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The use of a model in the analysis of the relation between skin temperature and the rate of sweating,

by K. Ibamoto.

(*Faculty of Engineering, Hokkaido University, Sapporo, Japan.*)

During heavy work skin temperature influences both the rate of evaporative heat loss and the thermal information to the central controller. A new index called the « chill level » is proposed. This relates the thermal stimulus to the rate of evaporative heat loss during different degrees of work and of external insulation (clothing).

Skin model.

A mechanical model of the skin may have the following properties :

1. For convective heat exchange the human body is equivalent to a long cylinder 30 cm in diameter.

2. The skin can be regarded as being composed of uniformly distributed punctuate areas which, at any time, may be either dry or wet.

The rate of evaporative heat loss will depend on the proportion of these small areas that are wet, and for the central control of this rate the controller must receive information concerning the extent of the wet areas.

This concept of the ratio of wet area to dry area differs from the concept of wettedness based on the water vapour pressure, as the theoretical relation between wettedness and the extent of the wet area is not constant.

The heat loss during sweating can be expressed in two ways : *a*) as the rate of heat flow down a thermal gradient is shown by the open squares in Fig. 1 A and by equation (1)

$$r_s = (1 - w)r_1 + wr_2 \tag{1}$$

where r = rate of heat flow, r_s, r_1 and r_2 = the rates of heat flow down the thermal gradients $(T_{so} - T_s)$, $(T_{so} - T_1)$ and $(T_{so} - T_2)$ respectively, T = temperature, w = wet area ratio, s = skin surface : 1 = dry spot and 2 = wet spot.

b) As the moisture flow down a vapour pressure gradient is shown by the open circles in Fig. 1 A and by the equation (2)

$$x_s = (1 - w)x_a + wx_2^* \tag{2}$$

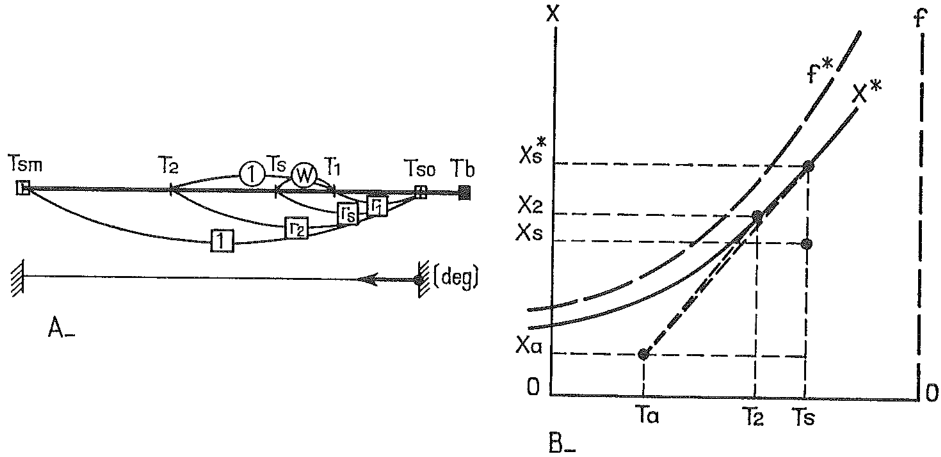

FIG. 1.

A. Schematic diagram of human temperature under steady heat exchange.

T_b = constant body temperature (38°C)
T_{so} = maximum skin temperature (36°C)
T_{sm} = minimum skin temperature (theoretical)
T_s = ordinary skin temperature
T_1 = dry spot temperature
T_2 = wet spot temperature

B. Illustration of equation 3 showing that wettedness is not proportional to wet area ratio.

where x = absolute humidity ; x_s, x_a and x_2 = absolute humidity at T_s, T_a and T_2 respectively and a = ambient air.

By definition,

$$\text{wettedness} = \frac{f_s - f_a}{f_s^* - f_a} = \frac{x_s - x_a}{x_s^* - x_a} = \frac{w\,(x_2^* - x_a)}{x_s^* - x_a} = \frac{T_2 - T_a}{T_s - T_a}\,w \tag{3}$$

where f = vapour pressure and* indicates saturation. Fig. 1 B illustrates equation 3 and explains that wettedness is not proportional to wet area ratio.

The assumption is made that there is a cutaneous thermosensor beneath each small area of skin and that this indicates whether water vapour loss is at rate r_1 or r_2. This situation is expressed in equations 4 and 5 :

$$r_2 = (1 - w) \exp [-8w . (1 - w)] \quad (4)$$

$$r_2 = \sqrt{1 - w} \exp [-4w . (1 - w)] \quad (5)$$

These equations are represented in Fig. 2 A, together with the skin temperature (Ts) curve. These differ from the ideal curves shown in Fig. 2 B.

It is surprising that no effort is made to maintain skin temperature at the level related to thermal comfort, and that skin temperature behaves in a trivalent manner. If these curves are correct, the control center must be able to interpret the compound signal. The integration of the different signals is refered to as the « chill level » which is an index of thermal sensation.

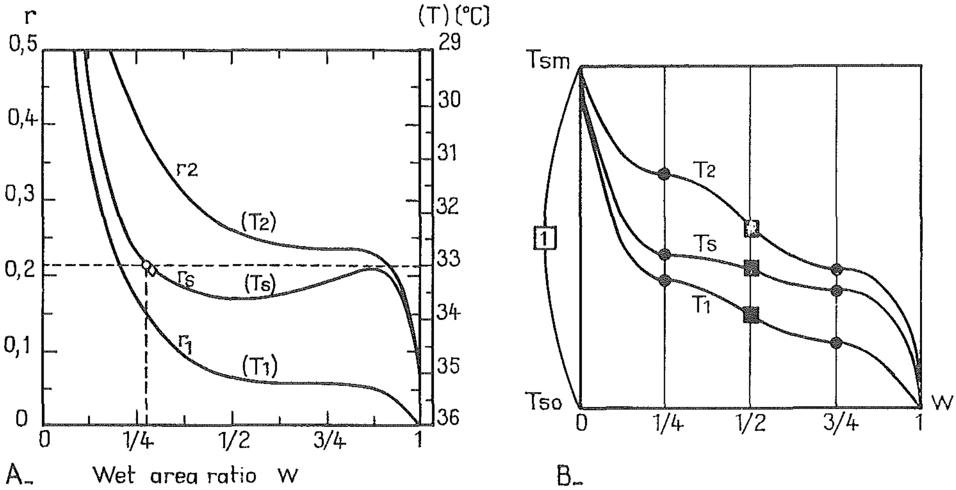

FIG. 2.

A. Curve relating wet area ratio to Ts, T_1 and T_2.

B. Ideal curves which relate wet area ratio to temperature which might maintain thermal comfort.

SKIN HEAT LOSS.

From the formula for respiratory enthalpy difference (IBAMOTO, 1969), the skin heat loss (H_s) can be expressed as follows :

$$H_s = 1.163n\ [50 - (8.241 - 0.061\ T_a - 0.151\ x_a)] \quad (W.m^{-2}\ skin) \quad (6)$$

where n is the metabolic rate in met units. When considered in terms of heat and mass transfer,

$$H_s = (T_s - T_a)\ (I_{cl} + I_a)^{-1} + 2.6\ f_{pcl}\ h_c\ (x_2{}^* - x_a)\ w \quad (W.m^{-2}\ skin) \quad (7)$$

where I_{cl} = insulation of clothing ($m^2.{}^oCW^{-1}$.)

I_a = insulation from clothing surface to uniform environment at T_a ($m^2.{}^oCW^{-1}$.)

f_{pcl} = permeation efficiency ND (NISHI and GAGGE, 1970)

h_c = convective heat transfer coefficient ($W.m^{-2}.{}^oC^{-1}$)

2.6 = modified Lewis relation [°C/(gr/Kg)]

w = wet area ratio.

Equi-chill lines.

Equations 6 and 7 are linear-type equations the parameters of which are T_s and x_2 (saturated at T_2). These two parameters are combined by the *wet area ratio* or the *chill level*.

A surprising feature of this analysis is that under equi-chill conditions, the relation between skin humidity and moisture loss is variable.

Summary.

From the concept of dry and wet spots on the skin surface, and the assumption that a sensor beneath each spot sends an individual thermosignal to the regulatory controller, the « chill level » has been developed as a theoretical thermal sensation index. This is expressed in terms of the skin temperature and the wet area ratio.

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