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CA010592

CLASSIFICATION UNCLASSIFIED	**SYSTEM NUMBER** 515446

TITLE

Windward cooling: a overlooked factor in the calculation of wind chill

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DCIEM SR 2000-011

Windward Cooling: An Overlooked Factor in the Calculation of Wind Chill

Randall J. Osczevski
Defence and Civil Institute of Environmental Medicine, Toronto, Ontario, Canada

ABSTRACT

Wind chill equivalent temperatures calculated from a recent vertical cylinder model of wind chill are several degrees colder than those calculated from a facial cooling model. The latter was based on experiments with a heated model of a face in a wind tunnel. Wind chill has sometimes been modeled as the overall heat transfer from the surface of a cylinder in cross flow, but such models average the cooling over the whole surface and thus minimize the effect of local cooling on the upwind side, particularly at low wind speeds. In this paper, a vertical cylinder model of wind chill has been modified so that just the cooling of its windward side is considered. Wind chill equivalent temperatures calculated with this new model compare favorably with those calculated by the facial cooling model.

1. Introduction

The head is usually the most exposed segment of the human body in cold weather. Much of it is normally protected to some extent, by hair, a hat, a raised collar, or a parka hood. The face, however, is usually bare, except for the chin and the ears, which are often protected by a collar or scarf. Because the greatest hazard and discomfort of wind chill occurs when the unprotected face is directly exposed to the wind, a model of facial cooling should be used to calculate wind chill equivalent temperatures (Osczevski 1995). Our model was based on a series of experiments with a computer-controlled, multizone, heated model of a human head in a wind tunnel. We found that wind chill equivalent temperatures calculated from this model were far less severe than those calculated in the normal fashion from the classic wind chill equation derived by Siple and Passel (1945).

Recently, Bluestein and Zecher (1999) modeled wind chill as the heat transfer from a vertical cylinder having a diameter equal to the average diameter of a human head. Their model was based on an established correlation between wind speed and the convective heat transfer from a cylinder, the Churchill–Bernstein equation (Churchill and Bernstein 1977). Otherwise it was similar to our facial cooling model. They also calculated wind chill equivalent temperatures that were much less severe than those normally reported by the media, but they were still several degrees more severe than the ones we had calculated for the same sets of conditions.

The two models probably give different results because the local convective heat transfer coefficient varies from the windward to the leeward side of a cylinder or head in wind. At first glance, however, it seems odd that the model that should involve the more intense cooling, the facial cooling model, predicts the less severe wind chill equivalent temperatures. We will examine how the enhanced local convective heat transfer from the windward side affects the calculation of wind chill equivalent temperature.

2. Convective heat transfer from the windward side

Convective cooling is usually greater on the windward side of a cylindrically shaped object, particularly

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Corresponding author address. Randall J Osczevski, Defence and Civil Institute of Environmental Medicine, 1133 Sheppard Ave West, Toronto, ON M3M 3B9, Canada.
E-mail. rjo@dciem.dnd.ca
In final form 12 May 2000.

at low wind speeds (Schmidt and Wenner 1941). A common way to sense the direction of air movement is to hold one wetted finger aloft and wait for one side to begin to feel cooler. Slight air movements thin the boundary layer on the upwind side relative to the downwind side and increase the local cooling.

The ratio of the heat transferred by convection from the upwind side of a cylinder, Q_{front}, to the total convective heat transfer from the whole curved surface of a cylinder, Q_{total}, is shown in Fig. 1. The data are from experiments by Schmidt and Wenner on cylinders with diameters of 5 and 10 cm.

The equation of the line in Fig. 1 is

$$Q_{front} Q_{total}^{-1} = 2.42\,\mathrm{Re}^{-0.142} \tag{1}$$

and the correlation coefficient R^2, is 0.97. Here Re is the Reynolds number, a dimensionless combination of wind speed V, the diameter D of the cylinder, and v, the kinematic viscosity of the air:

$$\mathrm{Re}_D = VDv^{-1}. \tag{2}$$

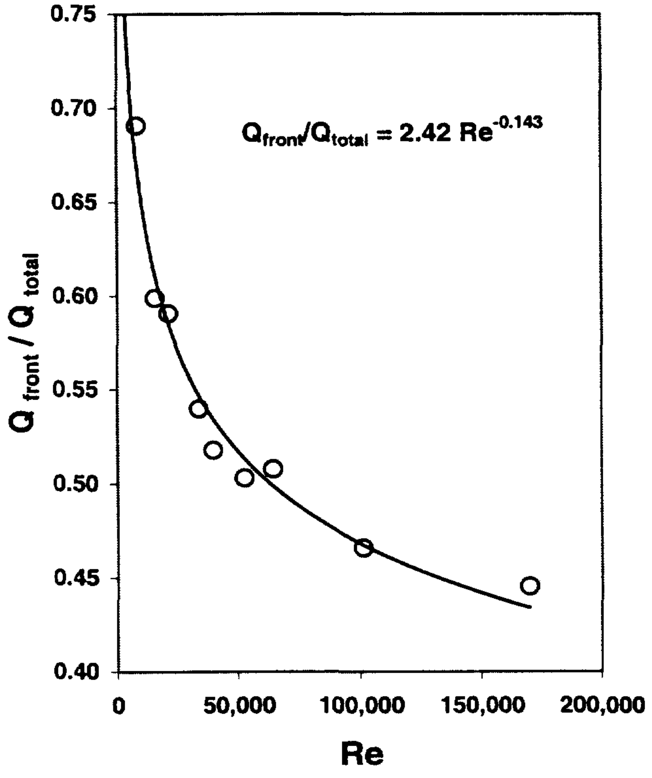

FIG. 1 Convective heat transfer from the windward side of a vertical cylinder in cross flow expressed as a fraction of the total convective heat transfer. Data from Schmidt and Wenner (1941).

Equation (1) suggests that if the dimensionless Reynolds number is less than about 65 000, more than half of the total convective heat loss from a cylinder will be from its windward side. For a cylinder representing an average head, which has a frontal width of 14.1 cm [as seen in U.S. Army pilot data, both males and females (Donelson and Gordon 1991)], the Reynolds number is 65 000 when the wind speed at face height is 6.6 m s^{-1} (15 mph).

The wind is strongest in a large open area, where the wind speed at face height (1.5 m or 59 in.) is about two-thirds of the speed measured at the standard anemometer height of 10 m (Buckler 1969; Steadman 1971). A wind of 6.6 m s^{-1} (15 mph) at face level would therefore be 10 m s^{-1} (22 mph) at the height of the standard anemometer.

In a residential area, houses, trees and other roughness elements reduce the wind speed near the ground so that at face height, it might only be one-third of the wind speed that is measured at anemometer height. The officially measured wind speed would therefore have to be about 18 m s^{-1} (45 mph) before the convective heat transfer from the upwind side of the model cylinder in a residential area would be exceeded by the convective heat transfer from its downwind side. Since the average measured wind speed at most weather stations is considerably less than even the open field value of 10 m s^{-1} (22 mph), heat transfer from a head-sized cylinder is normally greater on its windward side.

3. A windward cylinder model of wind chill

A whole cylinder model was modified to account for the effect of increased heat transfer on its windward side. It assumes a worst-case situation of a bare face continuously and directly exposed to the wind. Following Bluestein and Zecher, the average Nusselt number for the whole cylinder was calculated from the Churchill–Bernstein equation (Churchill and Bernstein 1977):

$$\overline{\mathrm{Nu}}_D = 0.3 + (0.62\,\mathrm{Re}_D^{0.5}\,\mathrm{Pr}^{0.333}) \times \left[1 + (0.4\,\mathrm{Pr}^{-1})^{0.667}\right]^{-0.25} \times \left[1 + (\mathrm{Re}_D \times 282{,}000^{-1})^{0.625}\right]^{0.8}, \tag{3}$$

where D is the cylinder diameter (m), Pr is the dimensionless Prandtl number, and k is the thermal conductivity of air ($\mathrm{Wm^{-1}\,K^{-1}}$). All quantities were evaluated standard wind chill, the wind speeds used in the calculations are those that would be measured at face height. They represent the worst case of wind in an open area. The facial cooling model equivalent temperatures were taken from a previously published chart (Osczevski 1995).

5. Discussion

The whole cylinder model, when modified to reflect the heat transfer from only its windward side, yields almost the same results as our facial cooling model (Fig. 2). The facial cooling model has some indirect physiological validation. It predicts the proper range of facial skin temperatures at combinations of wind and low temperature that have been shown to produce frostbite and various levels of cold discomfort (Osczevski 1995).

Bluestein and Zecher's model predicts more severe wind chill equivalent temperatures than our facial cooling model because of the large effect of low airspeeds on the heat transfer through the boundary layer on the windward side of a cylinder or head. The wind chill equivalent temperature (WCT) is the air temperature at which the heat transfer rate and skin temperature would be the same in the absence of wind. Thus

$$\mathrm{WCT} = 37 - h_v h_0^{-1}(37 - T_{\mathrm{air}}), \qquad (5)$$

where h_v is the total heat transfer coefficient at some wind speed v, from the core to the air, at temperature T_{air}, and h_0 is the value of the same heat transfer coefficient in still air. As the ratio of h_v to h_0 is smaller for the windward side of a cylinder than for the cylinder as a whole, WCT is higher for a windward cylinder model.

Because a whole vertical cylinder model averages the heat transfer rate over the entire curved surface of the cylinder, it largely overlooks the enhanced convective cooling on the windward side, especially in the reference "still air" condition. Because a whole cylinder model understates the "chilling" associated with the still air condition, it exaggerates the "coldness" at higher wind speeds. The windward cylinder model also averages the convective cooling but only over half of the cylinder. As the convective cooling on the windward side is greatest on the stagnation line, that is, on the center line of the face when facing the wind, to some extent, even a windward cylinder model exaggerates how cold the face feels in cold winds.

6. Conclusions

A model of the heat transfer from the windward side of a vertical cylinder is a more appropriate model for wind chill calculations than a whole cylinder. The average heat transfer for the whole cylinder does not adequately account for the locally enhanced cooling on the upwind side. This effect is particularly important when determining the still air heat transfer coefficient needed for calculating wind chill equivalent temperatures, because the effect of air motion on the local convective heat transfer from the windward side is most pronounced at walking speeds.

Both the hazard and the sensation of wind chill are due to the temperature of the skin in the coldest exposed area, which is almost always on the windward side. The average surface temperature over the whole head (or the heat loss from the whole, clothed body) is less relevant. At all wind speeds, a windward cylinder model should provide more realistic values of equivalent temperature than a whole cylinder model.

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at the mean temperature of the air and the skin. A value of 0.71 was assumed for the Prandtl number. The Pr for air varies only slightly with temperature, from 0.707 at +25°C to 0.720 at −25°C.

The average convective heat transfer coefficient for the windward side of the cylinder, $h_{\rm front}$, was derived from Eq. (1) as

$$h_{\rm front} = 2h_{\rm total} \times 2.42{\rm Re}^{-0.142}. \qquad (4)$$

The factor of 2 is the ratio of the surface areas from which heat is lost. Here $h_{\rm total}$ is derived from the Nusselt number for the whole cylinder, which is given by Eq. (3). The Nusselt number is defined as $h_{\rm total}\,D\,k^{-1}$, where D is the frontal width of the head, in meters, and k is the thermal conductivity of air (W m^{-1} K^{-1}). Because heads are not spherical, D is smaller than the average diameter of a head.

The model uses an iterative calculation method to determine the steady-state heat transfer, skin temperature, and wind chill equivalent temperature. At first, the radiative heat transfer is calculated from the air temperature and an assumed value for the surface temperature. A new surface temperature is then calculated by assuming a constant core temperature, a skin thermal resistance of 0.07 m^{2}K W^{-1}, which is appropriate for the cold cheek of an inactive individual (Osczevski 1995), the convective heat transfer, and the previously calculated value for the radiative heat loss. The mean radiant temperature of the surroundings is assumed to be equal to air temperature. New values for the radiative and convective heat loss are then calculated using the new skin temperature. The process is repeated until the consecutive solutions converge to a single value, which may take several hundred iterations.

When using an Excel spread sheet to find an iterated solution the calculation sometimes becomes unstable and fails to converge. It can oscillate between two relatively constant values or between widely separated and seemingly random numbers of differing sign. Sometimes it expands to infinity, which is disconcerting to say the least. These difficulties can be avoided by averaging the calculated contents of the most rapidly changing cells with their previous contents. Sometimes the previous contents must be weighted by a factor of 10 or so to encourage the solutions to converge. These weighting factors slow the rate of change of the solution but have no effect on the final answer.

A characteristic dimension of $D = 0.162$ m was used in both of the cylinder models. This is the frontal width of the temperature-controlled model head that we used in developing the facial cooling model. Assuming a more average frontal width of 0.14 m would increase the equivalent temperatures by about half a degree.

As usual, the wind speed at the level of the face in "calm" conditions was assumed to be 1.78 m s^{-1} (4 mph). The wind chill equivalent temperature should equal the air temperature when the wind speed at face height is 1.78 m s^{-1} (4 mph). Because the measured wind speed at anemometer height is 50% greater than the wind at face height in an open area, air temperature and wind chill equivalent temperature should be the same when the recorded wind speed at anemometer height is 2.7 m s^{-1} (6 mph) if this factor is correctly taken into account.

4. Results

Equivalent temperatures calculated from the modified model are presented in Fig. 2, along with those calculated from the unmodified cylinder model, the facial cooling model, and the standard wind chill equation (Siple and Passel 1945). An air temperature of −10°C (14°F) was assumed in all cases. Except for the

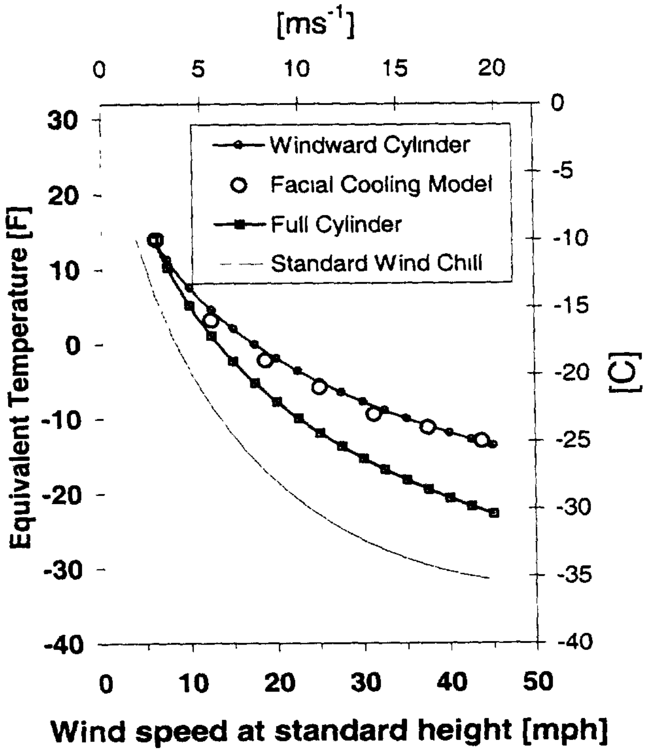

FIG. 2. Wind chill equivalent temperatures calculated at an air temperature of 14°F (−10°C).

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