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Humid Operative Temperature. A Biophysical Index of Thermal Sensation and Discomfort,

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Is it possible to describe the combined effects of radiant heat, air temperature, humidity, air movement and clothing as a single temperature, which has significance for both physiologists and engineers in judging comfort and thermal sensation and in predicting heat exchange ?

The heat balance equation for thermal equilibrium that describes how the net metabolic heat produced (M) is exchanged from the skin surface with the environment by radiation, convection and skin evaporation may be written as ;

$$M = F_{cl}\, h_r\, (T_{sk} - T_r) + F_{cl}\, h_c\, (T_{sk} - T_a) + F_{pcl}\, w\, h_e\, (P_{sk} - P_{dp}),\ (W/m^2) \qquad (1)$$

where T_r = mean radiant temperature ; T_a = ambient air temperature, both in °C ; P_{sk} = saturated vapor pressure in mmHg at mean skin temperature (T_{sk}) ; P_{dp} = saturated vapor pressure at dew point temperature (T_{dp}) and equals the ambient vapor pressure ; F_{cl} and F_{pcl} (N.D.) are efficiency factors of clothing for dry and wet heat exchange (BURTON and EDHOLM, 1969 ; NISHI and GAGGE, 1970). The linear radiative, convective and evaporative heat transfer coefficients are h_r, h_c in W/(m².°C) and h_e in W/(m².mmHg) respectively. w is the skin wettedness, defined as the ratio of the observed evaporative heat loss from skin surface to the maximum evaporation possible (E_{max}) from a completely wet skin surface. E_{max} itself is defined by the third term in eq. (1), when w = 1. Eq. (1) may be simplified by the modified Lewis Relation at sea level conditions, $h_e = 2.2\, h_c$, and the following approximate relation over normal temperature and humidity ranges (10°C∽40°C, rh $\geq$ 35 %) ;

$$P_{sk} - P_{dp} = 1.4\, (T_{sk} - T_{dp}). \qquad (1\,a)$$

The equation, defining Humid Operative Temperature (T_{oh}), is now given by,

$$M = h_{oh} (T_{sk} - T_{oh}), \tag{2}$$

where $$h_{oh} = A + B + w\,C,\ A = F_{cl}\,h_r,\ B = F_{cl}\,h_c,$$

$$\text{and } C = F_{pcl}\,(2.2 \times 1.4)\,h_c. \tag{3}$$

Thus $$T_{oh} = (A\,T_r + B\,T_a + w\,C\,T_{dp})/(A + B + w\,C). \tag{4}$$

SIMULATION MODEL OF TEMPERATURE REGULATION FOR A RESTING MAN after Stolwijk & Hardy - 1966

BASIC DIMENSIONS	:	WEIGHT - SKIN SHELL 3.4 kg . SURFACE AREA 2.0 m^2,	
		- CORE 78.3 kg .	
THERMAL NEUTRALITY	:	$T_{sk} = 34.1$ °C , $T_{cr} = 36.6$ °C , $E_{insen} = 0.06 E_{max}$,	
		NORMAL SKIN CONDUCTANCE 5.3 W/m^2·°C ,	
		NORMAL SKIN BLOOD FLOW (SKBF) 6.3 l/m^2·h .	
OTHER FACTORS	:	SPECIFIC HEAT - BODY 0.97 Wh/kg·°C, $R + C = (h_r + h_c)(T_{sk} - T_a) \cdot F_{cl}$,	5
		- BLOOD 1.163 Wh/kg·°C, $E_{max} = 2.2\,h_c\,(P_{sk} - P_{dp}) \cdot F_{pcl}$.	6
PASSIVE STATE	:	BODY STORAGE $S = S_{sk} + S_{cr}$ W/m^2	7
		SKIN SHELL $S_{sk} = (T_{cr} - T_{sk})(5.3 + 1.163\,SKBF) - E_{sk} - (R + C)$,	8
		CORE $S_{cr} = M - E_{res} - (T_{cr} - T_{sk})(5.3 + 1.163\,SKBF)$.	9
CONTROL SIGNALS	:	SKIN $\Sigma_{sk} = T_{sk} - 34.1$ (+) WARM SIGNAL ,	10
		CORE $\Sigma_{cr} = T_{cr} - 36.6$ (−) COLD SIGNAL .	11
REGULATION OF SKBF	:	$SKBF = (6.3 + 75\,\Sigma_{cr})/(1 - 0.5\,\Sigma_{sk})$ l/m^2·h .	12
		when Σ_{cr} is negative or Σ_{sk} is positive Σ is zero .	
REGULATION OF E_{sk}	:	$E_{sk} = E_{insen} + 70\,\Sigma_{sk}\,\Sigma_{cr}$ W/m^2 .	13
		when either Σ_{sk} Σ_{cr} is negative $E_{sk} = E_{insen}$.	
RESULTANT PHYSIOL. FACTORS at time t	:	$T_{sk} = 34.1 + [2.0/(0.97 \times 3.4)] \int_0^t S_{sk}\,dt$,	14
		$T_{cr} = 36.6 + [2.0/(0.97 \times 78.3)] \int_0^t S_{cr}\,dt$,	15
		$w = E_{sk} / E_{max}$	16

FIG. 1. — Stimulation Model of Temperature Regulation for a resting man.

From eq. (4) Humid Operative Temperature T_{oh} is defined as the average of T_r, T_a, and T_{dp} weighted by the applicable heat transfer coefficients and skin wettedness concerned. Weighting factors, A, B, and C, include the effect of clothing and air movement. T_{oh} is thus the single temperature that answers in rational terms our original question. The physiological variables, skin T_{sk} and core temperature T_{cr} and skin wettedness w are the resultant of various internal regulatory processes (skin blood flow, sweat secretion, and metabolism) and of the environmental factors (T_r, T_a, T_{dp}, h_r, h_c, F_{cl}, and F_{pcl}).

A simple model for temperature regulation after STOLWIJK and HARDY (1966) is used to simulate man's physiological response to various environmental stresses. The case for a sedentary subject in a uniform environment ($T_a = T_r$) is illustrated in Fig. 1.

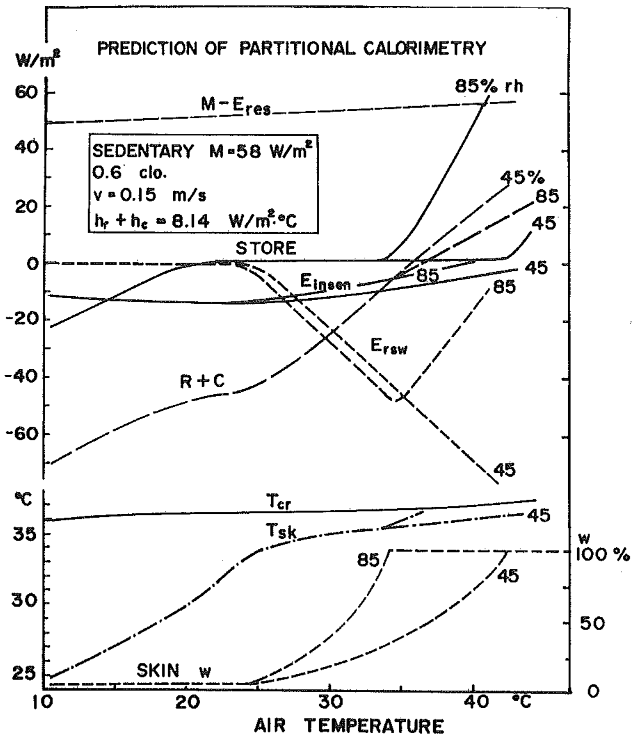

FIG. 2. — Prediction of Partitional Calorimetry.

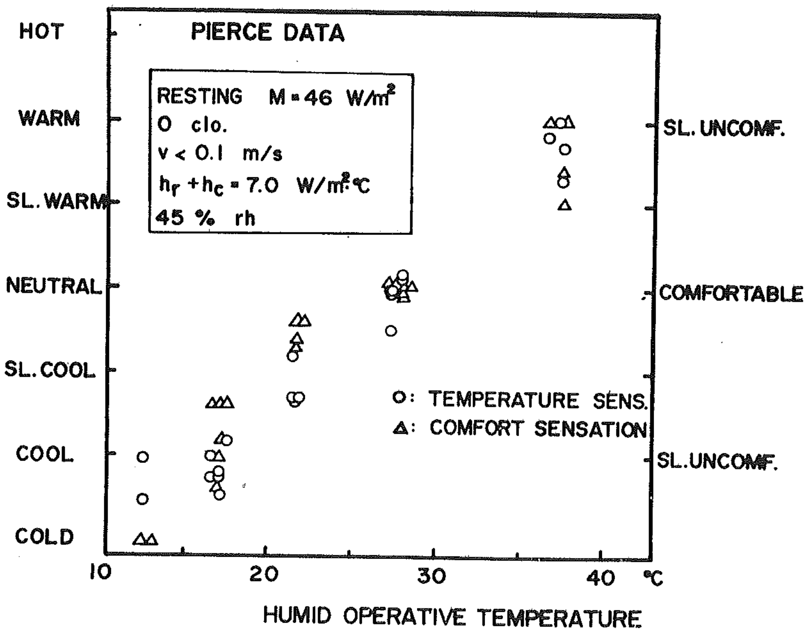

FIG. 3. — Comparison of Humid Operative Temperature with temperature and comfort sensation votes by unclothed subjects.

The physiological responses predicted at the end of one hour exposure to various T_a values are indicated in Fig. 2. The values $F_{cl} = 0.57$ and $F_{pcl} = 0.80$ apply for 0.6 clo and $h_c = 2.91$ W/(m^2.°C). The integrations of eqs (14) and (15) are made numerically by digital computer for minute time interval. The heat partitions as air temperature increases, are not significantly changed by humidity until the skin surface reaches 100 % wettedness. Since a part of secreted sweat may evaporate less effectively within inner clothing layers and not on the skin surface itself, skin wettedness may reach its true maximum value in a range 60∽100 %.

For our model w is a variable dependent only on the environmental factors. For any given activity, air movement and clothing, T_{oh} is essentially a unique function of three environmental temperatures T_a, T_r and T_{dp}.

In Fig. 3 Humid Operative Temperature is compared with the data of average sensations of both temperature and comfort for 6 unclothed male subjects while resting at the various air temperatures at normal humidity at 45 % rh (Gagge *et al.*, 1967).

In summary, Humid Operative Temperature, when derived from the heat balance equation for a temperature regulating physiological model incorporating the effector processes of sweating, vasodilation and vasoconstriction, is a unique function of the environmental variables. This temperature scale is useful as a rational index for biophysical thermometry and for predicting thermal sensations and discomfort in widely varying environments.

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