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ORIGINAL ARTICLE

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Meaningful wind chill indicators derived from heat transfer principles

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Abstract The wind chill index (WCI) and the more widely used wind chill equivalent temperature represent an attempt to combine several weather-related variables (temperature, wind velocity and solar radiation) into a single index which can indicate human comfort. Since its introduction in 1945, the WCI has been criticized mainly on the ground that the underlying model does not comply with modern heat transfer theory. In spite of that, the WCI, "calibrated" to human comfort, has proven to be successful in predicting discomfort and tolerance of man to the cold. Nevertheless, neither the WCI nor the wind chill equivalent temperature can be actually measured and, therefore, without the additional 'calibration' they are meaningless. In this study we have shown that the WCI represents the instantaneous rate of heat loss from bare skin at the moment of exposure to the cold, and as such, it correlates reasonably well with measurable variables that represent a feeling of cold. Two new wind chill indicators have been introduced: exposed skin temperature and maximum exposure time. These indicators yield more information than the WCI provides, are measurable, have physical meaning and are based on established heat transfer principles.

Key words Wind chill index · Wind chill equivalent temperature · Exposed skin temperature · Maximum exposure time for bare skin · Tolerance of cold

Introduction

During the winter months weathermen usually report the wind chill factor or wind chill temperature, in addition to the actual temperature. While the temperature is a measurable well-defined physical quantity, the wind chill temperature is a very vague term. Laymen may regard predicted temperature and wind chill temperature with the same level of trust, without realizing what the wind chill temperature actually represents.

Several definitions for wind chill temperature have been suggested. Kaufman et al. (1987) have defined it as "a temperature which, at low wind speed, will produce a rate of cooling equal to that of the wind-temperature combination reported." Steadman (1971) has defined wind chill equivalent temperature T_{wc} as "··· the cooling power of the wind such as would be felt on exposed flesh in a light wind". There are even more general descriptions. Beal (1974), for example, has referred to the wind chill temperature, as a "single index which would relate human comfort with the present or forecast temperature and wind speed".

The introduction of the wind chill concept is credited to Siple and Passel (1945). They carried out a series of atmosphere cooling measurements in Antarctica in 1941. The freezing rate of 1 l of water in a sealed plastic cylinder (length 5.875 in, diameter 2.259 in), suspended from a pole above the level of a building roof, was measured. The measurements were carried out in a range of ambient temperatures (T_a) between -56°C and -9°C and wind velocities in the range of 1 to 15 m s^{-1}. Based on these measurements, the wind chill factor (WCF) was calculated using the following equation:

$$\mathrm{WCF} = \frac{\Delta H/t}{(T_f - T_a)} \tag{1}$$

where ΔH is the latent heat of melting for 1 l of water (79.71 kcal · kg^{-1} or 333.5 kJ · kg^{-1}), t is the total freezing time (h), and T_f is the freezing temperature of the water (0°C). Siple and Passel (1945) correlated the WCF to the wind velocity (v) and found the best correlation to be the following

$$\mathrm{WCF} = (\sqrt{100\,v} + 10.45 - v) \tag{2}$$

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To calculate the rate of heat transfer from the human body, the temperature difference $(T_f - T_a)$ was replaced by the difference between the skin temperature (T_s) and the ambient temperature, to yield:

$$\mathrm{WCI} = \mathrm{WCF}(T_s - T_a) = (\sqrt{100\,v} + 10.45 - v)(T_s - T_a) \quad (3)$$

where WCI is the wind chill index ($\mathrm{kcal \cdot h^{-1} \cdot m^{-2}}$). For the skin temperature, Siple and Passel (1945) recommended using $T_s = 33°C$, which was considered a neutral, most comfortable skin temperature. Based on Eq. 3, they prepared a table of WCI up to wind velocities of $25\ \mathrm{m \cdot s^{-1}}$. To relate the WCI to human comfort, Siple and Passel (1945) carried out relative comfort observations simultaneously with measurements of atmospheric cooling. They described a scale between $\mathrm{WCI} = 100\ \mathrm{kcal \cdot h^{-1} \cdot m^{-2}}$ ($116\ \mathrm{W \cdot m^{-2}}$), which was considered warm, up to $\mathrm{WCI} = 2300\ \mathrm{kcal \cdot h^{-1} \cdot m^{-2}}$ ($2670\ \mathrm{W \cdot m^{-2}}$), where the exposed skin of an average individual would freeze within less than 0.5 min.

Falconer (1968) has realized that different combinations of wind velocity and ambient temperature would yield the same WCI. He has used this observation as a basis for deriving the wind chill equivalent temperature (T_{wc}), which is the ambient temperature that would yield the same WCI at a reference wind velocity (v_r, 3 mph or approximately $1.34\ \mathrm{m \cdot s^{-1}}$) as the actual temperature yields at the actual wind velocity. The nomogram which has been prepared by Falconer (1968) for calculating the wind chill equivalent temperature is the one which is used by weathermen for determining this temperature as part of the daily weather reports.

It should be mentioned that Eq. 3 for calculating the WCI does not take into account solar radiation. Falconer (1968), among others, has recommended the deduction of $200\ \mathrm{kcal \cdot h^{-1} m^{-2}}$ ($232\ \mathrm{W \cdot m^{-2}}$) from the WCI to account for solar radiation under conditions of bright sunshine.

During the early 1970s, researchers more familiar with heat transfer theory have introduced the interpretation of the WCI as a rate of heat loss from unclothed skin of a human body (see, for example, Steadman 1971). They have identified several faults, omissions, and inaccuracies in the original expression of Siple and Passel (1945). Some of the indicated faults are basic deficiencies of the model; others have evolved from the interpretation suggested for the WCI. In the following, some of the criticisms of Siple and Passel's (1945) model are discussed.

Analysis of model proposed by Siple and Passel (1945)

Actually, there was no need to carry out the water freezing experiments in Antarctica in order to estimate the rate of heat loss from the human body as a function of ambient temperature and wind velocity. At that time, there were available correlations for calculating the heat loss from a cylindrical body to air flowing at different velocities. According to heat transfer principles, the heat loss from the cylinder used by Siple and Passel (1945) can be calculated from the following equation:

$$q_s = \left\{\frac{1}{r_d + 1/h_c}\right\}(T_f - T_a) \quad (4)$$

where q_s is the rate of heat loss from the cylinder ($\mathrm{kcal \cdot h^{-1} \cdot m^{-2}}$), r_d is the thermal resistance of the cylinder wall ($\mathrm{°C \cdot m^2 \cdot h \cdot kcal^{-1}}$), and h_c is the forced convection heat transfer coefficient ($\mathrm{kcal \cdot °C^{-1} \cdot m^{-2} \cdot h^{-1}}$).

The value of h_c can be evaluated using the correlation developed by Hilpert (1933) based on an extensive series of experiments. Hilpert's correlation relates the dimensionless heat transfer coefficient (Nusselt number), $Nu = h_c d/k_f$, to the dimensionless flow velocity (Reynolds number), $Re = v\,d/v_f$:

$$Nu = C\,Re^m \quad (5)$$

where d is the diameter of the cylinder (m), k_f is the air thermal conductivity ($\mathrm{kcal \cdot h^{-1} \cdot m^{-1} \cdot °C^{-1}}$) and v_f is the air kinematic viscosity ($\mathrm{m^2 \cdot s^{-1}}$); C and m are dimensionless constants which vary according to the value of the Reynolds number. For the region of interest, Hilpert suggested the following constant values:

$$C = 0.174 \text{ and } m = 0.618 \text{ for } 4000 \le Re < 40\,000$$

$$C = 0.024 \text{ and } m = 0.805 \text{ for } 40\,000 \le Re < 400\,000 \quad (5a)$$

The physical properties of the air (k_f and v_f) are calculated at the mean temperature, $(T_f + T_a)/2$.

Experimental data are needed to calculate the cylinder's thermal resistance, r_d in Eq. 4, but this information is actually irrelevant for calculating heat loss from the human body.

Comparison of Eqs. 1 and 4 shows that both $\Delta H/[t(T_f - T_a)]$ and the expression $1/(r_d + 1/h_c)$ represent the WCF. The latter will be denoted as WCF_c. Introducing h_c from Eq. 5 into the expression for WCF_c yields:

$$\mathrm{WCF}_c = \frac{1}{r_d + d/(C\,k_f\,Re^m)} \quad (6)$$

with $d = 2.259$ in ($= 5.738 \times 10^{-2}$ m).

For calculating the physical properties of the air as function of temperature, correlations based on data from Welty et al. (1984) have been used. The values for the constants r_d, C and m were found by correlating Siple and Passel's (1945) measured data (RHS of

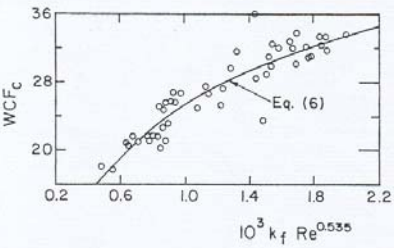

Fig. 1 Improved correlation for the revised wind chill factor (WCF_c). Data from Siple and Passel (1945) and curve calculated from Eq. 6. The expression on the abscissa ($k_f Re^m$) represents the effect of the wind velocity ($Re = vd/v_f$) but also the effects of the temperature on the physical properties of the air

Eq. 1). The optimal numerical values of the constants, obtained by nonlinear regression (numbers rounded to three decimal digits), are: $r_d = 0.0202\ \mathrm{kcal}^{-1} \cdot \mathrm{h} \cdot {}^\circ\mathrm{C} \cdot \mathrm{m}^2$ ($0.0174\ \mathrm{W}^{-1} \cdot {}^\circ\mathrm{C} \cdot \mathrm{m}^2$), $C = 0.823$ and $m = 0.535$.

The plot of WCF_c versus $k_f Re^m$ (experimental data and calculated curve) is shown in Fig. 1. It can be seen that the fit is good; actually, the fit is better than that obtained for the WCF of Siple and Passel, Eq. 2. The sum of squares of errors is 174.8 for WCF_c compared to 186.8 for WCF. Nevertheless, there are more important considerations in favor of the WCF_c.

Differentiating Eq. 2 with respect to v shows that the WCF reaches a maximum at $v = 25\ \mathrm{m} \cdot \mathrm{s}^{-1}$ and diminishes at higher velocities. It may even attain negative values for very high v. Thus, while Eq. 2 represents fairly well the data measured by Siple and Passel (1945), its asymptotic behavior is incorrect. Therefore, it cannot be used for extrapolation outside the region where the measurements were made. The WCF_c (from Eq. 6) increases monotonically with increasing v and approaches the value of $1/r_d$ for very high v. Indeed, at high v the atmospheric resistance to heat transfer becomes negligible, and the resistance of the cylinder wall is the dominant one.

Siple and Passel (1945) extended the results of their experiments (water freezing in a cylinder) to the human body by replacing the freezing temperature of water (T_f) with what is considered to be neutral skin temperature: $T_s = 33^\circ\mathrm{C}$. Such an extension does not agree with the theory of heat transfer in several respects. In the water cylinder, T_f is constant for the total duration of the freezing process, but uncovered skin will retain the neutral temperature only for a very short time after its exposure to cold (otherwise, we would not feel that it is cold). Moreover, T_f is the temperature inside the cylinder, while on the outside surface of the cylinder, the temperature must be lower than 0°C to yield the required driving force for heat transfer from the inside of the cylinder to the outside. Consequently, the temperature T_s in Eq. 3 should be the body temperature, 37°C.

It can be seen from Eq. 6 that the WCF is a function of the geometry of the body, the body resistance and the external temperature (through the temperature dependency of the air physical properties). But Siple and Passel (1945) used the same WCF for the small plastic cylinder and for the human body. It is questionable whether the geometry and body resistance difference of the two objects can be neglected.

When the WCI is interpreted as the rate of heat loss from the human body, many additional omissions and inaccuracies can be found (Steadman 1971; Beal 1974):

1. Effective wind velocity. The wind velocity close to the ground level is much lower than that at higher elevations. Because of that, Steadman (1971) has suggested the use of the average wind velocity, which is 0.57 times the measured wind velocity.
2. Radiative exchange with the environment and the sun was not taken into account by Siple and Passel (1945). Falkowski and Hastings (1958) have suggested reducing the WCI by $200\ \mathrm{kcal} \cdot \mathrm{h}^{-1} \cdot \mathrm{m}^{-2}$ ($232\ \mathrm{W} \cdot \mathrm{m}^{-2}$) for bright sunshine and by about $100\ \mathrm{kcal} \cdot \mathrm{h}^{-1} \cdot \mathrm{m}^{-2}$ ($116\ \mathrm{W} \cdot \mathrm{m}^{-2}$) for light cloud conditions.
3. Heat transfer resistance of clothing, heat loss through the lungs and heat loss to the ground by conduction, are not taken into account in the WCI.
4. Skin surface temperature is 30°C instead of 33°C.
5. The WCI yields grossly overestimated values for heat losses from the human body. The rate of human metabolism during normal activities is in the range $50\text{–}200\ \mathrm{kcal} \cdot \mathrm{h}^{-1} \cdot \mathrm{m}^{-2}$ ($58\text{–}232\ \mathrm{W} \cdot \mathrm{m}^{-2}$) while the WCI is over $400\ \mathrm{kcal} \cdot \mathrm{h}^{-1} \cdot \mathrm{m}^{-2}$ ($464\ \mathrm{W} \cdot \mathrm{m}^{-2}$) for cool conditions and reaches values as great as $2400\ \mathrm{kcal} \cdot \mathrm{h}^{-1} \cdot \mathrm{m}^{-2}$ ($2790\ \mathrm{W} \cdot \mathrm{m}^{-2}$) in severe weather. Obviously, humans cannot survive with such rates of heat losses.

There have been several attempts to correct these omissions and inaccuracies through more precise and detailed calculations (Steadman 1971; Beal 1974) and even by carrying out experiments with water-filled cylinders placed in a wind tunnel (Kaufman and Bothe 1986). But these, apparently more accurate correlations, have failed to replace the original WCI proposed by Siple and Passel (1945) and T_{wc} proposed by Falconer (1968) as indicators for the combined effect of the wind and ambient temperature. On the contrary, as stated in American Society of Heating, Refrigerating and Air Conditioning Engineers fundamental handbook (1981), "this index has provided a reliable way of expressing combined effects of wind and temperature on subjective discomfort and has proven useful for ordering the relative severity of environments".

We have two explanations for this apparent paradox. The WCI does not represent heat losses from the body over extended periods of time, but it provides a measure of the instantaneous heat loss from bare skin the moment the skin is exposed. Considering the uncertainty regarding the skin thermal properties and the geometrical differences between different parts of the human body, the WCI can correlate fairly well with the temperature sensed on the bare skin. Here we get to the second part of the paradox. Neither the WCI nor T_{wc} are measurable quantities. Thus, experimental results can neither verify nor dismiss them.

In the rest of this paper, two new wind chill indicators are developed which can be measured and are more meaningful than either the WCI or T_{wc}. We will also demonstrate the relationship between the new wind chill indicators and the established widely used WCI and T_{wc}.

New wind chill indicators

Exposed skin temperature

The temperature we (humans) actually sense is T_s. The T_s is often different on the exposed parts of the body (face, hands) from that on parts covered by clothing. The actual T_a and wind chill are sensed by the bare skin; clothing adds thermal resistance which can be different from person to person. Thus, the most adequate indicator for the combined effect on T_a, v, and solar radiation is the exposed skin temperature (EST). From the first moment of exposure, the T_s changes with time, but, after a while, it reaches a steady final value. We will use this steady-state as the EST.

For overcast conditions with no solar radiation, the steady-state T_s can be calculated from the heat balance on a human body:

$$q_s = \frac{(T_b - T_s)}{r_b} = \frac{(T_b - T_a)}{r_b + 1/h_c} \qquad (7)$$

where q_s is the heat loss ($\mathrm{kcal \cdot h^{-1} \cdot m^{-2}}$), T_s is the skin temperature (°C), and r_b is the body tissue thermal resistance ($\mathrm{°C \cdot m^2 \cdot h \cdot kcal^{-1}}$).

The body tissue thermal resistance, r_b, can be estimated from Eq. 7 by introducing known values of thermal comfort in a normal temperature room (Gagge et al. 1941). Under such conditions ($T_b = 36.7$°C, $T_s = 33.3$°C), the metabolic heat production while sitting at rest is approximately equal to $50\ \mathrm{kcal.h^{-1} \cdot m^{-2}}$ ($58\ \mathrm{W \cdot m^{-2}}$), and 76% of it is lost by convection to the environment. Thus, r_b is approximately $0.08\ \mathrm{kcal^{-1} \cdot h \cdot °C \cdot m^2}$ ($0.0689\ \mathrm{W^{-1} \cdot . °C \cdot m^2}$).

We have used a more recent and accurate version of Eq. 5 to calculate h_c:

$$Nu = (0.43 + 0.50\, Re^{0.5})\, Pr^{0.38} \quad 1 < Re \leq 1000 \qquad (8a)$$

$$Nu = 0.25\, Re^{0.6}\, Pr^{0.38} \quad 10^3 < Re < 2 \times 10^5 \qquad (8b)$$

This correlation has been proposed by Eckert and Drake (1974), and the second equation, 8b, can be used

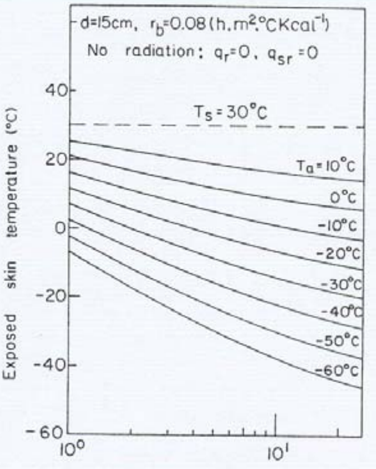

Fig. 2 Exposed skin temperature as a function of the ambient temperature (T_a) and wind velocity (v). Abscissa scale represents wind velocity normalised to average walking velocity, $v_r = 1.34\ \mathrm{m \cdot s^{-1}}$, T_s skin temperature, r_b body tissue thermal resistance, d characteristic diameter, q_r radiative heat loss, q_{sr} solar radiation

practically over the entire range of interest. It requires definition of a characteristic diameter for the human body. We have used d equal to 15 cm for calculations involving the face and d equal to 1.0 cm for fingers.

Since T_b, T_a, and r_b are known and h_c can be calculated from Eq. 8 for a specified wind velocity (given the physical properties of the air), Eq. 7 can be solved for T_s. It should be noted that, since the physical properties are to be taken at the mean temperature between T_s and T_a, Eq. 7 must be solved numerically.

The EST has been calculated in the range of v from v_r to $25\ \mathrm{m \cdot s^{-1}}$ (v_r = 3 mph or $1.34\ \mathrm{m \cdot s^{-1}}$, the average walking speed) and T_a from − 60°C to 10°C for the exposed human face (d = 15 cm). The results are shown in Fig. 2. (The velocity is shown in this figure is logarithmic scale, therefore v normalized with respect to v_r.)

Above 0°C, the EST may represent the actual T_s. Below 0°C, the EST is only an indicator for the intensity of the cold. Under such conditions, exposed areas freeze, and precautions are to be taken to prevent reaching the steady state temperature.

It should be also emphasized that the EST, as shown in Fig. 2, is meaningful when only a small portion of the body skin area is exposed. Otherwise, the total heat loss from the body may become higher than the rate of metabolic heat production, in which case the body temperature will drop below 37°C.

The relationship between the EST and the WCI, as proposed by Siple and Passel (1945), can be tested by correlating the EST versus the corresponding WCI.

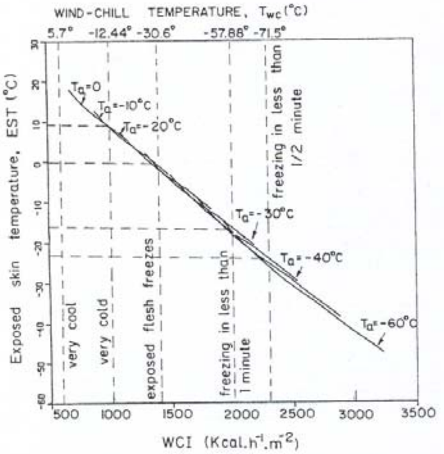

Fig. 3 Exposed skin temperature as a function of the wind chill index (*WCI*) and T_{wc}

A very good correlation between these two indicators is found for r_b equal to $0.08\ \mathrm{kcal}^{-1}\cdot\mathrm{h}\cdot\mathrm{m}^2\cdot{}^\circ\mathrm{C}$ ($0.0689\ \mathrm{W}^{-1}\cdot{}^\circ\mathrm{C}\cdot\mathrm{m}^2$) and d equal to 5.738 cm (the diameter of the cylinder used in Siple and Passel's experiments). The resultant plot of EST versus WCI and T_{wc} in the range of v between 1 and $15\ \mathrm{m}\cdot\mathrm{s}^{-1}$ and T_a between -60°C and 0°C is shown in Fig. 3. The curves obtained for different T_a are concentrated in a narrow band around a straight line which represents a good correlation between the two variables.

For other d, representing different parts of the body, the correlation between the WCI and the EST cannot be represented by a single line for the entire range. This is as would be expected, as Siple and Passel's model (1945) does not include the effect of the body geometry on the wind chill effect.

A few key points in relation to human comfort, from Fig. 3, are summarized in Table 1. The relative comfort calibration shown is that suggested by Siple and Passel (1945). The data in Table 1 clearly demonstrate the advantage of a physically meaningful indicator, such as the EST compared to the WCI and T_{wc}. For example, according to Siple and Passel's calibration, freezing of exposed flesh starts when WCI is equal to $1400\ \mathrm{kcal}\cdot\mathrm{h}^{-1}\cdot\mathrm{m}^{-2}$ ($1630\ \mathrm{W}\cdot\mathrm{m}^{-2}$) and T_{wc} is equal to -30.6°C, which corresponds to EST = 0°C. Clearly, both T_{wc} and WCI are meaningless without the calibration.

Solar radiation and radiative heat losses can also be included in the calculation of the EST. On sunny days, direct heat input due to solar radiation may significantly affect the exposed skin temperature. The solar constant I_0 (amount of solar radiation reaching the earth's atmosphere) = $1200\ \mathrm{kcal}\cdot\mathrm{h}^{-1}\cdot\mathrm{m}^{-2}$ ($1390\ \mathrm{W}\cdot\mathrm{m}^{-2}$).

Table 1 Relationship between human comfort and different wind-chill indicators. (*WCI* wind chill index, Siple and Passel (1945), T_{wc} wind chill equivalent temperature, *EST* exposed skin temperature)

Feeling and effect of cold	WCI ($\mathrm{k\,cal}\cdot\mathrm{h}^{-1}\cdot\mathrm{m}^{-2}$)	T_{wc} (°C)	EST (°C)
Very cool	500	5.7	20
Very cold	1000	-12.44	10
Freezing of exposed flesh starts	1400	-30.6	0
Exposed flesh freezes in less than 1 min	2000	-57.88	-14
Expoosed flesh freezes in less than 0.5 min	2300	-17.5	-23

Taking into consideration several factors, including mean zenith path, transmissivity of the atmosphere, radiation flux normal to the earth's surface, and the fraction which is absorbed by the bare skin (Beal 1974), the heat input from solar radiation, q_{sr} ($\mathrm{kcal}\cdot\mathrm{h}^{-1}\cdot\mathrm{m}^{-2}$) is given by:

$$q_{sr} = 144(1 - C_l^{1.33}) \quad 0 \le C_l \le 1 \tag{9}$$

where C_l is a correction factor included to reflect cloud cover.

Heat is also lost from the body through radiation. This loss can become significant, especially during calm cold days. The radiative heat loss, q_r, is calculated from the following equation:

$$q_r = \varepsilon\,\sigma(T_s^4 - T_a^4) \tag{10}$$

with σ equal to $4.88\times10^{-8}\ \mathrm{kcal}\cdot\mathrm{h}^{-1}\cdot\mathrm{m}^{-2}\cdot{}^\circ\mathrm{K}^{-4}$ ($5.67\times10^{-8}\ \mathrm{W}\cdot\mathrm{m}^{-2}\cdot{}^\circ\mathrm{K}^{-4}$) and ε equal to 1 for bare skin.

When solar radiation and radiative heat losses are included in the energy balance, Eq. 7 is replaced by the following equation:

$$q_s = h_c(T_s - T_a) - q_{sr} + \sigma(T_s^4 - T_a^4) = \frac{T_b - T_s}{r_b} \tag{11}$$

Equation 11 can be solved for the T_s (EST) in a manner similar to that of the solution of Eq. 7.

Figure 4 shows the EST when q_r and q_{sr} on a clear sunny day ($C_l = 0$) are included, compared to EST on a cloudy day without solar radiation ($C_l = 1$). It can be seen that at low v, solar radiation compensates for about 5–10°C ambient temperature difference. For example, at low v, an ambient temperature of -10°C on a sunny day will cause the same feeling of cold as 0°C on a cloudy day (very cool, EST < 18°C). On the other hand, 0°C on a sunny day will be considered cool (EST > 20°C). The effect of radiation diminishes for higher v.

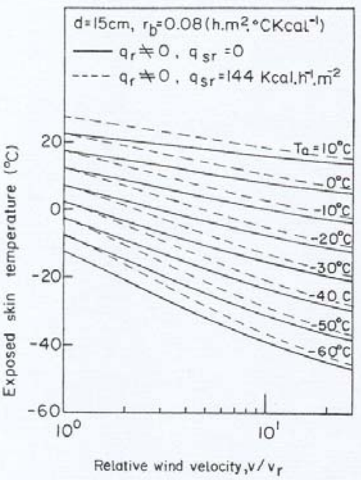

Fig. 4 Exposed skin temperature in relation to wind velocity with and without solar radiation. Abscissa scale represents wind velocity normalized to average walking velocity, $v_r = 1.34\ \mathrm{m \cdot s^{-1}}$, d characteristic diameter, r_b tissue thermal resistance, q_r radiative heat loss, q_{sr} solar radiation, T_a ambient temperature

Maximum exposure time

EST values below 0° C have little practical significance, as such temperatures may cause severe injury and should be avoided. Under conditions when skin exposure is dangerous, the time it takes for the exposed skin to reach the critical temperature of T_s equal to 0° C can provide much more meaningful and useful information. This maximum exposure time is denoted here as MET.

Rigorous calculation of the cooling time of the skin requires numerical solution of a partial differential equation, but the uncertainty regarding the thermal properties of human tissues and large differences between geometrical dimensions of different parts of the body render such a rigorous treatment unjustified. Instead, upper and lower limits for the MET can be evaluated from simplified models which yield closed form analytical expressions for the MET.

A lower limit for the MET has been calculated using the classical model of transient heat transfer in a semi-infinite solid (Mills 1992). This is a model where a thick hot solid object is suddenly plunged into cold fluid at temperature T_a with a convective heat transfer coefficient, h_c. During a short enough exposure period, the temperature variation penetrates only a short distance into the body tissues, hence the body can be modeled as a very thick or semi-infinite object. The analytical solution provides the temperature in the body as function of exposure time and distance from the exposed surface:

$$\frac{T_s(t) - T_s^0}{T_a - T_s^0} = \operatorname{erfc}\frac{x}{(4\alpha t)^{1/2}} - e^{h_c x/k + (h_c/k)^2 \alpha t} \times \operatorname{erfc}\left(\frac{x}{(4\alpha t)^{1/2}} + \frac{h_c}{k}(\alpha t)^{1/2}\right) \quad (12)$$

where T_s^0 is the T_s at the time of exposure (assumed to be $T_s^0 = 30°$ C), x is the distance from the skin surface into the body tissues (m), α is the thermal diffusivity of the skin ($\mathrm{m^2 \cdot s^{-1}}$), k is the thermal conductivity of the skin ($\mathrm{W \cdot m^{-1} \cdot {}^\circ C^{-1}}$), t is the time elapsed from exposure and erfc is the complementary error function (its definition and tabulated values can be found, for example, in Mills 1992).

The k and α of the skin can vary over a considerable range. We have used average values from the range given by Shitzer and Eberhart (1985) ($\alpha = 10^{-7}\ \mathrm{m^2 \cdot s^{-1}}$, $k = 1\ \mathrm{W \cdot m^{-1} \cdot {}^\circ C^{-1}}$). An additional source of inaccuracy in Eq. 12 is that this model does not take into account the heat generated by metabolism during the cooling. But since the rate of metabolism for a walking person is about $100\ \mathrm{kcal \cdot h^{-1} \cdot m^{-2}}$ ($116\ \mathrm{W \cdot m^{-2}}$), while the initial rate of heat loss from the bare skin is over $1000\ \mathrm{kcal \cdot h^{-1} \cdot m^{-2}}$ ($1160\ \mathrm{W \cdot m^{-2}}$, under conditions that yield EST below zero), the neglect of the metabolism has very little effect during short cooling times.

For calculating the MET, the value $x = 0$ and $T_s(t) = 0$°C are substituted into Eq. 12 to yield:

$$\frac{T_a}{T_a - T_s^0} - e^{\xi^2}\operatorname{erfc}(\xi) = 0 \quad (13)$$

where $\xi = (h_c/k)(\alpha t)^{1/2}$.

This equation can be solved for t = MET. The effect of q_{sr} can also be included by adding the appropriate term to Eq. 12. The resultant equation is:

$$\frac{1}{T_a - T_s^0}\left[T_a + \frac{2q_{sr}}{\sqrt{\pi}h_c}\xi\right] - e^{\xi^2}\operatorname{erfc}(\xi) = 0 \quad (14)$$

Figure 5 shows the MET as function of T_a and v on sunny and clouded days for exposed face (d = 15 cm).

It can be seen that q_{sr} has a significant effect at relatively high T_a and low v. Its effect diminishes for very high v. Under very severe conditions ($T_a \leq -50$°C, $v > 20\ \mathrm{m \cdot s^{-1}}$) the MET can be less than 1 min, but on a calm, sunny day very long exposure time is still safe, even for very low T_a (2 h, for $T_a = -50$°C). This is consistent with the observations of Siple and Passel (1945).

It should be noted that the MET becomes shorter as the characteristic d of the exposed surface decreases. Based on Eq. 13, it can be shown that for specified T_a and v, the MET is approximately proportional to $d^{0.8}$. For example, when a finger of d equal to 1 cm is exposed instead of the face (d = 15 cm), the MET is reduced by a factor of approximately 9. Indeed, it is

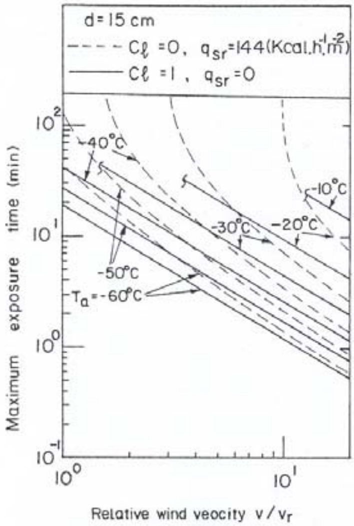

Fig. 5 Maximum exposure time with and without solar radiations. q_{sr} solar radiation, T_a ambient temperature; C_l factor reflecting extent of cloud cover. Abscissa scale represents wind velocity normalized to average walking velocity, $v_r = 1.34$ m.s^{-1}

well known that frostbites appear first on fingers or the nose, unless they are well protected.

We have calculated the EST using a different model, which takes into account the transfer of heat from the body to the skin. In this model, an unsteady state heat balance is made on a finite slab representing skin tissues, with a linear temperature profile between the constant body temperature (T_b) and the varying $T_s(t)$. For long exposure time, this model yields a T_s which approaches the EST. The equation obtained for calculating the maximum exposure time is:

$$t = \frac{k^2}{2\alpha} \frac{r_b^2}{(B_i + 1)} \ln\left[1 - \frac{(B_i + 1) T_s^0}{(B_i T_a + T_b)}\right] \quad B_i = h_c r_b \qquad (15)$$

Using this model, the calculated MET values are always longer than those shown in Fig. 5 (up to one order of magnitude longer at high v). But since the heat transfer rate from the body to the critical, most rapidly freezing areas, such as nose and fingers, is not well known, we recommend the use of the cooling of a semi-infinite solid model, which gives more conservative and safer values.

Conclusion

Two new wind chill indicators have been introduced in this paper; the EST and MET. These are much more meaningful and informative then the WCI of Siple and Passel (1945) for predicting human comfort in cold.

It has been shown that the WCI represents an approximation for the instantaneous rate of heat loss from the bare skin at the moment of exposure. As such, with appropriate calibration, the WCI can indeed provide an indication of human comfort under the combined effect of v and T_a. However, the WCI must be used together with the scale provided by the calibration; otherwise, it is meaningless or even misleading.

The two new wind chill indicators are measurable and therefore they can be further improved by objective experiments under well controlled conditions.

Recent developments of biomedical measurement technology can provide more accurate data for the physical properties of human tissues. These data are essential for improving the accuracy of physically meaningful wind chill indicators.

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