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Estimating Outdoor Thermal Comfort Using a Cylindrical Radiation Thermometer and an Energy Budget Model

by

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ABSTRACT. – A mathematical model to estimate outdoor thermal comfort for humans from micrometeorological data has been formulated using the energy balance concept and the simultaneous satisfaction of four criteria for comfort from the literature: (a) a comfortable perspiration rate, (b) a comfortable core body temperature, (c) a comfortable skin temperature, and (d) a near-zero energy budget. A cylindrical modification of the globe thermometer is proposed as a simple monitor of outdoor radiation absorption for a person, and the effect of windspeed on the thermal resistance of clothing is considered. Results show a correlation coefficient of 0.91 between model output and subjective comfort ratings of 59 different situations with a variety of temperatures, insolations and windspeeds.

INTRODUCTION

The traditional goal of human thermal comfort has been to create artificial indoor climates that are comfortable for people to live and work in. Studies on outdoor climates, meanwhile, have mainly emphasized conditions causing stress rather than evoking comfort. Outdoor facilities, needed to meet the demands of high interest in recreation activities, will be most effectively used if they are thermally comfortable over as long a time period as possible. The technology is available to make any outdoor place comfortable, but this may necessitate very high energy costs while society is presently looking for low energy solutions to problems. Therefore, it would be advantageous to determine the inherent thermal comfort of the various microclimates existing on a site. Then best advantage could be taken of positive climatic characteristics in subsequent planning and design such that comfort is maximized within the constriant of minimizing energy use.

Because humans must hold their body core temperature at a nearly fixed value, the balance between incoming and outgoing energy streams has been identified as an important aspect of thermal comfort (e.g. Waggoner, 1963). The major energy streams involved are convective heat loss or gain, evaporative heat loss, radiative exchange, and metabolic heat production. In previous studies involving thermal stress it has some-

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times been sufficient to consider only the dominant energy stream(s) causing stress, only specific seasons, or only indoor situations. For example, the wind chill index of Siple and Passel (1945) is essentially a consideration of convective heat loss only. Steadman's (1979 a, b) index of sultriness considers all major energy streams but with specific reference to summer clothing and conditions. Fanger (1970) developed a complete energy budget model which he applied mostly to indoor situations with very low windspeeds and no solar radiation. This study tests the complete energy budget approach including the effect of wind on the thermal resistance of clothing, against comfort ratings in a wide variety of microclimatic situations and suggests the use of a cylindrical modification of the globe thermometer as a simple monitor of outdoor radiative absorption for a person.

METHODS

A central hypothesis in the energy budget approach is that thermal comfort demands a near-balance between incoming and outgoing energy fluxes (e.g. Waggoner, 1963).

$$M + R - H - L - E = S \approx 0 \tag{1}$$

where: M = metabolic heat conducted to body surface
R = absorbed short and long wave radiation
H = sensible heat gain or loss
L = emitted long wave radiation
E = evaporative heat loss
S = sum of all terms in the energy budget

Conduction heat exchanges are usually negligible and are excluded. The allowable deviation of S from zero will be discussed later. Paramaterization of the various fluxes in Eq. 1 is as follows.

METABOLIC HEAT PRODUCTION. – Metabolic heat (M^*) is dissipated through two major pathways: a small fraction (f) is consumed by respiratory latent (LA) and sensible (SE) heat losses, while the remainder (M) is conducted to the outer body surfaces where it is lost by convection, evaporation, and radiation. Fanger (1970) has given equations relating LA and SE to metabolic rate and to ambient vapour pressure (e) and temperature (T_a), respectively. Converting his equations to Wm^{-2}, KPa, and °C yields:

$$f = LA/(M^*) + SE/(M^*)$$
$$= 0.150 - 0.0173\ e - .0014\ (T_a)$$

Thus: $$M = (1-f)(M^*) \tag{2}$$

Core temperature (°C) is given by (Campbell, 1977)

$$T_c = 36.5 + (4.3 \times 10^{-3})\ (M). \tag{3}$$

ABSORBED SHORT AND LONG WAVE RADIATION. – In previous human comfort studies a globe thermometer (Kuehn, Stubbs and Weaver, 1970) has sometimes been used to measure the incoming radiation, even in outdoor environments (e.g. Clarke and Bach, 1971). The simplicity of this device is appealing and its black colour and spherical shape are appropriate for isotropic fluxes of long wave radiation. However, outdoors where a significant portion of the radiant flux is parallel rays of short wave energy, neither geometry nor colour of the globe are suitable.

In this study a tan-coloured 11.0 cm long x 1.3 cm diameter aluminium cylinder was employed as a miniature analogue of a person (Fig. 1). The cylindrical shape mimics the interception of short and long wave radiation by a standing human and the colour (Munsell 7.5YR 7/3) was chosen to have an albedo (~ .37) and emissivity (~ 1.0) which are similar to "average" skin and clothing (Monteith, 1973). A mercury-in-glass thermometer (calibrated to 0.1 °C) was inserted to its immersion mark so that the thermometer bulb was positioned about half way down the aluminium cylinder, which was milled inside so that the thermometer fitted snugly. A heat-conducting "Thermal Compound" (Wakefield Engineering) was smeared on the thermometer bulb before insertion to ensure maximum thermal contact and thus minimize equilibration time. An acrylic tube, half covered with reflective tape, was used to protect and shade the thermometer stem. After hanging the cylinder vertically near chest

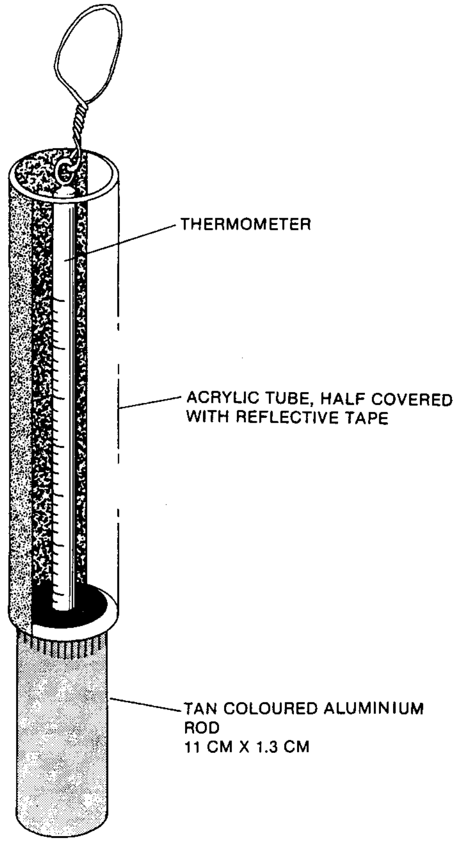

Fig. 1. Cylindrical radiation thermometer. This analogue of a standing person was used in the study to measure absorbed short and long wave radiation.

height for a short time in the environment to be monitored, an equilibrium temperature (T_e) was reached when short and long wave radiation gains were balanced by long wave and convective losses. Utilizing the Ohm's law analogy for convection, and taking the resistance to heat flow for a 1.3 cm diameter cylinder from engineering heat transfer theory (Kreith and Black, 1980), the energy budget for the cylinder becomes:

$$R = \sigma\,(T_e + 273)^4 + (\varrho C_P)\,(T_e - T_a)/r_m \tag{4}$$

where: σ = the Stefan-Boltzmann constant (5.67×10^{-8} Wm^{-2} K^{-4}).

$\varrho\, C_p$ = volumetric heat capacity of air ($\sim$ 1200 Jm^{-3} K^{-1}).

The resistance r_m is determined from the expression:

$$r_m = D/(A\, Re^n\, Pr^{.33}\, k) \tag{5}$$

where: Re = Reynolds number = $V \infty D/v$

Pr = Prandtl number $\sim$ 0.71

D = diameter of cylinder

V = free stream air velocity

v = kinematic viscosity

k = thermal diffusivity of air

and A and n are empirical constants derived through experiments on heat flow from cylinders (Kreith and Black, 1980. Equation 5-26 and table 5-2). This equation can be used to estimate radiation absorbed per unit area by a standing person since the cylinder has an analogous shape and colour. It is not necessary that the cylinder have the same characteristic diameter as a person because convection from the person is estimated independently.

SENSIBLE HEAT GAIN OR LOSS: – An Ohm's law analogy (e.g. Campbell, 1977) was used to describe the flow of heat from the body core at temperature T_c (°C) through series thermal resistances offered by body tissues (r_t), clothing (r_c), and the boundary layer (r_a) between clothing or skin and the free atmosphere at temperature T_a (°C).

$$H = \varrho C_p\,(T_c - T_a)/(r_t + r_c + r_a) \tag{6}$$

The value of r_t (s/m) decreases with metabolic rate (M^*, Wm^{-2}) according to:

$$r_t = -0.1\,(M^*) + 65. \tag{7}$$

This relationship was derived by applying the Ohm's law analogy to data given by Fanger (1970) on skin temperature, core temperature, and transfer of metabolic heat from the core to the skin of thermally comfortable persons. This equation is therefore a specification that comfort demands a certain value of skin temperature which is dependent on metabolic rate.

The thermal resistance of clothing depends on the nature of the fabric and the windspeed. Clothing resistances for near zero windspeeds (r_{co}) have often been determined in clo-units and these can be converted to sm^{-1} through multiplication by 200 (Monteith, 1973), but the effect of wind on clothing thermal properties has been much less thoroughly researched. A modification of the approach by Campbell (1977) that best fits our data leads to the expression:

$$r_c/r_{co} = 1 - (0.05\, P^{0.4}\, U^{.5}) \quad \text{for } u > .0.7 \text{ ms}^{-1} \tag{8a}$$

$$= 1 \quad \text{for } u < .7\text{ms}^{-1} \tag{8b}$$

where P is the air permeability of the fabric (Campbell, 1977, Table 8.2) and u is windspeed (ms^{-1}). The inclusion of the expression for permeability leads to a significant improvement in model results, particularly at high wind speeds, as shown below.

To compute the boundary layer resistance (r_a), the person was modelled as a vertical cylinder of equivalent diameter 0.17 m (Campbell, 1977) for which:

$$r_a = 0.17\ (A\ Re^n\ Pr^{.33}\ k) \qquad (9)$$

analogous with Eq. (5).

EMITTED LONG WAVE RADIATION. – Since the long wave emissivity of skin and clothing is near unity (Fanger, 1970), the radiative losses from the person are closely approximated by:

$$L = \sigma\ (T_s + 273)^4 \qquad (10)$$

where T_s is the surface temperature. By analogy with three electrical resistors in series, T_s may be found from:

$$(T_s - T_a)/r_a = (T_c - T_a)/(r_t + r_c + r_a) \qquad (11)$$

EVAPORATIVE HEAT LOSS. – Latent heat losses occur through respiration and perspiration. The latter may be divided into "insensible" losses through the skin and "sensible" losses through sweating. Respiration losses were dealt with in earlier discussion of metabolic heat, and Fanger (1970) has determined experimentally that sensible perspiration rates (E_s, Wm^{-2}) for comfortable persons are also dependent on metabolic rates. His data may be summarized as:

$$E_s = 0.42\ (M - 58) \text{ for } M > 58\ Wm^{-2} \qquad (12a)$$

$$= 0 \qquad \text{ for } M < 58\ Wm^{-2} \qquad (12b)$$

Insensible perspiration rates (E_i) are determined from:

$$E_i = \varrho\ L\ (q_s - q_a)/(r_{cv} + r_{av} + r_{tv}) \qquad (13)$$

where: the v-subscript indicates resistances to water vapour,
L = latent heat of vaporization ($J\ kg^{-1}$)
q_s and q_a = saturation specific humidity ($kg\ kg^{-1}$) at skin temperature and air dew point temperature, respectively.

Similar to the surface temperature determination above, a series resistance analog allows skin temperature (T_k) to be found using:

$$(T_k - T_a)/(r_a + r_c) = (T_c - T_a)/(r_t + r_c + r_a) \qquad (14)$$

A value of $7.7 \times 10^{-3}\ s\ m^{-1}$ was used for r_{tv} (Campbell, 1977), and $r_{av} = 0.92 r_a$, owing to the difference in molecular diffusivities of water vapor and heat. It was assumed that $r_{cv} = r_c$ in the absence of much definite information on this relationship. There is room for model improvement here, but the assumption has a very small effect on E_i since r_{tv} is overwhelmingly large. Total evaporation (E) is simply

$$E = E_i + E_s \qquad (15)$$

In the event of very high atmospheric specific humidities (q_a), it is possible that evaporation cannot occur rapidly enough to consume the comfortable rate of perspiration delivery to the skin surface. A maximum possible evaporation (E_m, Wm^{-2}) is therefore calculated for moist skin from Eq. (13) by setting $r_{tv} = 0$.

$$E_m = \varrho\ L\ (q_s - q_a)/(r_{av} + r_{av}) \qquad (16)$$

For the energy budget computation (Eq. (1)), E is taken to be the lowest of E or E_m.

SUMMARY OF THE METHOD. – As input, the model requires measurements or estimates of air temperature, windspeed, humidity, cylinder thermometer equilibrium temperature, clothing resistance and permeability, and metabolic rate which is estimated from activity level (e.g. Fanger, 1970). Core temperature is computed from (3). The resistances through tissue, clothing and air are calculated from (7), (8), and (9). Evaporation is found from (15) or (16), long wave emission from (10), absorbed all-wave radiation from (4), metabolic heat supply to the skin surface from (2), and sensible heat exchange from (6). Finally, (1) is solved for S and the result is compared to zero. The condition of thermal comfort therefore requires the satisfaction of four criteria:

(a) a comfortable perspiration rate,
(b) a comfortable core body temperature,
(c) a comfortable skin temperature, and
(d) a near-zero energy budget.

RESULTS AND DISCUSSION

TESTING OF THE MODEL. – In the paramaterization of something as nebulous as "comfort", there are bound to be uncertainties. For example, Fanger's (1970) results of comfortable skin temperatures and perspiration rates show significant scatter among individuals. Also, the equations for resistance and permeability of clothes are based on a growing but still small pool of quantitative information in clothing science.

Testing was achieved as follows. In early September of 1980 and 1981, third year Resources Management students from the University of Guelph attended a field camp on Manitoulin Island in Lake Huron, Ontario. Twelve separate groups of 3 or 4 persons visited 21 different sites on eight days during the two trips and conditions varied from full sun to deep shade, near-calm to 5 ms^{-1} winds, and 15 to 25°C temperatures. The subjective comfort rating scheme of very cold, cold, comfortable, hot and very hot was employed. Data on temperature and humidity were taken with a sling psychrometer (Bacharach Model 12-7011, Pittsburgh, U.S.A.), on wind with a cup anemometer (Casella, London, England), and on radiation with an early model of the radiation thermometer constructed out of a copper tube instead of aluminium. It was arranged that each person in a group had similar clothing and activity level, and an average comfort rating at each site was agreed upon. These ratings were then plotted against S from Eq. (1). Zero budget values coincided closely with neutral comfort ratings and the correlation coefficient was .93.

The method of recording subjective votes on thermal comfort levels was improved for the next test. In september 1982, fifteen students from second year Landscape Architecture at the University of Guelph were taken to each of seven microenvironments which differed mainly in terms of sun and wind exposure. Data on temperature and humidity were taken with the same instruments described above. Activity levels (hence metabolic rates) and clothing types were kept constant, and each person was asked to rate every site according to the following set of instructions: "Please respond, at each test point, using the representative number of a statement from the list provided that best represents your comfort level" (Table 1).

These values were averaged for each site and regressed against S computed from Eq. (1), resulting in a correlation coefficient of 0.96.

In early September of 1984, third year Resources Management students from the University of Guelph again attended a field camp on Manitoulin Island. Groups of up to twenty-four persons tested 31 different sets of conditions in four days and atmospheric conditions varied from full sun to deep shade, near-calm to 2.5 ms^{-1} winds, and 12 to 17°C temperatures. The comfort rating scheme from –2 to +2 was again used with the addition of the following line of instruction: "If you feel you cannot select one statement exclusively, please feel free to use decimals or fractions (e.g. if you feel it is somewhere between –2 and –1 an acceptable answer would be –1.5 or –1 1/2, etc.)."

Table 1. Comfort levels allowed in testing.

−2 = I would prefer to be much warmer.
−1 = I would prefer to be warmer.
0 = I would prefer no change, warmer or cooler.
1 = I would prefer to be cooler.
2 = I would prefer to be much cooler.

Microclimatic measurements were taken with a more accurate set of instruments, including a Rimco anemometer (Rauchfuss Instruments Victoria Australia), an Assmann Psychrometer (model h331 Weathermeasure Corp, Sacramento, California and a fast response aluminium cylinder thermometer. Each person was allowed to select one of five clothing ensembles from a list (Table 2). Activity was limited to standing, and individual comfort ratings were recorded. The average comfort rating under each set of conditions was plotted against S from equation (1). Zero budget values again coincided closely with neutral comfort ratings and the correlation coefficient was 0.90 which is again very strong considering that a continuous variable (S) has been correlated with an ordinal variable that takes only discrete values.

When all 59 points of data are represented on one graph (Fig. 2) the correlation coefficient = 0.91 and the best fit line, determined from least squares analysis, is:

$$Y' = 97X - 1 \qquad (16)$$

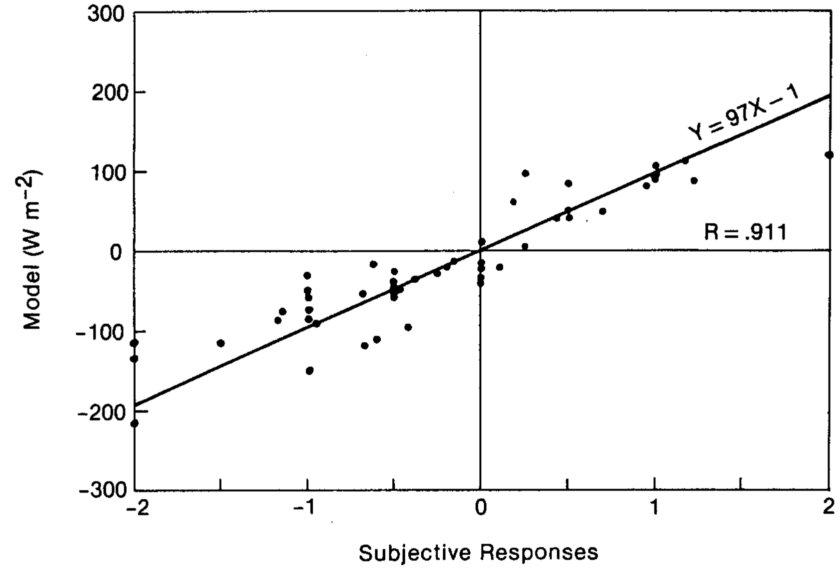

Fig. 2. Results of COMFA plotted against subjective comfort responses of study participants when permeability of clothing P was considered. Equation of least-squares line is: $Y = 97X - 1$. $R = 0.911$.

Table 2. Clothing ensembles allowed in testing.

	r_c	P
A: T-Shirt, short pants, socks, running shoes	50	175
B: T-Shirt, long pants, socks, shoes or boots	75	150
C: T-Shirt, long pants, socks, shoes, windbreaker	100	100
D: Shirt, long pants, socks, shoes, windbreaker	125	65
E: Shirt, long pants, socks, shoes, sweater	175	125
F: Shirt, long pants, shoes, sweater, windbreaker	250	50

where: r_c = resistance of clothing (s m^{-1})
P = permeability of clothing

which suggests that the zero offset is only 1 Wm^{-2}. The results of the model can therefore be interpreted as shown in Table 3.

In a test to determine whether the consideration of the permeability factor P was appropriate, the data were input to the model but the resistance of the clothing was not changed with windspeed. The model worked reasonably well, but the correlation coefficent was lower, at 0.78, and the zero offset was 29 Wm^{-2} (Fig. 3).

DISCUSSION. – The energy budget model (also called COMfort formulA, or COMFA) has several characteristics that make it unique:

(1) It simultaneously satisfies 4 criteria for thermal comfort,
(2) the outdoor radiant environment is monitored through the use of a cylindrical radiation thermometer as an analog of a person, and
(3) the effect of wind on the thermal characteristics of clothing has been considered through the use of a permeability factor P. The inclusion of this significantly improves the model.

In all the tests COMFA related well to comfort ratings by a variety of individuals in a wide range of microenvironments. It is therefore proposed as a useful tool for many applications, including outdoor planning and design. It considers all major energy fluxes and meteorological variables, yet is simple enough to load into a pocket computer (e.g. Radio Shack TRS-80) which has been used in the field and office. It may be

Table 3. Interpretation of model based on test results

Model (Wm^{-2})	Subjective	Interpretation
$S < -150$	–2	Would prefer to be much warmer
$-150 < S < -50$	–1	Would prefer to be warmer
$-50 < S < 50$	0	Would prefer no change
$50 < S < 150$	1	Would prefer to be cooler
$150 < S$	2	Would prefer to be much cooler

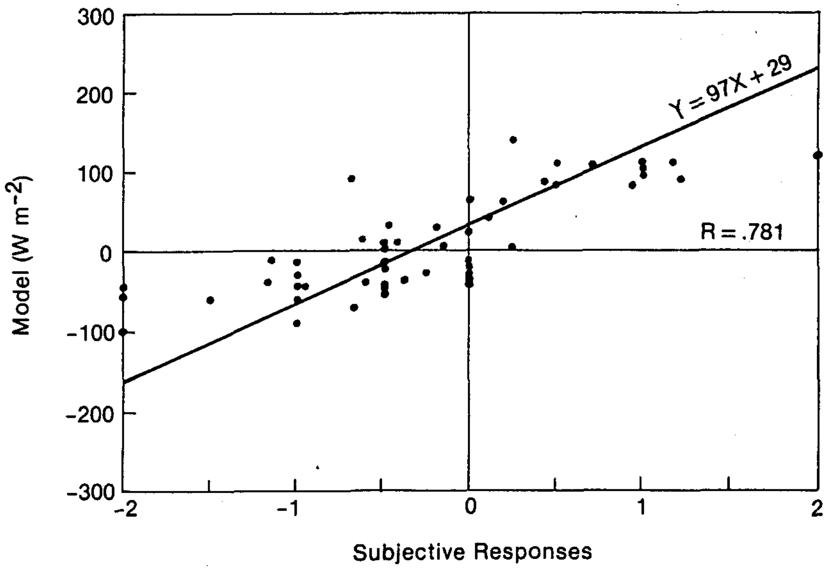

Fig. 3. Results of COMFA plotted against subjective comfort responses of study participants when permeability of clothing P was **not** considered. Equation of least-squares line is: $Y = 97X + 29$. $R = 0.781$.

used with micrometeorological data that is measured, or with data that is synthesized from macroclimatic and topographic information, to take advantage of the inherent comfort characteristics of a site when locating outdoor activities (Brown, 1982). As each activity has different inputs of metabolic rate and clothing parameters, optimum locations will be discrete entities with little overlap.

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