A New Approach to an Accurate Wind Chill Factor

Maurice Bluestein and Jack Zecher
Department of Manufacturing Technology, Purdue School of Engineering and Technology,
Indiana University–Purdue University at Indianapolis, Indianapolis, Indiana

ABSTRACT

Winter weather often shows a severity marked by low dry-bulb temperature combined with high wind speed. The wind chill factor is now a standard meteorological term to express this severity. This factor, or more appropriately the wind chill temperature, represents that air temperature without wind that would effect the same heat loss rate from bare human skin as that due to the actual combined dry-bulb temperature and wind. Currently used wind chill factors derive from a study conducted by the U.S. Antarctic Service over 50 years ago. The data then collected was used to develop a cooling rate as a function of wind speed, which in turn was used to formulate an equation still in use today. The equation is based on primitive experiments with a container of freezing water and an unrealistically high human skin temperature. A more appropriate estimate of the thermal properties of the skin and implementation of modern heat transfer theory can provide a more realistic wind chill factor. Recent research studies suggest that the wind chill equation currently used overestimates the effect of the wind for the range of temperatures and wind speeds expected. This paper provides a new formula for the wind chill factor and a chart of wind chill temperatures for various combinations of dry-bulb temperatures and wind speeds as measured by standard techniques.

1. Introduction

Severe winter weather, characterized by low dry-bulb temperature and high wind speed, has been described by the wind chill factor. This factor represents that air temperature without appreciable wind that would effect the same heat loss rate from exposed human skin as that due to the actual combination of temperature and wind. Such wind chill temperatures are now available from a formula developed over 50 years ago by researchers of the U.S. Antarctic Service. That research, conducted by Siple and Passel (1945, hereafter SP45), while of considerable value in predicting the discomfort and hazard of cold winter weather, has been shown to be greatly flawed by subsequent investigators. This has prompted a new approach to provide a more accurate measure of the influence of wind on heat loss from humans in cold weather.

The SP45 study as published reveals many problems. Their test involved determining the heat loss from water as it froze in a plastic container suspended from a tall pole. A single thermohm (an electrical resistance thermometer) placed in the center of the water was used to determine the time to freeze the 250 g of water. A cup anemometer placed nearby recorded wind speed. Air temperature was measured by another thermohm; all measurements were made in the absence of sunlight. Using the heat of fusion of water, the heat loss rate was found by noting the amount of time that the water spent at the freezing point.

Many investigators (Bluestein 1998; Buettner 1952; Burton and Edholm 1955; Elsner and Bolstad 1963; Kessler 1993; Milan 1961; Molnar 1960; Osczevski 1995; Steadman 1971) have found the following flaws in the SP45 work.

(a) Their data for a heat transfer coefficient, misidentified as a cooling rate, versus wind speed are widely

Corresponding author address: Dr. Maurice Bluestein, Department of Manufacturing Technology, Purdue School of Engineering and Technology, Indiana University–Purdue University at Indianapolis, 799 West Michigan Street, Indianapolis, IN 46202.
E-mail: bluestei@tech.iupui.edu
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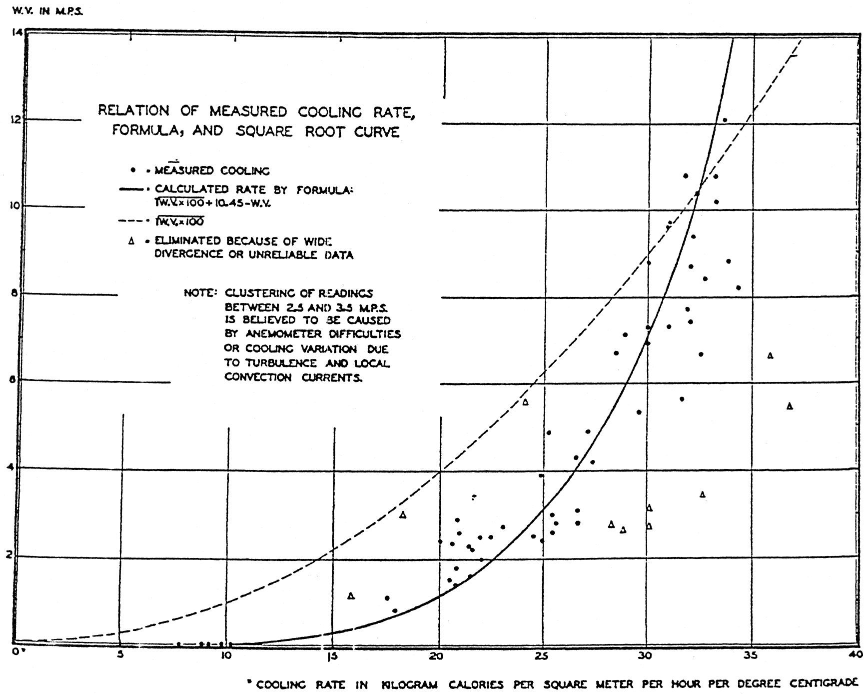

FIG. 1. Wind velocity vs total heat transfer coefficient from Siple and Passel, reproduced with permission.

scattered, as shown in Fig. 1, a reproduction of SP45's chart. They used a best-fit parabolic curve through these points, which peaks at a speed of 25 m s^{-1}. This is an unrealistic relationship for convective cooling since cooling rate should continue to increase with increasing wind speed.

(b) SP45 ignored the thermal resistance of the plastic container, assuming its surface temperature to be that of the water. Thermal gradients through the water were also ignored.

(c) SP45 extrapolated their data to humans assuming a constant skin temperature of 33°C. Skin exposed to severe cold drops well below this value.

(d) SP45 did not distinguish the effects of radiation heat loss from convective heat loss.

Such problems have prompted further studies of wind chill effects.

2. Current method of wind chill determination

SP45 determined a cooling rate for a container of water as it froze by measuring the time for a known amount (250 cc) to remain at 0°C. Knowing the heat of fusion of water and the surface area of the container yields a rate in kilocalories per hour per square meter (their units). Noting the average dry-bulb air temperature during this time, they developed what they called a wind chill factor. In reality this was an overall heat transfer coefficient, found by dividing the cooling rate by the difference between the air temperature and the freezing point, in kilocalories per hour per square meter per degree Celsius. They then plotted this coefficient, which they mistakenly called the cooling rate, against wind velocity (see Fig. 1). The best-fit line through the widely scattered points followed the formula

$$h = (100v)^{0.5} + 10.45 - v, \qquad (1)$$

where h is the heat transfer coefficient [in Kcal (hr m^2 °C$)^{-1}$] and v is the velocity (in m s^{-1}).

Even though this coefficient should include the effects of conduction through the container and radiation from the container's surface as well as convection to the air, SP45 treated it as a purely surface effect. To relate this heat transfer coefficient to humans, an exposed skin temperature of 33°C was assumed for all cases. Hence the heat loss rate from human skin would be

$$q = [(100v)^{0.5} + 10.45 - v)](33 - T_a), \qquad (2)$$

where q is the heat loss rate [in Kcal (hr $m^2)^{-1}$] and T_a is the air temperature (in °C).

What is referred to as the wind chill temperature (WCT) is that temperature for a "still-air" condition that would result in the same heat loss rate. The still-air condition has been defined as an airspeed of 1.79 m s^{-1} (4 mph) since there is always a relative velocity between the body and the surrounding air, even during calm conditions (Crane 1989). Equating the heat transfer rates for the two conditions, one with an actual air temperature T_a and velocity v, the other with a temperature WCT and velocity 1.79 m s^{-1}, yields

$$\begin{aligned} \mathrm{WCT} = 33 - 0.0454[10(v)^{0.5} \\ + 10.45 - v](33 - T_a). \end{aligned} \qquad (3)$$

Charts prepared from this formula are in use today by meteorologists nationwide, unaware of its origins in a flawed research project of over 50 years ago. Note that the velocity used in this equation is the airspeed recorded at weather stations 10 m above the ground, even though it refers to humans standing on the ground.

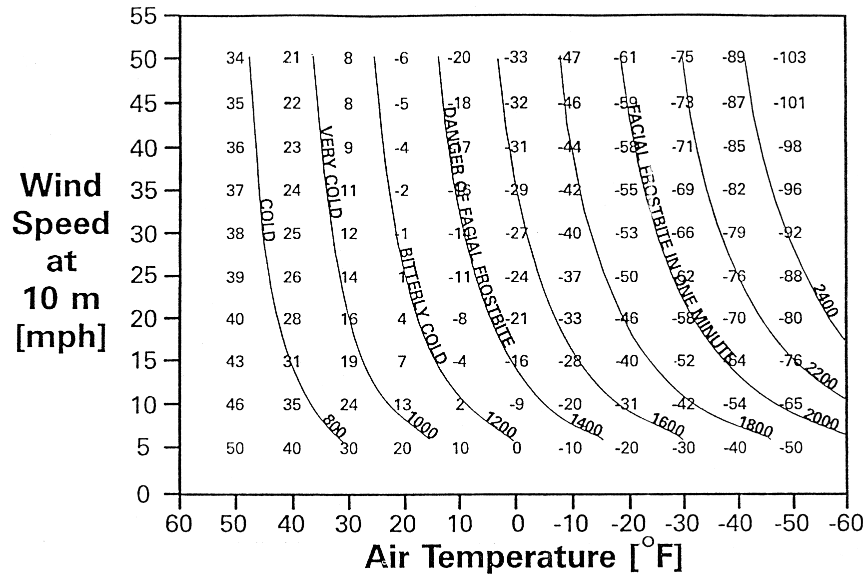

FIG. 2. Wind chill temperatures using the facial cooling model of Osczevski (reproduced with permission).

3. Areas for improvement in the current method

The WCT determined from Eq. (3) was based on widely scattered data, ignored important thermal resistance factors, assumed an unrealistically high skin temperature, and did not account for the fact that meteorological wind speeds are recorded well above ground level.

These deficiencies can be overcome by the reanalysis of the SP45 data with modern heat transfer theory. Such an analysis is based on the heat transfer path from the water through the container wall by conduction and then by the parallel paths of convection and radiation to the air. SP45 identified the container material and so its thermal conductivity may be found. The convective heat loss coefficient from a cylinder in cross flow of air is also available (Churchill and Bernstein 1977). Radiation heat loss from a body that is small relative to its surroundings has also been well studied (Incropera and DeWitt 1996). This permits the determination of a total heat transfer coefficient for the cylinder. Such a coefficient has been found as a function of airspeed and compared to the graph developed by SP45 (Bluestein 1998). The results show that SP45 overestimated the heat transfer coefficients and so the WCTs they determined are too low; that is, the wind chill is not as severe.

The rationale that the wind chill is less severe is supported by SP45's choice of skin temperature. The temperature of unclothed skin subjected to extreme cold drops well below 33°C very quickly. LeBlanc (1975) showed that temperatures of the face, cheek, and nose can drop about 10°C in 3 min of exposure to –5°C air with no wind. The addition of a 20-mph (8.94 m s^{-1}) wind caused the temperature of the nose to fall to 10°C and that of the forehead to fall to 20°C. Analysis of Eq. (3) shows that for a lower skin temperature the WCT is higher.

4. A new approach for humans

A study of the effects of wind chill on humans should focus on the head or face, which is normally uncovered in cold weather. An experimental approach was taken by Osczevski (1995), who fabricated an instrumented model of the adult head. Heat transfer coefficients and surface temperatures were determined in a series of wind tunnel experiments. Osczevski used a value of 0.07 m^2 K W^{-1} for the thermal resistance of cold facial skin. He also noted that wind speeds as measured at weather stations are made at 10-m elevations. Using the approach of Steadman (1971), Osczevski showed that meteorological wind speeds are at least 50% greater than that at face level. His resultant chart is shown in Fig. 2. By comparison, the current chart used by the U.S. National Weather Service, which relies on the SP45 method, is shown in Table 1. Both charts are in English units since these are used exclusively in U.S. weather forecasting. It is clear that the wind chill temperatures using the SP45 method are too low.

To further test this conclusion, a theoretical approach was taken for an adult head with heat loss from the exposed surfaces. The head may be approximated by a hollow circular cylinder with covered ends. The cylinder has an interior temperature of 37°C and the

TABLE 1. Wind chill equivalent temperature as a function of air temperature and wind speed (courtesy of the National Climatic Center).

Wind speed at 10 m (mph)	Air temperature (°F)																		
	45	40	35	30	25	20	15	10	5	0	−5	−10	−15	−20	−25	−30	−35	−40	−45
4	45	40	35	30	25	20	15	10	5	0	−5	−10	−15	−20	−25	−30	−35	−40	−45
5	43	37	32	27	22	16	11	6	0	−5	−10	−15	−21	−26	−31	−35	−42	−47	−52
10	34	28	22	16	10	3	−3	−9	−15	−22	−27	−34	−40	−46	−52	−58	−64	−71	−77
15	29	23	16	9	2	−5	−11	−18	−25	−31	−38	−45	−51	−58	−65	−72	−78	−85	−92
20	26	19	12	4	−3	−10	−17	−24	−31	−38	−46	−53	−60	−67	−74	−81	−88	−95	−103
25	23	16	8	1	−7	−15	−22	−29	−36	−44	−51	−59	−66	−74	−81	−88	−96	−103	−110
30	21	13	6	−2	−10	−18	−25	−33	−41	−49	−56	−64	−71	−79	−86	−93	−101	−109	−116
35	20	12	4	−4	−12	−20	−27	−35	−43	−52	−58	−67	−74	−82	−89	−97	−105	−113	−120
40	19	11	3	−5	−13	−21	−29	−37	−45	−53	−60	−69	−76	−84	−92	−100	−107	−115	−123
45	18	10	2	−6	−14	−22	−30	−38	−46	−54	−62	−70	−78	−85	−93	−102	−109	−117	−125

conduction thermal resistance of its wall is equal to that of human skin exposed to the cold. The same value used by Osczevski was used herein. The diameter of the cylinder is based on the average occipital frontal circumference of young adults, 176.7 mm (Nellhaus 1968). The length of the cylinder, 218.4 mm, is an average of measurements made on 25 acquaintances. This length measurement is of little importance in the determination of the heat transfer coefficient for a cylinder in cross-flow since neither of the two important dimensionless numbers for convective heat transfer, the Reynolds number and the Nusselt number, is a function of cylinder length.

Convection from the cylinder to the air was assumed to be governed by the Churchill–Bernstein equation since it is applicable to the range of air temperatures and airspeeds to be investigated (Churchill and Bernstein 1977). The Churchill–Bernstein formula provides a Nusselt number from which the convective heat transfer coefficient h_c in W (m^2 K)$^{-1}$ is easily found. Solution of the Churchill–Bernstein equation was accomplished with a computer program developed by DeWitt (1995, personal communication), which requires the cylinder's external dimensions, the ambient and surface temperatures, and the wind speed. The program then yields the convection heat transfer coefficient as well as the heat flow rate.

Radiation heat loss occurs in parallel with convection. The radiation heat transfer coefficient is found using the following formula (Incropera and DeWitt 1996), assuming a surface emissivity of 1:

$$h_r = \sigma(T_s + T_a)(T_s^2 + T_a^2), \qquad (4)$$

where h_r is the radiation heat transfer coefficient in W (m^2 K)$^{-1}$, σ the Stefan–Boltzmann constant 5.669×10^{-8} W (m^2 K^4)$^{-1}$, T_s the surface (skin) temperature, and T_a the ambient air temperature, both in Kelvins.

To combine the effects of conduction, radiation, and convection into a total heat transfer rate requires the calculation of a conduction heat transfer coefficient. This is expressed as a heat rate per unit cross-sectional area. For the case of radial conduction through a cylindrical annulus the cross-sectional area is changing as one moves radially outward. Thus, in this case the area based on the average radius was used.

The total heat transfer rate from the interior of the body to the ambient air may be expressed as

$$q = \Delta T/R, \quad (5)$$

where q is the total heat transfer rate in watts per square meter, ΔT the temperature difference between the interior of the body (assumed to be 37°C) and the ambient air, and R the total thermal resistance (in $m^2\,K\,W^{-1}$).

The total thermal resistance is the conduction resistance plus that of convection and radiation resistances in parallel. Since thermal resistance is the inverse of the heat transfer coefficient, the total heat transfer rate becomes

$$q = \Delta T/[0.07 + 1/(h_c + h_r)]. \quad (6)$$

In the steady state, the total heat loss with the actual air temperature and wind speed is set equal to that with the temperature WCT and a wind speed of 1.79 m s^{-1}. This equation is solved for the WCT. The interior body temperature remains at 37°C. An iterative process is required since the convective heat loss depends on the surface temperature, which is unknown, and the radiation heat loss varies with both the surface temperature and the ambient temperature. A computer program was developed to solve this problem. The procedure is as follows for each combination of dry bulb temperature and wind speed.

(a) Estimate the steady-state surface temperature. Use this to find the heat transfer coefficients with the methods of Incropera and DeWitt (1996).
(b) Solve for the total q. Use this to correct the surface temperature by solving Eq. (5) for ΔT between the interior and the surface with $R = 0.07$.
(c) With the corrected surface temperature, correct the values of the convective and radiation heat transfer coefficients. Redo step b.
(d) Continue with step c until there is no change in the value of q.
(e) Use the DeWitt method to find h_c with a velocity of 1.79 m s^{-1}, the surface temperature found in step c, and the actual ambient temperature. Solve Eq. (6) for WCT using the value of q found in step d.
(f) With the WCT found in step e, correct the values of the convective and radiation heat transfer coefficients. Redo step e.
(g) Continue with step f until there is no change in WCT.

The resultant values of WCT for the various combinations of ambient temperature and wind speed are shown in Table 2. Using the current U.S. National Weather Service chart as a guide, the air temperature range studied was –45° to +45° F, with wind speeds, recorded at 10-m elevations, ranging from 5 to 45 mph. These wind speeds were assumed to be 50% greater than the speed at the face that was used in the calculations. Since U.S. weather data are normally given in English units, these were used in the charts, even though the actual calculations were done in SI units to conform to scientific practice. For comparison, the current U.S. National Weather Service chart is shown in Table 1. In both tables, speeds are at 10-m elevations. It can be seen that the WCTs found are not as low as those currently utilized. While not as markedly different as Osczevski's results, there is still sufficient difference to conclude that current meteorologic WCT charts should be revised.

5. Discussion

Since, as noted by Osczevski (1995), wind chill effects are felt most at the face, a theoretical approach using a frontal or half cylinder model could be utilized. An analysis by Achenbach (1975) describes the variation of convective heat transfer coefficient around a cylinder in cross-flow with Reynolds number. From this study, it appears that the convective heat transfer coefficient at a wind speed of 1.79 m s^{-1} for a frontal cylinder model would be greater than that for the full cylinder and result in WCTs that are higher, that is, less severe, than those given in Table 2. This further supports the conclusion that the existing WCT chart used by the U.S. National Weather Service should be changed to less severe values.

An excellent summary of the errors inherent in the present wind chill chart is given by Kessler (1993) with support from Driscoll (1994), Steadman (1995), and Schwerdt (1995) in follow-up letters to Kessler's paper. In particular the authors refer to the way in which wind chill temperatures are presented to the public by the media and what should be done to improve such presentations. At a recent workshop, Kessler (1997) restated the rationale for changes in the WCT chart and proposed a meeting of a panel of experts in meteorology, sociology, and communications to recommend a

TABLE 2. Revised wind chill temperature as a function of air temperature and wind speed.

	Air temperature (°F)																		
Wind speed at 10 m (mph)	45	40	35	30	25	20	15	10	5	0	−5	−10	−15	−20	−25	−30	−35	−40	−45
5	45.0	40.0	35.0	30.0	25.0	20.0	15.0	10.0	5.0	0.0	−5.0	−10.0	−15.0	−20.0	−25.0	−30.0	−35.0	−40.0	−45.0
10	39.6	34.1	28.5	22.9	17.3	11.6	6.0	0.4	−5.3	−11.0	−16.7	−22.4	−28.1	−33.9	−39.6	−45.3	−51.0	−56.7	−62.5
15	35.0	29.0	22.9	16.8	10.6	4.4	−1.7	−8.0	−14.2	−20.5	−26.8	−33.1	−39.5	−45.8	−52.0	−58.3	−64.6	−71.0	−77.5
20	31.7	25.2	18.8	12.2	5.7	−0.9	−7.5	−14.1	−20.8	−27.5	−34.2	−41.0	−47.7	−54.4	−61.1	−67.8	−74.7	−81.6	−88.5
25	29.0	22.3	15.5	8.7	1.9	−5.0	−11.9	−18.9	−25.9	−32.9	−40.0	−47.1	−54.1	−61.1	−68.2	−75.3	−82.5	−89.8	−97.1
30	26.8	19.8	12.9	5.8	−1.3	−8.4	−15.6	−22.8	−30.1	−37.4	−44.8	−52.0	−59.3	−66.6	−73.9	−81.3	−88.9	−96.4	−103.6
35	25.0	17.8	10.6	3.4	−3.9	−11.3	−18.7	−26.1	−33.6	−41.2	−48.6	−56.1	−63.6	−71.2	−78.7	−86.4	−94.2	−102.0	−109.8
40	23.4	16.1	8.7	1.3	−6.2	−13.7	−21.3	−28.9	−36.6	−44.4	−52.0	−59.6	−67.3	−75.1	−82.8	−90.7	−98.7	−106.7	−114.8
45	22.0	14.6	7.1	−0.5	−8.1	−15.8	−23.5	−31.4	−39.2	−47.1	−54.8	−62.7	−70.5	−78.4	−86.4	−94.5	−102.6	−110.8	−119.0

revision to the current practice. We join the many researchers in support of such a meeting.

6. Conclusions

The current method for indicating the severity of low air temperature combined with high wind speed has been analyzed. This wind chill factor has been shown to be based on questionable methods. A new approach has been taken based on modern heat transfer techniques. Assuming that the exposed adult head can be approximated by a cylinder in a cross-flow of air, a new chart of wind chill temperatures, those still-air temperatures that would effect the same heat loss rates as the actual air temperatures and wind speeds, has been developed. It shows wind chill temperatures that are higher than currently accepted values. This same conclusion was reached in a recent experimental study by Osczevski using an instrumented model of the human head. Many other researchers believe the current wind chill temperatures in use are overstated and should be modified. Thus there is now ample support by heat transfer theory to revise the present wind chill temperature chart to more realistic values.

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