convection are:

$$h_r = 4 . (A_r/A_D) . \sigma . \varepsilon . [(T_{cl} + T_r)/2]^3 \qquad (W/m^2.K) \quad (12)$$

and $h_c = 8.6 . v^{0.53}$ $(W/m^2.K)$ (13)

Equation 12 is a direct result of the linearization of the Stefan-Boltzmann equation for radiant heat transfer. Equation 13 is based on experimental results from an extensive study on human subjects by Nishi and Gagge (1970a). For further discussions of convective and radiative heat transfer from human subjects, the reader is referred to ASHRAE Fundamentals (Chapter 8, pp. 2-7, 1985) and Rapp (1970).

Since the coefficient of radiative heat transfer depends on clothing temperature, the equations for clothing temperature, for dry heat transfer, and for radiative heat transfer coefficient (which is nonlinear in t_{cl}) must be solved simultaneously. Note that the resistance to heat transfer of clothing (reciprocal of h_{cl}) takes into account the thin air layer under clothing.

As seen in Figure 1b, the mass transfer part of the total energy balance is given by:

$$E_{sk} = w . h'_e . (p_{ssk} - p_a) \qquad (W/m^2) \quad (14)$$

where w is the fraction of skin surface wet with perspiration. E_{sk} is a physiologically controlled variable and is a function of the heat stress imposed on the subject. Wettedness, w, ranges from a fraction of 0.06 for vapor diffusion through the skin alone (Brebner et al. 1956) to a theoretical maximum of unity when the skin is completely wet. For the present analysis, the maximum evaporation from the skin surface is assumed to be:

$$E_{max} = h'_e . (p_{ssk} - p_a) \qquad (W/m^2) \quad (15)$$

In Equations 14 and 15, the effective mass transfer coefficient, h'_e, is given by:

$$h'_e = [1/(LR . f_{cl} . h_c) + 1/(LR . h_{cl} . i_{cl})]^{-1} \qquad (W/m^2.kPa) (16)$$

where LR, derived earlier (Equation 5'), is the Lewis Relation Coefficient. When the mass transfer potential is expressed in terms of water vapor partial pressure, ($LR . h_c$) and ($LR . h_{cl} . i_{cl}$) are the evaporative heat transfer coefficients for the air boundary layer and the clothing layer, respectively. The factor i_{cl} may be interpreted as the ratio of the mass transfer coefficients of a clothing layer and an air layer that have the same sensible heat transfer coefficients. For example, i_{cl} smaller than one indicates that clothing imposes a higher resistance to mass transfer than would an equivalent air layer. Even though, there are no known fabrics for which i_{cl} is greater than one, it is theoretically possible that some clothing material may impose a greater transfer resistance to heat than to water vapor. Values for i_{cl} based on measurements of naphthalene sublimation by Nishi and Gagge (1970b) are slightly greater than one. Selected measurements of relative mass and heat transport efficiencies measured by Berglund are reported by Oohori et al. (1985). In the same paper, Oohori describes a factor, i_L, proposed earlier by Lotens, which is identical to the i_{cl}

defined above. Lotens' definition for i_L is the ratio of the Lewis Relation Coefficients for clothing and for air (1983).

Equations 14, 15, and 16 imply the following two assumptions: (1) h_c and hence the convective mass transfer coefficient are constant over the whole body area (for cylinders or spheres, the ratio between maximum and minimum local heat transfer coefficients can reach a value of two to three). (2) The similitude between heat and mass transport for a wet surface, when applied to clothing, requires an imaginary film of sweat to be located at the outer surface of clothing (where the convection takes place) and not at the skin surface. The Lewis Relation is based on the similarity of temperature and water vapor concentration profiles within a boundary layer. It is unlikely that the water vapor concentration profile from the skin, through an air layer and a clothing layer, can ever be similar to the temperature profile from the outer surface of clothing. The simplified two-layer description (clothing and air layer) is used here as an approximation to the extremely complex problem of water and water vapor transport from the skin surface to the environment.

EFFECTIVE TEMPERATURE (ET*): EXTENSION OF THE LEWIS RELATION CONCEPT TO ENERGY EXCHANGE BETWEEN SKIN SURFACE AND ITS ENVIRONMENT

The index ET* for the human environment is defined as the temperature of a hypothetical reference environment in which the energy balance of the subject is equal to that in the actual environment. For the Effective Temperature (ET*) environment, the total skin heat transfer, the proportion of skin wet with sweat, the clothing, insulation and the transfer coefficients are assumed to be the same as in the actual environment. The hypothetical environment is defined as having its air dry-bulb temperature equal to its mean radiant temperature, which, when related to the actual environment, results in shifting the balance between convective and radiative sensible heat transfer without altering the total sensible heat transfer. The hypothetical environment has 50% relative humidity, which results in shifting the balance between total sensible heat transfer and total latent heat transfer without altering the total skin heat transfer. The following equations are the expressions for the total skin heat transfer in the actual and in the Effective Temperature (ET*) environments, respectively:

$$\dot{q}_{sk} = DRY + E_{sk} = h'.(t_{sk} - t_o) + w.h'_e.(p_{ssk} - p_a) \qquad (W/m^2) \qquad (17)$$

$$\dot{q}_{sk} = h'.(t_{sk} - ET^*) + w.h'_e.[p_{ssk} - p_s(ET^*)/2] \qquad (W/m^2) \qquad (18)$$

Equation 17 can also be interpreted as the steady-state human thermal balance. The heat flux, $\dot{q}_{sk}$, represents the metabolic heat production minus the work performed and minus the heat exchanged directly from the inner part of the body to the environment through respiration. It follows, from Equations 17 and 18, that the two points on a psychrometric chart that have (t_o, p_a) and (ET*, p_s(ET*)/2) as coordinates characterize two environments that have the same potential for total heat transfer with the same human subject. This is true for any point on a constant ET* locus. Thus ET*, for energy exchange between a humid air environment and the skin of a clothed human subject, plays a role analogous to that of the wet-bulb temperature for the convective energy exchange with a wet surface.

The one distinction in the analogy between WBT and ET* is that WBT is equal to dry-bulb temperature at the saturation line, whereas ET* is chosen to be equal to the operative temperature ,t_o, at the 50% relative humidity line. A relative humidity of 50% is typical of indoor environments and is justified as a reference for constant ET* lines. The "Humid Operative Temperature" (t_{oh}, Nishi and Ibamoto 1969) and the "Adiabatic Equivalent Temperature" (Monteith 1973; Büttner 1938) are based on the same heat and mass transfer principles. For a humid operative temperature environment, 100% relative humidity is chosen as a reference, whereas it is 0% for the adiabatic equivalent temperature environment.

Eliminating $\dot{q}_{sk}$ from Equations 17 and 18 gives:

$$(w.h'_e/h') = -(t_o - ET^*)/[p_a - p_s(ET^*)/2] \qquad (K/kPa) \qquad (19)$$

Equation 19 shows that, without affecting the total energy balance, a temperature difference can be replaced by an equivalent water vapor partial pressure difference or vice versa through the use of the ($w.h'_e/h'$) factor. This factor plays a role analogous to the Lewis Relation Coefficient. Equivalence implies that the total energy transfer is conserved. Replacing the expressions for h' and h'_e from Equations 10 and 16 gives for the ($w.h'_e/h'$) ratio:

$$w.h'_e/h' = w.LR.[(h_c.i_{cl})/(h_{cl}.i_{cl} + f_{cl}.h_c)].[(f_{cl}.(h_c + h_r) + h_{cl})/(h_c + h_r)] \quad (K/kPa) \quad (20)$$

LR represents the slope of constant wet-bulb temperature lines on Mollier psychrometric charts, and ($w.h'_e/h'$) represents the slope of constant ET* lines (Figure 2). Equation 20 demonstrates that, when there is no radiative heat transfer ($h_r = 0$), when the ratio of mass to heat transfer diffusivities of clothing is equal to that of air ($i_{cl} = 1$) and when skin is completely covered with sweat (w equal to 1), the ($w.h'_e/h'$) ratio is equal to LR. In this hypothetical case, constant ET* loci coincide with constant wet-bulb temperature lines. Since in all practical conditions i_{cl} and w are less than one, and h_r is greater than zero, the slope $w.h'_e/h'$ is never as steep as LR. A second limiting case of the slope of ET* loci is deduced by setting w = 0. Then, slope is 0 and ET* loci fall on operative temperature (t_o) lines; this equivalence indicates that t_o is a valid index of the environmental energy transfer potential when there is no or very little sweating. Equation 20 applies also to nude subjects: when there is no clothing, h_{cl} is infinite and the slope ($w.h'_e/h'$) is equal to $w.LR.[h_c/(h_c + h_r)]$. The dimensionless variable i_a is used to refer to the ratio $[h_c/(h_c + h_r)]$ of convective to total sensible heat transfer coefficients (Oohori et al. 1985).

All the equations for latent heat transfer through clothing are defined so far in terms of the intrinsic mass transfer property, i_{cl}. Woodcock (1962) used the following equation for his evaluation of the combined mass transfer characteristics of clothing and air layer:

$$E_{max} = LR.(i_m.h').(p_{ssk} - p_a) \quad (W/m^2) \quad (21)$$

where h' is identical to the heat transfer coefficient derived in Equation 10. From Equation 14, the expression of E_{sk} in Equations 17 and 21, the latent heat transfer coefficient can be expressed as:

$$h'_e = h'.i_m.LR \quad (W/m^2.kPa) \quad (22)$$

Using the factor i_m, the expression for the slope of ET* loci becomes:

$$w.h'_e/h' = w.i_m.LR \quad (K/kPa) \quad (23)$$

Equations 20 and 23 give the relationships between i_{cl} and Woodcock's i_m in terms of heat transfer coefficients (h_c, h_r, h_{cl}), and clothing properties f_{cl} and i_{cl}. Oohori (1985) has derived similar relationships between i_{cl}, i_m, and i_a in terms of Burton's clothing efficiency factor F_{cl}:

$$1/i_m = F_{cl}/i_a + (1-F_{cl})/i_{cl} \quad (N.D.) \quad (24)$$

Finally, the sensible and latent heat transfer potentials are combined into an enthalpy potential so that the total heat transfer can be written in a form analogous to that of Equation 6':

$$\dot{q}_{sk} = DRY + E_{sk} \quad (W/m^2) \quad (25)$$

$$\dot{q}_{sk} = \rho . h'_m . (H'_{sk} - H'_a) \qquad (W/m^2) \qquad (25')$$

where

$$h'_m = h'/(\rho . c_p) \qquad (m/s) \qquad (26)$$

$$H'_{sk} = c_p . [t_{sk} + (w.i_m.LR).p_{ssk}] \qquad (kJ/kg) \qquad (27)$$

and $$H'_a = c_p . [t_o + (w.i_m.LR).p_a] \qquad (kJ/kg) \qquad (28)$$

$$= c_p . [ET^* + (w.i_m.LR).p_s(ET^*)/2] \qquad (kJ/kg) \qquad (28')$$

H'_a and H'_{sk} measure the effective enthalpy of air in the environment and at the skin surface, respectively. The prime is used to differentiate the newly defined effective enthalpy from its thermodynamic counterpart, i.e., air enthalpy, H (Equation 6'). Equation 26 is the analog of the Lewis Relation (Equation 3). Equation 28' demonstrates the relationship between ET* and effective enthalpy, H'_a. Note that the modifier $(w.i_m)$ to the Lewis Relation Coefficient LR is present in both expressions for air and skin effective enthalpy (Equations 27, 28, and 28').

Replacing the expressions for h'_m, H'_a and H'_{sk} in Equation 25':

$$\dot{q}_{sk} = h' \; (tH_{sk} - tH_a) \qquad (W/m^2) \qquad (29)$$

where tH, defined for practical purposes as "enthalpy temperature," represents the quantity (H'/c_p). The enthalpy temperature tH is similar to the "Adiabatic Equivalent Temperature" (Monteith 1973; Büttner 1938); it is based on the assumption that variations of the specific heat of humid air are small. The variable tH has the dimension of temperature.

In light of Equations 28 and 28', the Effective Temperature, ET*, may be redefined as the hypothetical temperature of a uniform environment at 50% relative humidity in which the effective enthalpy is the same as in the real environment.

APPLICATIONS

The recent two-node model of human thermal physiology (Gagge et al. 1986) is used to illustrate the theoretical relationships derived in this paper. The integration loop of the model predicts the effector responses by sweating and by skin blood flow necessary to maintain normal body temperature for the heat load caused by the environment. The model provides consistent information on skin temperature and wettedness necessary for the calculation of ET*. It also predicts the heat transfer coefficients from the skin to the environment.

Figures 2 to 7 are derived from the two-node model simulation of a subject whose metabolic rate is 175 W normalized per square meter of skin surface (three Met, light work conditions) and who is wearing clothing with a heat transfer coefficient, h_{cl}, of 28.3 $W/m^2.K$ (0.23 clo). The environmental conditions range from 0 to 50°C for operative temperature and from 0 to 100% for relative humidity. Duration of exposure is one hour. It is assumed that, initially, the body is in a state of physiological thermal neutrality- no regulatory sweating, vasoconstriction, nor vasodilation. Table 1 shows additional information on the simulations. The results are presented on Mollier type psychrometric charts (partial pressure of water vapor as abscissa, air temperature as ordinate).

As an example, Figure 2 shows an ET* locus and its slope $-(w.i_m.LR)$. The humid operative temperature, t_{oh}, is the intersection of the ET* locus with the 100% relative humidity curve. The effective enthalpy temperature of the environment, tH_a, is the intersection of the ET* locus with the 0% relative humidity line. Also shown are effective enthalpy temperatures for the skin, tH_{sk}, and the effective enthalpy gradient $(tH_{sk} - tH_a)$. The present data are based on a simulation for an environment at 23°C operative temperature, and 75% relative humidity.

Figure 3 demonstrates that either ET* or effective enthalpy (tH_a) can be used as a measure of the total energy transfer potential of the environment (Equation 28'). Note that ET* (and thus tH_a) depends on both the skin wettedness and temperature and on the transfer properties of clothing. In other words, changing the metabolic rate or clothing will affect the shape of the relationship in Figure 3.

Figures 4 to 7 show loci for ET*, i.e., constant perceived enthalpy (Figure 4), wettedness w (Figure 5), sweating rate (Figure 6), and skin temperature (Figure 7) for the same set of conditions (Table 1).

On Figure 4, in conjunction with ET* lines, several points of interest based on physiological events are shown. Points selected for illustration are: (1) failure to achieve thermal steady state after a one-hour exposure (body temperature keeps decreasing towards the cold, increasing in the extreme heat); (2) onset of regulatory sweating, where w = 0.06 (lower limit of zone of evaporative regulation); and (3) maximum evaporative cooling, where w = 1.

The slope ($w.h_e'/h'$) of ET* loci is expressed as ($w.i_m.LR$), where LR is constant at 16.5 K/kPa and i_m is a function of the clothing layers. The slope of constant ET* lines depends primarily on skin wettedness, w. In cold, skin wettedness is minimal at 0.06. The slope of ET* lines varies from 0.6 (cold) to 9.0 K/kPa (hot).

The effect of humidity on the skin energy balance may be illustrated as follows (Figure 4): at constant operative temperature of 40°C, where skin wettedness is maximum, as humidity is raised from 40% to 50%, the water vapor partial pressure increases by about 0.7 kPa and results in a 2.2°C increase in ET*. For ET* of about 18°C, where wettedness is minimal, an increase in relative humidity from 20% to 80% results in an Effective Temperature change of less than 1°C.

Graphs of physiological responses as function of operative temperature and water vapor pressure describe the transition from cold environments, where humidity has no influence, to warm environments, where humidity has a large impact. For comparison, Figure 5 shows lines of constant skin wettedness, w, from 8% to 96% by increments of 4%; Figure 6 shows lines of constant sweating rate from 0.02 to 0.50 $kg/m^2.h$ by 0.02 increments; and Figure 7 shows lines of constant skin temperature ranging from 25°C to 39°C by 1°C increments. Except near the region of maximum evaporative cooling, regulatory sweating and skin temperature depend on the stress of the environment as measured by operative temperature, as may be seen from their weak response to humidity in Figures 6 and 7. In contrast, skin wettedness (Figure 5) depends on both regulatory sweating and the evaporative power (mass transfer potential) of the environment. For a given level of regulatory sweating required for thermoregulation, a low evaporative power of the environment results in an undesirably high wettedness.

Lines of constant ET* and constant wettedness do not exactly coincide, even though the definition of ET* expresses that skin wettedness should be equal both in the actual and in the hypothetical ET* environments. This small difference is explained as follows: respiratory heat fluxes change with the psychrometric conditions of the environment and affect the core energy balance, which, in turn, influence the heat load, E_{sk}, to be dissipated by sweating.

CONCLUSION

An expression for the effective enthalpy, H_a', of a humid environment as perceived by humans (Equations 28 or 28') has been derived from fundamental heat transfer and thermodynamic principles by analogy with heat transfer from a wet surface. The effective enthalpy gradient ($H_{sk}' - H_a'$) measures the potential of the total environment to exchange heat with a human subject (Equation 25'). In classical thermodynamics, enthalpy is an intrinsic property: it is a function of the state of the environment alone. The effective enthalpy, H_a', however, is a function of skin wettedness and of the transfer barriers, namely, the air boundary layer and clothing. The concept of enthalpy for the human environment is intimately linked to the Effective Temperature ET* (Equation 28'); constant ET* and constant H_a' loci on a Mollier chart have the same slopes $-(w.i_m.LR)$.

Wet-bulb temperature (WBT), operative temperature (t_o), and Effective Temperature (ET*) all serve as indices of the human environment. On the Mollier charts, constant WBT lines and t_o lines (t_a lines when $t_a = t_r$) are limiting cases for ET* lines: (1) Slopes of constant WBT lines correspond to the maximum impact of humidity (no radiative heat transfer, skin completely covered with perspiration, and heat and mass transfer properties of clothing similar to those of air). (2) At the other limit, toward the cold, humidity has a negligible influence on the human thermal balance, and the slopes of t_o and ET* lines are essentially the same. In typical indoor environments, WBT over-evaluates the impact of humidity. In contrast, t_o completely ignores humidity. ET* on the other hand, within the limits of the assumptions listed in the section on energy transfer from human skin, reflects the true impact of humidity.

In summary, the principal steps taken in evaluating the energy exchange between the human and his environment and the resulting conclusions are:

<u>For a wet surface:</u>

1. Wet-bulb temperature is an index of the environment that accounts for the sensible and latent heat transfer by convection.
2. The Lewis Relation links the coefficients of heat and mass transfer. The driving potentials are dry-bulb temperature (heat transfer) and water vapor pressure (mass transfer and resulting evaporative heat transfer).
3. The Lewis Relation Coefficient (LR) is a measure of the relative importance of dry-bulb temperature and water vapor pressure on the energy balance of a wet surface. On the Mollier psychrometric chart, the Lewis Relation Coefficient is given, to a close approximation, by the negative slope of constant enthalpy (or wet-bulb temperature) lines.

<u>For the human environment:</u>

4. ET* represents an index analogous to WBT, which combines sensible and evaporative heat transfer. ET* also accounts for both convection and radiation.
5. The effective sensible (h') and latent (h_e') heat transfer coefficients are derived from the energy balance at the skin surface. The driving potentials are operative temperature (analogous to dry-bulb temperature) and water vapor pressure. The ratio ($w.h_e'/h'$) of the effective latent and sensible heat transfer coefficients is analogous to the Lewis Relation Coefficient.
6. The ratio ($w.h_e'/h'$) is a measure of the relative importance of operative temperature and water vapor pressure on the energy balance of a partially wet skin surface. On a psychrometric chart, this ratio is given by the negative slope of ET* lines.
7. The negative slope of ET* lines is given by ($w.i_m.LR$). The permeation efficiency factor, i_m, for the combined air and clothing layers is a dimensionless modifier of the Lewis Relation Coefficient. This factor is related to the efficiency factors, i_{cl} for clothing layer and i_a for air layer, in terms of the fundamental heat transfer coefficients and the intrinsic properties of clothing (Equation 24).
8. By analogy with heat transfer from a wet surface, H_a' is a measure of the total energy transfer potential of a humid air environment and may also be interpreted as the effective enthalpy of the human environment.
9. Finally, the thermal impact of humidity perceived by the human subject is best reflected by ET*, rather than either WBT or t_o.

<u>NOMENCLATURE</u>

<u>Nondimensional groups</u>

C_f = friction factor = $\tau_w/(\rho.v^2/2)$; τ = tangential wall stress, in kg/m.s^2.

j_h = Chilton-Colburn heat transfer j-factor.

j_m = Chilton-Colburn mass transfer j-factor.

Le = Lewis number = D/α = Pr/Sc. For air, Le = 1.20 (Rosner 1986).

Nu_L = surface average Nusselt number (heat transfer) = $\dot{q}_{h,conv}/[k.(t_s - t_a)/L] = h_c.L/k$.

Pr = Prandtl number = ν/α. For air, Pr = 0.72.

Re_L = Reynolds number based on characteristic length of surface = $v.L/\nu$.

Sc = Schmidt number = ν/D. For air, Sc = 0.60.

Sh_L = surface average Sherwood number (mass transfer) = $\dot{m}/[D.\rho.(W_s - W_a)/L] = h_m.L/D$.

St_h = Stanton number (heat transfer) = $\dot{q}_{h,conv}/[\rho.v.c_p.(t_s - t_a)]$.

St_m = Stanton number (mass transfer) = $\dot{m}/[\rho.v.(W_s - W_a)]$.

English symbols

A = area, m^2

A_D = DuBois surface area (human body) = $0.202\ w^{0.425}.h^{0.725}$, where w is body mass in kilogram, and h is height in meter, m^2.

A_r = radiative area of human body, m^2.

c_p = specific heat of humid air kJ/kg.K. For air at 25°C and 50% relative humidity, c_p = 1.013 kJ/kg.K.

D = mass diffusivity, m^2/s. For water vapor in air $D = 0.25\text{x}10^{-4}\ m^2/s$.

DRY = sensible heat flux from skin (convection and radiation), W/m^2.

E_{max} = maximum skin latent heat flux, W/m^2.

E_{sk} = skin latent heat flux, W/m^2.

ET* = Effective Temperature, °C.

F_{cl} = Burton's clothing efficiency factor = $h_{cl}/[f_{cl}.(h_c + h_r) + h_{cl}]$, dimensionless (Equation 10).

f_{cl} = factor for exterior surface area increase due to clothing, dimensionless.

H_a = air enthalpy in free flow (away from surface), kJ/kg.

H'_a = effective enthalpy of human thermal environment, kJ/kg.

H_s = air enthalpy next to the surface, kJ/kg.

H'_{sk} = effective air enthalpy next to skin surface, kJ/kg.

H_{fg} = latent heat of vaporization, kJ/kg. For sweat, H_{fg} = 2450 kJ/kg

h' = effective sensible heat transfer coefficient for clothing and air layer combined, $W/m^2.K$.

h_c = convective sensible heat transfer coefficient, $W/m^2.K$.

h_{cl} = heat transfer coefficient of clothing, $W/m^2.K$.

h'_e = effective latent heat transfer coefficient for clothing and air layer combined, $W/m^2.K$.

h_m = mass transfer coefficient for a wet surface, m/s.

h'_m = effective mass transfer coefficient for skin surface, m/s.

h_r = radiative sensible heat transfer coefficient, $W/m^2.K$.

i_a = mass to heat transfer property for air layer i.e., ratio of convective to total sensible heat transfer coefficients = $h_c/(h_c + h_r)$, dimensionless.

i_{cl} = mass to heat transfer property of clothing, Equation 15, dimensionless.

i_m = mass to heat transfer property for clothing and air layer combined, Equation 21, dimensionless.

k = thermal conductivity, W/m.K. For air, k = 0.025 W/m.K

L = characteristic length in non-dimensional groups, m.

LR = Lewis Relation Coefficient, Equation 5', K/kPa. For water evaporating in air, LR = 16.5 K/kPa.

$\dot{m}$ = convective mass flux, kg/m^2.s.
M_w = molecular weight of water = 18.015 kg/kgmole.
p_a = partial pressure of water vapor in air, kPa.
P_{AM} = mean density factor, Equation 3. P_{AM} = 1.04.
p_s = partial pressure of water vapor at saturation near the wet surface, kPa.
$p_s(ET^*)$ = partial pressure of water vapor at saturation at ET*, kPa.
p_{ssk} = partial pressure of water vapor at saturation near the skin, kPa.
$\dot{q}_{conv}$ = convective heat flux (sensible and latent heat), W/m^2.
$\dot{q}_{h,conv}$ = convective heat flux (sensible heat), W/m^2.
$\dot{q}_{m,conv}$ = convective heat flux (latent), W/m^2.
$\dot{q}_{sk}$ = total (sensible and latent) skin heat flux, W/m^2.
R_u = universal gas constant = 8314 J/kgmole.K.
t_a = air temperature, ^{o}C.
t_{cl} = clothing surface temperature, ^{o}C.
t_o = Operative Temperature, Equation 11, ^{o}C.
t_{oh} = Humid Operative Temperature (Nishi and Ibamoto 1969), ^{o}C.
t_r = mean radiative temperature of the environment (4 π solid angle), ^{o}C.
t_s = wet surface temperature, ^{o}C.
t_{sk} = skin surface temperature, ^{o}C.
tH_a = Enthalpy temperature of the environment = H_a'/c_p (Equation 29), ^{o}C.
tH_{sk} = Enthalpy temperature at the skin = H_{sk}'/c_p (Equation 29), ^{o}C.
T = absolute temperature, K.
v = air velocity, m/s.
w = skin wettedness, fraction of total skin area A_D covered with sweat.
W = humidity ratio, mass ratio of water vapor to dry air, kg/kg.

Greek symbols

α = thermal diffusivity, m^2/s. For air, α = 0.21x10^{-4} m^2/s.
ϵ = emissivity of clothing surface, dimensionless.
ν = dynamic viscosity, m^2/s. For air, ν = 0.15x10^{-4} m^2/s.
ρ = specific mass, kg/m3. For air at 25^{o}C and 50% humidity, ρ = 1.16 kg/m^3.
σ = Stefan-Boltzmann constant = 5.6697 10^{-8} W/m^2.K^4.

Subscripts

a = air
c = convective
conv = convection
cl = clothing
h = sensible heat
m = mass
o = operative
r = radiative
s = wet surface

sk = skin
w = water

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TABLE 1

Input Variables to the Two-Node Model Simulations

Physiological constants:			
TTSK	33.7	°C	reference (neutrality) for skin temperature
TTCR	36.8	°C	reference (neutrality) for core temperature
CSW	170.	$g/m^2.h$	sweating constant
CSTR	0.5	N.D.	vasoconstriction constant
CDIL	200.	$l/m^2.h.K$	vasodilation constant
SKBFL	90.	$l/m^2.h$	max. skin blood flow
RGSWL	500.	$g/m^2.h$	max. sweating rate
Initial values of physiological variables:			
TSKI	33.7	°C	skin temperature
TCRI	36.8	°C	core temperature
ALPHAI	0.1	N.D.	skin to total mass ratio
SKBFI	6.3	$l/m^2.h$	skin blood flow
ESKI	7.3	W/m^2	total skin evaporative heat loss
Metabolic heat:			
ACT	3.0	Met	activity level (1 Met = 58.15 W/m^2)
WE	0.	N.D.	part of activity in effective work
Clothing:			
CLO	0.23	clo	intrinsic insulation (1 clo = .155 $m^2.K/W$)
KCLO	0.25	N.D.	factor of increase of area due to clothing
EVEF	1.	N.D.	maximum evaporation efficiency
ICL	0.45	N.D.	effectiveness of mass transfer for clothing
Environment:			
ATA	1.	atm.	atmospheric pressure
TA	0 to 50	°C	ambiant air temperature (1°C increments)
VEL	0.2	m/s	air velocity
TR	TR = TA	°C	mean radiant temperature (TR = TA)
RH	0. to 1.	N.D.	relative humidity (0.25 increments)
TIME	60	min	duration of exposure

TABLE 2

Conversion Factors (SI to IP)

Quantity	Units (SI)	x	Factor	=	Units (IP)
Temperature	^oC		1.8 + 32		F
Absolute temperature	K		1.8		R
Mass	kg		2.205		lb
Length	m		3.281		ft
Area	m^2		10.76		ft^2
Pressure	kPa		0.145		psi
Energy	kJ		0.948		Btu
Enthalpy	kJ/kg		0.430		Btu/lb
Power	W		3.412		Btu/hr
Specific mass	kg/m^3		0.0624		lb/ft^3
Specific heat	kJ/(kg.K)		0.239		Btu/(lb.R)
Energy flux	W/m^2		0.317		$Btu/hr.ft^2$
Mass flux	$kg/m^2.s$		0.205		$lb/(ft^2.s)$
Diffusivity	m^2/s		10.76		ft^2/s
~~Thermal conductivity~~	~~W/(m.K)~~		~~0.578~~		~~Btu/(hr.ft.R)~~
Heat transfer coefficient	$W/(m^2.K)$		0.1761		$Btu/(hr.ft^2.F)$
Mass transfer coefficient	m/s		3.281		ft/s
Evaporative mass transfer coefficient	$W/(m^2.kPa)$		2.186		$Btu/(hr.ft^2.psi)$
Lewis Relation Coefficient	K/kPa		12.41		psi/R

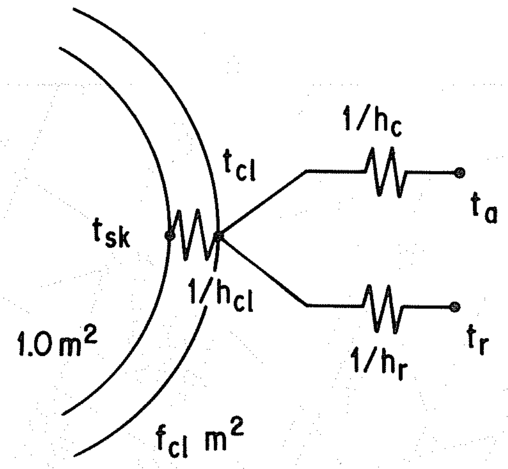

Figure 1a Sensible heat transfer from the human skin surface

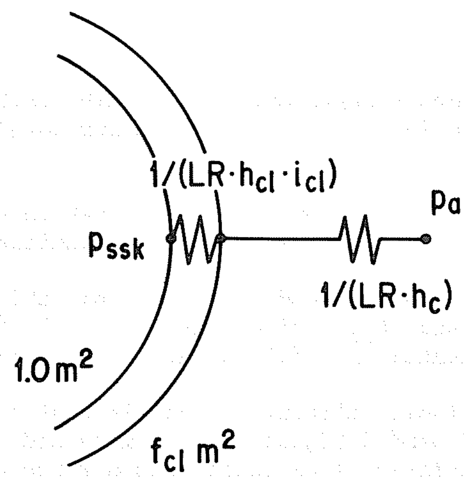

Figure 1b Latent heat transfer from the human skin surface

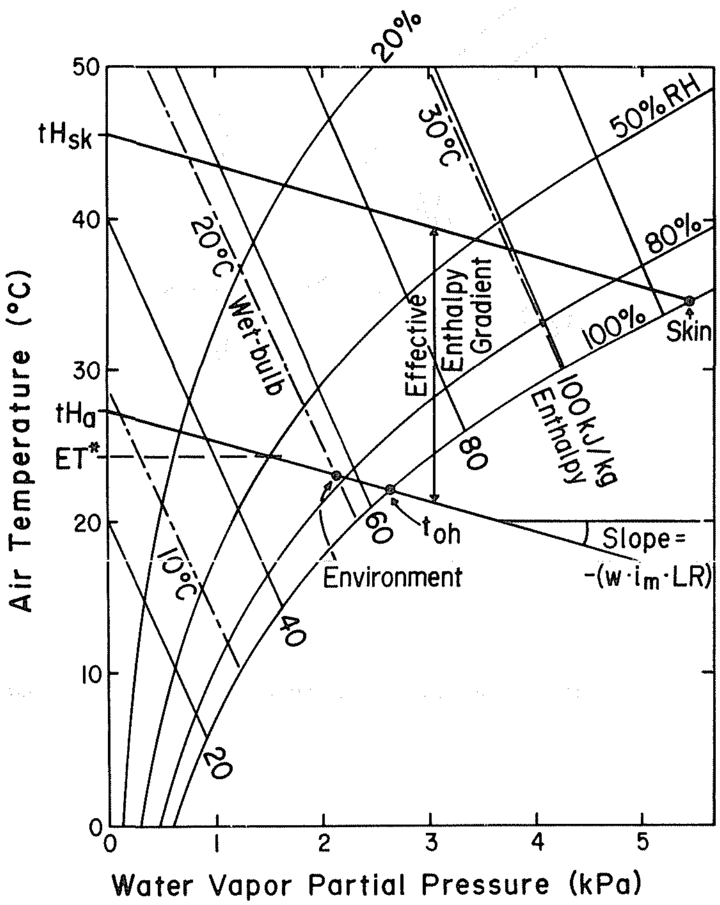

Figure 2 Mollier chart representation of ET*, enthalpy temperature tH and effective enthalpy gradient for total heat transfer from humans.

Simulation conditions: air temperature = 23°C, relative humidity = 75%. (See Table 1 for additional data).

From the two-node model simulation: skin temperature and wettedness: t_{sk} = 34.4°C and w = 0.22; heat transfer coefficients: h_c = 7.6 and h_r = 4.4 W/m²·K.

Calculations: effective sensible heat transfer coefficient h' = 8.8 W/m²·K (Equation 10); mass and heat transfer characteristic of clothing plus air boundary layer i_m = 0.56 (Equation 24); enthalpy temperatures tH_{sk} = 45.6°C and tH_a = 27.3°C (Equations 27, 28, 29); total skin heat transfer $\dot{q}_{sk}$ = 161 W/m² (Equation 29); Effective Temperature ET* = 24.2°C (Equation 18).

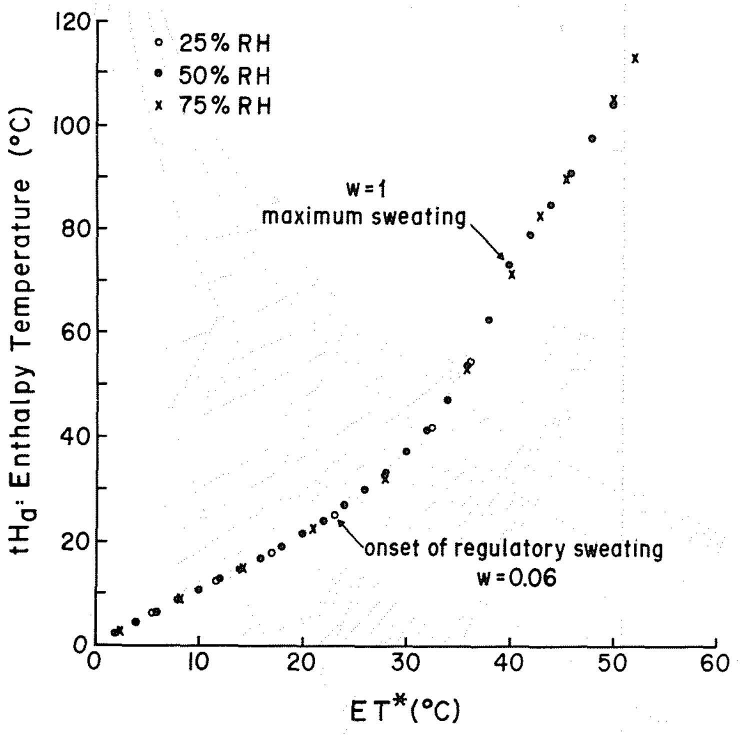

Figure 3 Plot of enthalpy temperature tH_a as a function of ET*. Simulation conditions: Table 1.

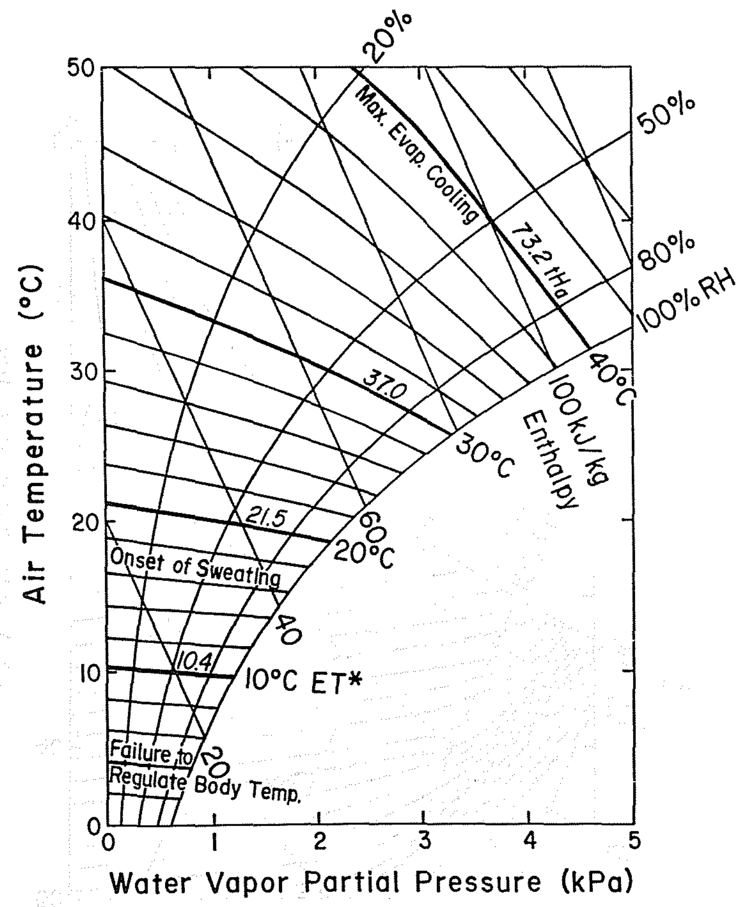

Figure 4 ET* loci for a clothed subject with high activity level. Simulation conditions: Table 1.

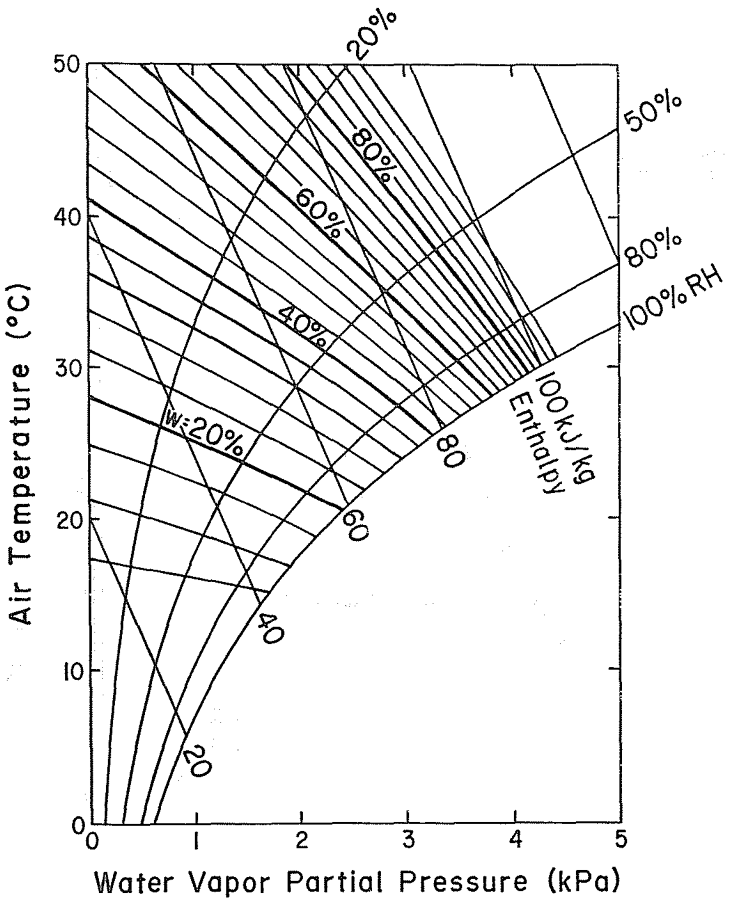

Figure 5 Skin wettedness loci for a clothed subject with high activity level. Simulation conditions: Table 1.

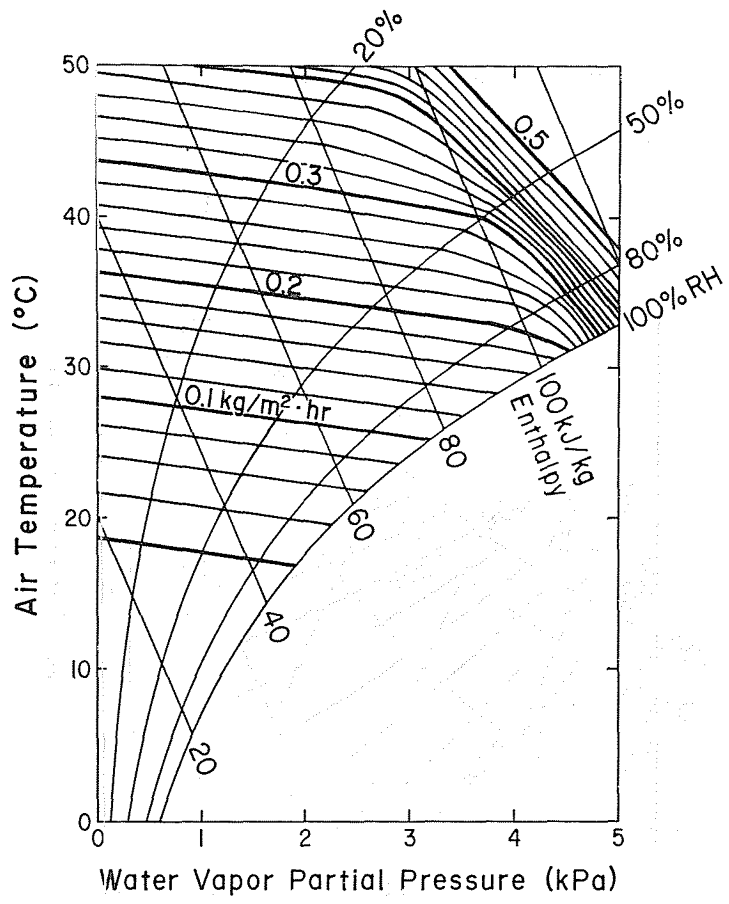

Figure 6 Evaporative sweating loci for a clothed subject with high activity level. Simulation conditions: Table 1.

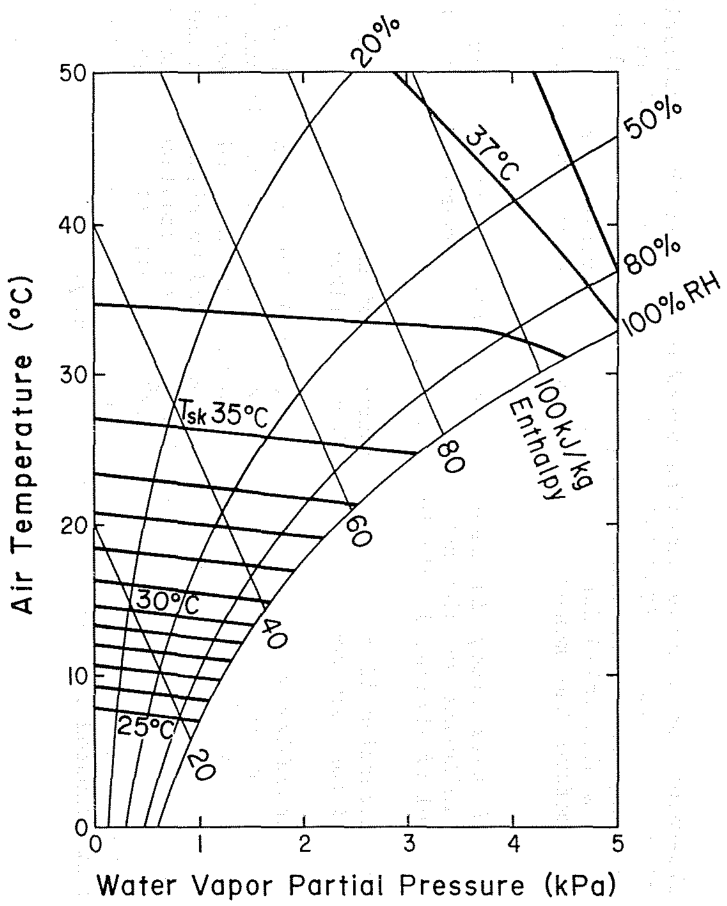

Figure 7 **Skin temperature loci for a clothed subject with high activity level. Simulation conditions: Table 1.**