THE MEANING, DERIVATION, AND USEFULNESS OF WIND CHILL TABLES

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Introduction

Movement of air influences the rate of heat loss from the human body. A moderate breeze can increase the rate of cooling such that a cool day feels bitterly cold. The concept of "wind chill" was introduced by Siple (1939)[6] to describe the combined effects of wind and temperature. Siple and Passel (1945)[7] later conducted experiments and obtained an equation to predict the rate of cooling as a function of temperature and wind speed. From this data, the Climatic Research Unit of the Office of Quartermaster General prepared a "Table of Wind Chill Values". The table yields temperatures under calm conditions that would result in the same cooling rate as the actual temperature-wind conditions. These temperatures are referred to as equivalent temperatures. A typical wind chill table (US Army Research Institute of Environmental Medicine)[9] is shown in Table 1. These tables are used by the military, NASA, the Weather Service, mountain climbers, sportsmen, and others who have occasion to be outdoors in cold temperatures. Weather reports frequently include statements such as "Although the temperature is 10° (F) above zero, the 20 MPH wind will make it feel as if it were -25°".

Despite the widespread use of wind chill tables, the information is frequently interpreted incorrectly. It is often not understood that (1) the equivalent temperature given by wind chill tables is applicable only to dry exposed human flesh, and (2) the temperature of the dry exposed area cannot drop below the ambient temperature, even though the equivalent temperature may be very low. Misconceptions have led people to worry unnecessarily or to take usual precautions, such as trying to protect automobile radiators against expected equivalent wind chill temperatures. For this reason alone, widespread quotation of equivalent temperatures without a discussion of the applications should be discouraged.

However, in addition to possible problems arising from misinterpretation of the tables, a review of Siple's original paper indicates that fundamental errors were made in the analysis of the data from which the tables were prepared. In this paper the original work is examined and the results are compared to results calculated from well established theory in heat transfer.

Background

Heat is dissipated from the human body by convection, conduction, radiation and evaporation. In the case of a dry body, only convective losses are significantly affected by the motion of the surrounding air.

The rate at which a body dissipates heat by convection from the surface is given by Newton's Law of Cooling (Holman, 1972)[3]:

$$q = h\,(T_S - T_{oo}) \qquad (1)$$

where q is the heat flux (W/m^2), h is the heat transfer coefficient (W/m^2°K), and T_s and T_{oo} are the temperatures (°K) of the surface of the body and the air, respectively.

The heat transfer coefficient is a function of the air velocity past the body, the diameter and shape of the body, and physical characteristics of the fluid. The data have been correlated by an equation of the form

$$\frac{hd}{k} = C\left(\frac{\rho Vd}{\mu}\right)^{n}\left(\frac{Cp\mu}{k}\right)^{1/3} \qquad (2)$$

where h is the heat transfer coefficient ($W/m^{2\circ}K$), d is the characteristic diameter of the object (m), V is the velocity of the air past the object (m/s), C and n are parameters which must be determined experimentally, and k, ρ,μ and Cp are the thermal conductivity ($W/m^{2\circ}K$), density (kg/m^3), viscosity (kg/ms) and heat capacity (kJ/kg° K) of air evaluated at the average film temperature $\left(\frac{T_s + T_\infty}{2}\right)$

The first term, hd/k, is a dimensionless term know as the Nusselt number; ρVd/μ is the dimensionless Reynolds number; and Cpμ/k is the dimensionless Prandtl number.

The heat transfer coefficient for the flow of air perpendicular to single cylinders was measured experimentally by many investigators during the 1920's and 1930's. McAdams (1942)[4] correlated the data from thirteen investigators on a single logarithmic plot of Nu vs. Re. Several correlations have been developed to fit the data over different ranges of the Reynolds number. Table 2 indicated the values of C and n given by Holman (1972)[3] for use with Equation 2.

Similarly, heat transfer correlations have been developed for the cooling of spheres. Ranz and Marshall (1952)[5] give

$$Nu = 2.0 + 0.60\, Re^{1/2} Pr^{1/3} \qquad (3)$$

These equations were not specifically developed to predict the cooling of the human body, but are applicable in as much as the shape of the body can be approximated by cylinders or spheres and represent at least a reasonable approximation. Plummer developed the following correlation from the data on infinite cylinders collected by McAdams and it used it to predict cooling rates from the body exposed to wind (Court, 1948)[1]:

$$h = 12.962 + 0.671\sqrt{V} + 2.166V \qquad (4)$$

where h is the heat transfer coefficient ($W/m^{2\circ}K$), and V is the wind velocity (m/s).

Several other investigators have attempted to predict the rate of cooling of the human body by measuring the rate of cooling of katathermometer (an alcohol thermometer with an oversized cylindrical bulb). Stone[8] (1943) and Court discuss these experiments and present the cooling formulas derived.

Siple and Passel performed the atmospheric cooling measurements which lead to the development of the wind chill tables while stationed at Little America, Antarctica in 1941. They indicate that "lacking adequate library facilities.... it was impossible for us to acquaint ourselves with past experimentation of the cooling power of the atmosphere" and were thus probably unaware of the previously noted developments in heat transfer. The experiments and analysis performed by Siple and Passel are discussed in detail in the following sections.

Siple's Experiments

Siple and Passel's measurements of dry atmospheric cooling were conducted using a "relative comfort thermometer" designed by Siple. The thermometer was a cylindrical container 0.149 meters long and 0.0573 meters in diameter constructed form 0.00381 meter thick pyrolin (an early plastic) with a thermohm suspended in the center. The cylinder was filled with 0.250 kg of water and suspended from a wooden cross-arm on the roof of a building. A second thermohm was placed 0.60 meters upwind to measure the ambient temperature, and a Robinson cup anemometer was used to measure wind speed. The temperature of the water, the air temperature, and the wind speed were recorded during the experiments.

The rate of cooling at a given wind speed was determined by dividing the heat of fusion of the 0.250 kg of water by the time required for the water to freeze (the time that the water remained at 0°C). A wind chill factor - actually a heat transfer coefficient -was then obtained by dividing the cooling rate by the temperature driving force (the ambient temperature in °C since all experiments were conducted at sub-freezing temperatures).

Siple fitted his experimental data with a polynomial to obtain an expression for the cooling rate:

$$h = (1.1630)\,(10.45 + 10\sqrt{V} - V)\,(T_s - T_{oo}) \tag{5}$$

where q is the energy flux (W/m^2), V is the wind speed (m/s) and T_s and T_{oo} are the temperatures (°C) of the surface of the body and the air, respectively. The second term on the right should be recognized as the heat transfer coefficient. The temperature of the surface, T_s, was set by Siple at 33°C, the average skin temperature.

The Climatic Research Unit used Siple's equation to prepare the wind chill charts. This was accomplished by first calculating the heat loss under the actual conditions of wind and temperature, and then determining the equivalent temperature as that temperature which resulted in the same heat loss under calm conditions. Calm conditions were taken at wind speed of 2 m/s.

Analysis of Siple's Results

The heat transfer coefficient obtained by Siple (from Equation 5) is plotted against the wind speed in Figure 1. The correlations for air flowing past single cylinders (Equation 2, values of C and n from Table 2), and single spheres (Equation 3) are also shown in Figure 1.

The diameter of 0.05 m is approximately equal to the outside diameter of Siple's relative comfort thermometer as well as the diameter of the forearm; the diameter of 0.175m corresponds to the average diameter of a human head.

It is apparent that the heat transfer coefficient predicted by Equation 5 predicts a comparatively large value of the heat transfer coefficient at low wind speeds, and a comparatively low value at high speeds. Furthermore, while the other correlations predict that the heat transfer coefficient continues to increase as the wind speed increases, which is consistent with the physical situation, Siple's coefficient remains nearly constant at wind speeds greater than 20 m/s.

The explanation for the apparent discrepancy can be found by reconsideration of Siple's experiment. Siple measured the rate of cooling of a freezing cylinder of water. This is a complex process which involves several mechanisms in addition to convection form the surface. Heat must be transported to the surface of the cylinder by convection and conduction in the water and conduction through the plastic container.

These present additional resistances to heat transfer. The situation is further complicated by the fact that the phase changed from liquid to solid during the experiments. Siple did not consider these mechanisms, implicitly assuming that all of the resistance was in the surface convection. At low wind velocities, where the surface heat transfer coefficient is small, this assumption might be reasonable. However, at higher wind velocities, the internal resistances become the major resistance, and the rate of cooling is limited by the rate at which energy is transported to the surface of the container. The rate is not significantly dependent on wind velocity.

Siple's analysis, by not accounting for the internal resistances, predicts a heat transfer coefficient which is too low and independent of wind velocity at high velocities. The experiments performed by McAdams and others do not suffer from this difficulty since the experiments were designed to minimize internal resistances.

The Error in Wind Chill Tables

Equation 5 overestimates heat loss under calm conditions, and underestimates loss at high wind velocities. Consequently, the wind chill charts, which were prepared from Equation 5, may drastically underestimate the cooling effect of the wind. Table 3 shows a skeleton of a wind chill chart prepared using Equations 2 and 3, assuming a surface temperature of 33°C and calm conditions defined as a wind speed of 2 m/s, for cylinders and spheres having a diameter approximately equal to the human head (0.175m).

Numbers from the standard table (Table 1) prepared from Siple's data (Equation 2) are also shown for comparison. Equations 2and 3 both predict much lower effective temperatures than those calculated from Siple's equation (Equation 2).

It is also apparent that the shape of the object has a significant effect on the rate of cooling. The equivalent temperatures calculated assuming a cylindrical shape are appreciably lower than those obtained assuming a spherical shape. The arms and the head are not smooth infinite cylinders, nor are they spheres. There may be considerable error in using data obtained from either of these idealized surfaces (Siple's cylindrical relative comfort thermometer and katathermometers included) to predict the rate of cooling of any exposed portion of the human body.

It should be emphasized that the recalculated "equivalent" temperature shown in Table 3 are presented only to indicate the numbers that are obtained using well verified heat transfer correlations. They are not necessarily meaningful, due to other problems inherent in the preparation of such a table. These are discussed below.

Other Considerations

The equivalent temperatures are based on calm air, arbitrarily defined at wind velocity of 2 m/s. The values are very sensitive to this basis. Table 4 indicates the equivalent temperatures for an exposed cylindrical body of diameter 0.175 m where the actual temperature is 0°C and the wind velocity is calculated based on "calm" winds of 1, 2, and 3 m/s.

For example, at -7°C an actual wind speed of 4.47 m/s, the "equivalent" temperature based on "calm" winds of 1.0 m/s is -73°C. An actual wind speed of more than double 4.47 m/s would be required to obtain the same "equivalent" temperature if the basis was 3 m/s. It should also be noticed that the "equivalent" temperature for wind speed of 17.88 m/s based on "calm" winds of 1.0 m/s is an impossible -292°C, 22°C below absolute zero. The fact that such a number is obtained underlies a fundamental problem in the concept of "equivalent" temperatures. Goetz (1975)[2] discusses the problem and meaning of "calm" conditions.

The rate of cooling, as discussed depends on the temperature driving force. Siple assumed that the skin temperature was maintained at 33°C. At high cooling rates (high wind, low temperature) this is only true initially because under these conditions the body does not supply heat to the skin at a rate sufficient to maintain that temperature. At sufficiently high cooling rates, the skin is cooled to 0°C and frostbite occurs. However, as the skin temperature decreases, the cooling rate also decreases. Calculation assuming a low skin temperature yield higher "equivalent" temperatures. Table 5 shows the "equivalent" temperatures for a cylindrical body exposed to air at -18°C for three different surface temperatures. Notice that the "equivalent" temperatures are considerably higher at the lower skin temperatures. Indeed, for a wind of 4.47 m/s and skin temperature of 0° C, the "equivalent" temperature is 2°C, which is greater than the actual temperature of -18° C. This implies that the surface would dissipate less heat at –18° C and with a 4.47 m/s wind if its surface was at 33°C. It is apparent that the skin temperature is a very critical parameter and must be taken into account if wind chill tables are to be prepared. However, this requires the use of a dynamic model which includes the mechanisms for heat transfer to the surface of the skin as well as the convective loses. Since the resulting cooling equations would be a function of time, in addition to windspeed and temperature, it would be very difficult to prepare a useful wind chill table.

It should also be mentioned that the original wind chill tables do not take into account the effect of radiation on the cooling rate, which accounts for considerable heat transfer but is not affected by the wind speed, would have the effect of reducing the calculated "equivalent" temperatures.

Finally, of course, it is necessary to consider the very subjective nature of "equivalent temperatures". What does it really mean if the temperature is equivalent to a temperature of X° under calm conditions? Goetze presents an interesting discussion of the interpretation of equivalent temperatures, concluding that the table is "only marginally useful and serves principally to improve or exaggerate stories".

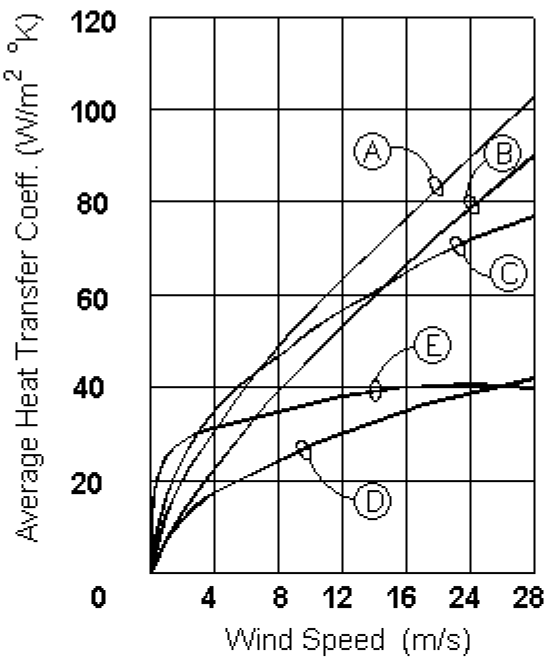
Summary and Conclusions

Wind chill tables have been used and quoted extensively since the 1940's. These tables were derived from a dry atmospheric cooling equation developed by Siple based on experiments that he conducted. Siple's results, however, are not consistent with well verified results obtained by other investigators. Examination reveals that the discrepancy is a result of Siple's failure to eliminate or account for internal heat transfer resistances in analyzing the original experimental data. The cooling equation developed by Siple over estimates heat loss at low wind speeds and underestimates loss at high wind speeds. The wind chill tables prepared using this equation are incorrect, predicting consistently high values of the effective temperature thus "under-estimating" the effect of wind chill.

Wind chill values, even if based upon well verified experimental data, may still be of limited usefulness:

1. It is difficult to take into account the shape factor which strongly influences the results.
2. The skin does not remain at a constant temperature under dynamic cooling conditions.
3. The effective temperatures are very strongly dependent on the definition of "calm" conditions, and this is very subjective.
4. Windchill charts are not understood by many people, and have led to misconceptions.

It is recommended that the use of the incorrect wind chill tables be discontinued and that no attempt be made to prepare and disseminate new tables in light of the inherent difficulties in interpreting the tables.



The Average Heat Transfer Coefficient for Cylindrical And Sperical Objects Exposed to Wind as Predicted Heat Transfer Correlations and Siple's Correlation.

A.	Equation 2	Cylinder	D = 0.05 m
B.	Equation 2	Cylinder	D = 0.175 m
C.	Equation 3	Cylinder	D = 0.05 m
D.	Equation 3	Cylinder	D = 0.175 m
E.	Equation 5	Siple's Cylinder	D = 0.05 m

Table 1. Cooling Power of Wind on Exposed Surface Maintained at 33°C Expressed as an Equivalent Temperature (Under Calm Conditions)

	Actual Air Temperature					
Windspeed MPH	**40**	**20**	**0**	**-20**	**-40**	**-60**
	Equivalent Wind Chill Temperature, °F					
10	28	4	-24	-46	-70	-95
20	18	-10	-39	-67	-96	-124
30	13	-18	-48	-79	-100	-140
40	10	-21	-53	-85	-116	-148

Table 2.Constants for Use with Equation 2

RE	**C**	**n**
0.4 - 4	0.989	0.330
4 - 40	0.911	0.325
40 - 4000	0.683	0.466
4000 - 40,000	0.193	0.618

40,000 - 400,000	0.0266	0.805

Table 3. Cooling Power of Wind on Exposed Spherical and Cylindrical Surfaces Maintained at 33°C Expressed as an Equivalent Temperature at a Wind Speed of 2.0 m/s. Temperatures from Army Table (Table 1) are Shown for Comparison.

	Equivalent Wind Chill Temperature, °F (°C)								
Wind speed MPH (m/s)	**Table 1**	**Sphere**	**Cylinder**	**Table 1**	**Sphere**	**Cylinder**	**Table 1**	**Sphere**	**Cylinder**
10 (4.47)	28 (-2)	15 (-9)	2 (-17)	4 (-16)	-15 (-25)	-33 (-36)	-24 (34)	-44 (-42)	-69 (-56)
20 (8.94)	18 (-8)	-16 (-27)	-64 (-54)	-10 (-28)	-58 (-50)	-126 (-88)	-39 (-55)	-100 (-23)	-189 (-126)
30 (13.41)	13 (-11)	-38 (-40)	-125 (-90)	-18 (-34)	-91 (-68)	-211 (-135)	-48 (-63)	-142 (-97)	-298 (-183)
40 (17.88)	10 (-12)	-60 (-51)	-181 (-118)	-21 (-36)	-119 (-84)	-289 (-178)	-53 (-67)	-178 (-116)	-400 (-239)

Table 4. Equivalent Temperature for Cylindrical Body Maintained at 33°C and Exposed to Air at -7°C, Calculated Based on "Calm" Conditions of 1.0, 2.0 and 3.0 m/s.

Wind Speed MPH (m/s)	Equivalent Wind Chill Temperature, °F (°C)		
	Calm = 1.0 m/s	**Calm = 2.0 m/s**	**Calm = 3.0 m/s**
10 (4.47)	-100 (-73)	-33 (-36)	-6 (-21)
20 (8.9)	-243 (-153)	-126 (-88)	-78 (-61)
30 (13.41)	-372 (-224)	-211 (-135)	-144 (-98)
40 (17.78)	-493 (-292)*	-289 (-178)	-205 (-132)

* Absolute zero is -273°C

Table 5. Comparison of Equivalent Temperatures for Cylindrical Body Exposed to Air at -18°C at Surface Temperatures Maintained at 33°C, 15°C and 0°C, Based on "Calm" Conditions where the Surface is Maintained at 33°C.

Wind Speed MPH (m/s)	**Equivalent Wind Chill Temperature, °F (°C)**		
	Skin Temp. 33°C	**Skin Temp. 15°C**	**Skin Temp. 0°C**
10 (4.47)	-69 (-56)	-12 (-25)	35 (2)*
20 (8.94)	-189 (-123)	-90 (-68)	-7 (-22)
30 (13.41)	-248 (-183)	-160 (-107)	-45 (-43)
40 (17.88)	-400 (-239)	-255 (-143)	-80 (-62)

* This "equivalent" temperature is greater than the actual temperature.

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