ASSESSMENT OF THE EFFECTS OF ENVIRONMENTAL RADIATION ON WIND CHILL EQUIVQALENT TEMPERATURES

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Abstract

Combinations of wind-driven convection and environmental radiation in cold weather, make the environment "feel" colder. These mechanisms form the basis for estimating wind chill equivalent temperatures (WCETs). Distinction is made between direct solar radiation and environmental radiation. Solar radiation, which is not included in the analysis, has beneficial effects, as it counters and offsets some of the effects due to wind and low air temperatures. Environmental radiation effects, which are included, have detrimental effects in enhancing heat loss from the human body, thus affecting the overall thermal sensation due to the environment. This study compares the relative contributions of wind-driven convection and environmental radiation on calculated WCETs. The analysis is performed by a simple, steady-state analytical model of human-environment thermal interaction using upper and lower bounds of environmental radiation heat exchange. It is shown that, over a wide range of relevant air temperatures and reported wind speeds, convection heat losses dominate over environmental radiation. At low wind speeds radiation contributes up to about 23% of the overall heat loss from exposed skin areas. Its relative contributions reduce considerably as the time of the exposure prolongs and exposed skin temperatures drop. At still higher wind speeds, environmental radiation effects become much smaller contributing about 5% of the total heat loss. These values fall well within the uncertainties associated with the parameter values assumed in the computation of WCETs. It is also shown that environmental radiation effects may be accommodated by adjusting reported wind speeds slightly above their reported values.

Keywords: Convection heat exchange; Cold weather; Wind chill; Environmental radiation; Upper and lower bounds.

Introduction

The study of human-environment thermal interactions, particularly in extreme cold or hot environments, has been of great interest. The present study focuses on exposure to cold environments. The pioneering experimental work of Siple and Passel (1945) in the Antarctic formed the basis for the formulation of the wind chill index. A derivative of this concept, namely, wind chill (equivalent) temperature (WCET), has been used for decades by weather services in North America to report to the public the effects of cold winds, e.g., (ASHRAE 1997). The scientific validity of this index of cold weather conditions has been criticized over the years by many (e.g. Molnar 1958; Kessler 1993). These criticisms have eventually led to the development and implementation in 2001 of a "new" wind chill chart (National Weather Service USA 2001; Environment Canada 2001). This chart is more scientifically based and addresses many of the shortcomings of the previous method (Osczevski and Bluestein 2005).

Heat exchange between humans and the environment is quite a complex process the estimation of which requires a host of assumptions (e.g. Osczevski and Bluestein 2005). The problem may be somewhat simplified by focusing the analysis on exposed skin areas, e.g., head, face, ears, hands, etc. The heat exchange process involves the mechanisms of convection, radiation, evaporation and conduction. Of these mechanisms, the effect of evaporation is relatively small, contributing less than about 4% of the total heat loss from the skin of the head (Froese and Burton 1957, quoted by Osczevski 1995). Its contribution becomes even smaller, as skin temperatures drop in a cold exposure, and may be safely ignored (Osczevski 1995). The effects of conduction are also small, due to the high thermal resistance of air, and are usually included as an indirect part of the overall convection heat transfer coefficient. This leaves two mechanisms to be considered - wind-driven convection and environmental radiation, as was done in the development of the "new" wind chill chart (Osczevski and Bluestein 2005).

Heat exchange with the environment by radiation may be differentiated between heat gain and heat loss. Heat gain by radiation occurs on bright sunny days and may result in a decrease of 233 W/m^2 (200 kcal/hr m^2) in the wind chill index (Siple and Passel 1945). This reduction in the cooling load of the environment may increase WCET by about 6ºC (Osczevski 1995), 2.4-7.4ºC (Steadman 1984) or 6-10ºC, as advised in the "new" wind chill chart (National Weather Service USA 2001; Environment Canada 2001). Heat loss, which is the focal point in the present context, will occur on cloudy days or after sunshine hours. Its effects are determined by the difference in the 4^{th} power of the absolute temperatures of the two radiating entities – exposed skin surface and the environment, respectively. While skin surface temperature changes upon exposure to a cold environment, its radiating surface nevertheless represents a small area compared to the vast engulfing environment and may be approximated by a single, usually time dependent, temperature. The environment, on the other hand, is not only vast in its dimensions but presents a variety of different radiant temperatures. As an example, consider a snow covered ground as part of the radiating environment. Geiger (1971) estimated the average radiant temperature of the snow covered ground to be 2.5 ºC lower than air temperature. Sky radiation is another example. Tikuisis and Osczevski (2002) used an expression for the "effective atmospheric radiant temperature," or "clear-sky temperature," which depends on air temperature, the emissivity of clear sky and the partial ambient vapor pressure. This complicates the analysis quite considerably and suggests the introduction of simplifying assumptions. One of the most common assumptions used in this context, is to equate the mean radiant temperature (MRT) of the environment with air temperature (e.g. Osczevski and Bluestein 2005; Osczevski 1995). Osczevski (1995) stated that this assumption is more appropriate for cloudy and windy conditions than for calm, clear weather. As this assumption was also made in the development of the "new" wind chill chart (Osczevski and Bluestein 2005), it is adopted, for simplicity, in the following analysis.

The other heat loss factor, convection heat exchange, is determined by wind speed and by air and skin surface temperatures. It is customary to take the mean of these temperatures for calculating their effects on the convection heat exchange coefficient, h_{con} (Kreith 1973). Osczevski (1995) has shown that h_{con} changes by only 5% as the mean of air-skin surface temperature varies over a wide range which is of interest to wind chill. Thus, wind speed may be taken as the dominant factor in determining the value of h_{con} the effects of which are factored in through experimentally established expressions. Over the years a variety of expressions have been used, as summarized recently by Shitzer (2006a). As is to be expected, these expressions yield a variety of different results for calculated WCETs (Shitzer 2006a). One of these expressions, which was used in the development of the "new" wind chill chart (Osczevski and Bluestein 2005), is used herein, for demonstration purposes.

The purpose of this study is to quantify the separate effects, and the relative magnitudes, of wind-driven convection and environmental radiation on the human-environment heat exchange process, in cold and windy environment. Solar radiation is not included in the analysis as it offsets the cooling effects of the environment and may thus be considered as a "safety factor" for these conditions.

Analysis

Convection heat exchange between man and a cold and windy environment is governed by an equation of the type (e.g. Kreith 1973):

$$\mathbf{Q_{con} = h_{con}\, A\,(T_{sur} - T_{env})} \qquad (1)$$

where Q_{con} is the heat exchanged by convection, W; h_{con} is the convection heat transfer coefficient, W/m^2 K; A is skin surface area, m^2; and T_{sur} and T_{env} are skin surface and environmental temperatures, K, respectively. The convection heat transfer coefficient is determined experimentally and is presented for a cylinder in cross wind by an empirical equation (e.g. Kreith 1973; Osczevski and Bluestein 2005):

$$\mathbf{h_{con} = 1.14\frac{k_{air}}{D} Re^{0.5} * Pr^{0.4}[1-(\omega/90)^3]} \qquad (2)$$

where k_{air} is the thermal conductivity of air, W/m K; Re=U*D/ν is Reynolds number wherein U is wind speed, m/s, D is cylinder outer diameter, m, and ν is air kinematic viscosity, m^2/s; Pr=ν/α is Prandtl number wherein α is thermal diffusivity of air, m^2/s; and ω is the windward angle at which the heat transfer coefficient is evaluated. This expression was used in the development of the "new" wind chill chart (Osczevski and Bluestein 2005). Review of other expressions used in the analysis of wind chill effects was given by Shitzer (2006a).

Heat exchange by radiation is governed by the well known 4^{th} power law (e.g. Kreith 1973):

$$\mathbf{Q_{rad} = \varepsilon f \sigma A\,(T^4_{sur} - T^4_{env})} \qquad (3)$$

where Q_{rad} is the energy exchanged by radiation, W; ε is the radiating surface emissivity; f is radiation shape, or view, factor; σ is the Stefan-Bolzmann constant, $5.67*10^{-8}$ $W/m^2 K^4$; and A is the skin surface area, m^2.

Equation (3) introduces non-linearities into the computational process of the skin surface temperature, due to the presence of the 4^{th} power of the temperatures. This requires the employment of an iterative solution procedure which may be accomplished numerically, as was done in the development of the "new" wind chill chart (Osczevski and Bluestein 2005). Alternatively, Eq. (3) may be rewritten in a format similar to Eq. (1):

$$\mathbf{Q_{rad} = h_{rad}\, A\, (T_{sur} - T_{env})} \qquad (4)$$

where, h_{rad} is the radiation heat transfer coefficient, W/m^2 K expressed by (e.g. Kreith 1973):

$$\mathbf{h_{rad} = \varepsilon\, f\, \sigma\, (T_{sur} + T_{env})(T_{sur}^2 + T_{env}^2)} \qquad (5)$$

This equation facilitates the evaluation of the total heat loss to the environment by a combined expression:

$$\mathbf{Q_{total} = Q_{con} + Q_{rad} = (h_{con} + h_{rad})\, A\, (T_{sur} - T_{env}) = h_{combined}\, A\, (T_{sur} - T_{env})} \qquad (6)$$

We next compare the relative magnitudes of the two heat transfer coefficients in Eq. (6). Comparison is done over a range of environmental (230 – 280K) and skin surface temperatures (270 – 310K) which are of interest to wind chill. In evaluating the values of the radiation heat transfer coefficient, a "worst case" scenario is assumed by setting both the emissivitity, ε, and shape factor, f, to their maximal values, unity. Additionally, it is assumed that the mean radiation temperature of the environment is equal to the air temperature, as was done in the development of the "new" wind chill chart (Osczevski and Bluestein 2005). Utilizing Eq. (5), a range of values for the radiation heat transfer coefficient, h_{rad} = 3.57 to 5.84 W/m^2 K is obtained, as shown in Fig. 1. Bluestein (1998) estimated these values to range between 3.4 to 4.3 W/m^2 K for air temperatures in the range of -14ºC (259K) to -55ºC (218K), and applied a mean value of 3.85 W/m^2 K in his calculations.

The convection heat transfer coefficient is expressed by Eq. (2). This coefficient is dependent on environmental temperatures, through the physical properties, on the geometry of the heat exchanging object (face, in this case) and on wind speed. As was shown by Shitzer (2006a), the dependence of this parameter on environmental temperatures is relatively weak. Thus, using average property values over the shown temperature range, introduces a maximal deviation in the calculated values of ±7%. Osczevski (1995) estimated h_{con} to increase by only 5% as the mean of the air and surface temperatures varies from 30ºC (303K) to -20ºC (253K).

The effect of wind speed, which appears in the Reynolds number, is introduced through an "effective" wind speed. This variable reconciles the difference between the "reported" wind speed, that is measured at 10 m heights above ground level, and the region closer to the ground that is occupied by humans. A value for the "effective" wind speed, which was used in the development of the "new" wind chill chart, is (Osczevski and Bluestein 2005):

$$\mathbf{U_{eff} = 1.34 + 2/3\,U_{rep}} \tag{7}$$

where 1.34 m/s is the assumed "calm" wind speed (Osczevski and Bluestein 2005) and U_{rep} is the wind speed measured by standard meteorological stations. Equation (7) is used to calculate the convection heat transfer coefficient over a range of 1.34 – 40 m/s reported wind speeds, as shown in Fig. 2. Also plotted in this figure are the maximal and minimal effects on the combined convection-radiation heat transfer coefficient, due to both convection and environmental radiation. These effects are obtained by adding the maximal (dotted line) or minimal (broken line) values of the radiation heat transfer coefficient (see Fig. 1) to the convection coefficient. It is seen that at low reported wind speeds, the maximal and minimal relative contributions of environmental radiation to the combined heat transfer coefficient, $h_{combined}$, are about 23% to 15%. With increasing wind speed, the relative contributions of environmental radiation decrease considerably, reaching less than 8% to 5%, respectively, at a 40 m/s reported wind speed. These percentages present the "worst case" upper and lower bounds for the actual effects of environmental radiation on the combined convection-radiation heat transfer coefficient in the assumed temperature ranges.

An alternative method of expressing radiation effects on $h_{combined}$ is by modifying (increasing) the reported wind speed such that it accommodates both the effects of convection and radiation.

This is done by first solving Eq. (2) for the effective wind speed, which appears in the Reynolds number:

$$\mathbf{U_{eff} = const * h^2_{con}} \tag{8}$$

where **const** includes all other terms in Eq. (2). Next, the effects of radiation heat transfer are added to Eq. (8) yielding a modified effective wind speed:

$$\mathbf{U^{mod}_{eff} = const\ (h_{con} + h_{rad})^2} \tag{9}$$

Dividing these two equations and re-arranging:

$$\mathbf{U^{mod}_{eff} = U_{eff}\ (1 + h_{rad} / h_{con})^2} \tag{10}$$

Equation (10) may now be used to solve for the modified reported wind speed which includes the combined effects of convection and radiation:

$$\mathbf{U^{mod}_{rep} = U_{rep} + U_{eff} \frac{3h_{rad}}{2h_{con}} (2 + h_{rad} / h_{con})} \tag{11}$$

When radiation effects are absent, the modified reported wind speed equals the actual reported wind speed. Figure 3 shows the maximal and minimal modifications of the reported wind speed due to environmental radiation over the indicated range of wind speeds. An example in Fig. 3 assumes a reported wind speed of 20 m/s. In the absence of environmental radiation, wind speed will remain unmodified, as shown in the figure. For minimal environmental radiation effects, the modified wind speed will increase to about 23 m/s, further increasing to about 25 m/s for maximal radiation effects. These lower and upper values of the modified wind speed, which are calculated by Eq. (11), fully accommodate the added effects of environmental radiation.

Results and discussion

The expressions listed above may now be used to estimate the separate and combined effects of wind-driven convection and environmental radiation on wind chill equivalent temperatures (WCETs). WCET is commonly defined as "the ***temperature*** of an **equivalent environment** that will produce the same heat loss to the environment, under “**calm**” wind conditions, as the actual (real) environment produces, under **steady-state** conditions" (Osczevski and Bluestein 2005). In equation form this definition becomes:

$$\mathbf{WCET = T_{sur} - \frac{h_{combined}}{h_{calm}} * (T_{sur} - T_{env})} \qquad (12)$$

where T_{sur} and T_{env} are skin surface and environmental temperatures, ºC, respectively; $h_{combined}$ is the combined convection-radiation heat transfer coefficient at the skin surface, W/m^2 K ; and h_{calm} is the convective heat transfer coefficient estimated for "calm" wind conditions, W/m^2 K.

Before proceeding with the estimation of WCETs, the reader is reminded that the present analysis applies to steady state conditions, as was done in the development of the "new" wind chill chart (Osczevski and Bluestein 2005). The problem to be solved is non-linear due to the dependence of the convection heat transfer coefficient on skin surface and environmental temperatures (Shitzer 2006a) and the appearance of the 4th power in Eq. (3). Thus, a precise analytical solution may not be possible, and a numerical solution should be applied, as was done in the development of the "new" wind chill chart (Osczevski and Bluestein 2005). In the present analysis an approximate solution procedure is applied which is based on a simple analytical model of the problem (Shitzer 2006a). The application of this solution is facilitated by relaxing the sources of the two non-linearities from the analysis. Accordingly, we first estimate the dependence of the wind-driven convection heat transfer coefficient, h_{con}, on the mean value of skin and environmental temperatures. This is the common method employed in evaluating the convection heat transfer in similar cases (Kreith 1973). As noted above, the deviation of h_{con} due to the variability of environmental temperatures, T_{env}, is relatively small, and falls within ±7% of a mean value (Shitzer 2006a), or even within 5% (Osczevski 1995), over a range of T_{env} of interest to wind chill. We may thus assume a temperature-averaged value for h_{con} in the analysis. This relaxes one source of non-linearities and facilitates the approximation that the convection heat transfer coefficient is dependent on wind speed alone, varying from about 20 to 71 W/m^2 K over the assumed range of wind speeds shown in Fig. 2.

The remaining non-linearity due to environmental radiation is circumvented by using numerical upper and lower bounds to represent its effects. We use the maximal (5.84 W/m^2 K), and minimal (3.57 W/m^2 K) radiation-driven heat transfer coefficients {see Eq. (5) and Figs. 1 and 2} to estimate the range of effects of environmental radiation on WCETs. These maximal or minimal values due to environmental radiation are added to h_{con} and yield, respectively, the upper and lower bounds of variability of WCETs.

Next we distinguish between two cases: (a) wind-driven convection alone, and, (b) wind-driven convection combined with maximal or minimal radiation. The calculations are based on an analytical model of man-environment heat exchange (Shitzer 2006a), and are performed for a cylindrical model with a 0.18m outer diameter (Osczevski and Bluestein 2005). The inner diameter, where the constant body temperature of 38ºC is applied (Osczevski and Bluestein 2005), is set to 0.12m in this example. Results are shown in Fig. 4. As is to be expected, the inclusion of radiation effects, either minimal or maximal, lowers the calculated WCETs. The effects are much more pronounced at low wind speeds and gradually diminish as wind speed intensifies and its effects become dominant.

Figure 5 includes, for comparison purposes, values calculated by the "new" wind chill formula published by the National Weather Service USA (2001) and Environment Canada (2001). It is seen that at relatively high environmental temperatures, "new" WCETs are generally higher than those calculated by convection alone in the present model. As environmental temperatures decrease, "new" WCETs seem to be bounded by convection alone and combined convection and maximal radiation. It is noted that different values may be obtained for WCETs for other values of the various parameters, e.g. inner diameter, assumed for the model (Shitzer 2006b). This comparison of results is not intended to check the accuracy and/or validity of either method of calculation. Nevertheless, the close conformity of the values, and their similar trends of change, lend support to the observation that environmental radiation effects are less important, and may, under certain circumstances, even be neglected for all practical purposes, in the estimation of WCETs when compared to the dominant effects of wind-driven convection, as was also asserted by Tikuisis and Osczevsky (2003).

This observation is accentuated when certain additional factors concerning environmental radiation are considered. First of these is the value assumed to represent the mean radiation temperature (MRT) of the environment. Eliminating solar radiation from the analysis and assuming a cloudy day, the environmental MRT may be approximated by air temperature, as was assumed in the development of the "new" wind chill chart (Osczevski and Bluestein 2005). However, an individual walking in cold and windy surroundings, may encounter and be exposed to a variety of radiating surfaces, e.g., snow. Many of these radiating surfaces may be characterized by temperatures that are lower than air temperature (e.g. Geiger 1971). This will decrease the MRT and will subsequently reduce the radiation heat transfer coefficient, as is evident from Fig. 1.

Another factor relates to the radiation shape, or view, factor, f {see Eq. (3)}. This quantity is defined as: "The fraction of the diffuse radiation leaving (radiating) surface A_1 in all directions which is intercepted by surface A_2" (Cravalho 1996). This factor quantifies the complex geometrical aspects of heat exchange by radiation between an object and its multi-component surroundings. In a complete enclosure, presenting a single radiating temperature, the value of f is unity. In other situations f may assume lower values, each representing a segment of the surroundings. In this study f is assumed at its maximal value of unity, thus yielding maximal radiation effects on WCETs.

Yet another factor determining the effects of radiation on WCETs is skin surface radiation emissivity, ε {see Eq. (3)}. This factor ranges between 0.95 (Incropera and DeWitt 1996) and 0.97 (Togawa 1989). In the present analysis it was set to unity (Osczevski and Bluestein 2005) thus also yielding maximal radiation effects on estimated WCETs.

Conclusion

In this study the separate and combined effects of wind-driven convection and environmental radiation on estimated WCETs are studied. As the term WCET implies, it is actually intended to quantify the effects of wind in cold environments on exposed skin areas. However, heat loss to the environment includes the mechanism of radiation, in addition to wind-driven convection and therefore needs to be considered. Using a simple analytical model and approximating assumptions, which are designed to relax non-linearities in the analysis, and following the assumptions which underlie the development of the "new" wind chill chart, we differentiate between these two effects on WCETs. Results, which are presented in terms of upper and lower bounds, quantify the relative contributions of these two mechanisms. It is clearly seen that environmental radiation effects on the combined convection-radiation heat transfer coefficient are small, ranging from 5% to 23%, over a wide range of skin surface and environmental temperatures. These relative effects may be even smaller if the radiation shape factor and skin surface emissivity were assumed at lower than their maximal values.

Based on the present calculation procedure it may be concluded that environmental radiation effects on WCETs are most pronounced for low wind speeds and low environmental temperatures. They diminish as these variables change: wind speed intensifies and environmental temperatures increase. It follows that, under certain circumstances, environmental radiation effects may be assumed relatively minimal and may be neglected altogether for practical purposes.

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Figure legends

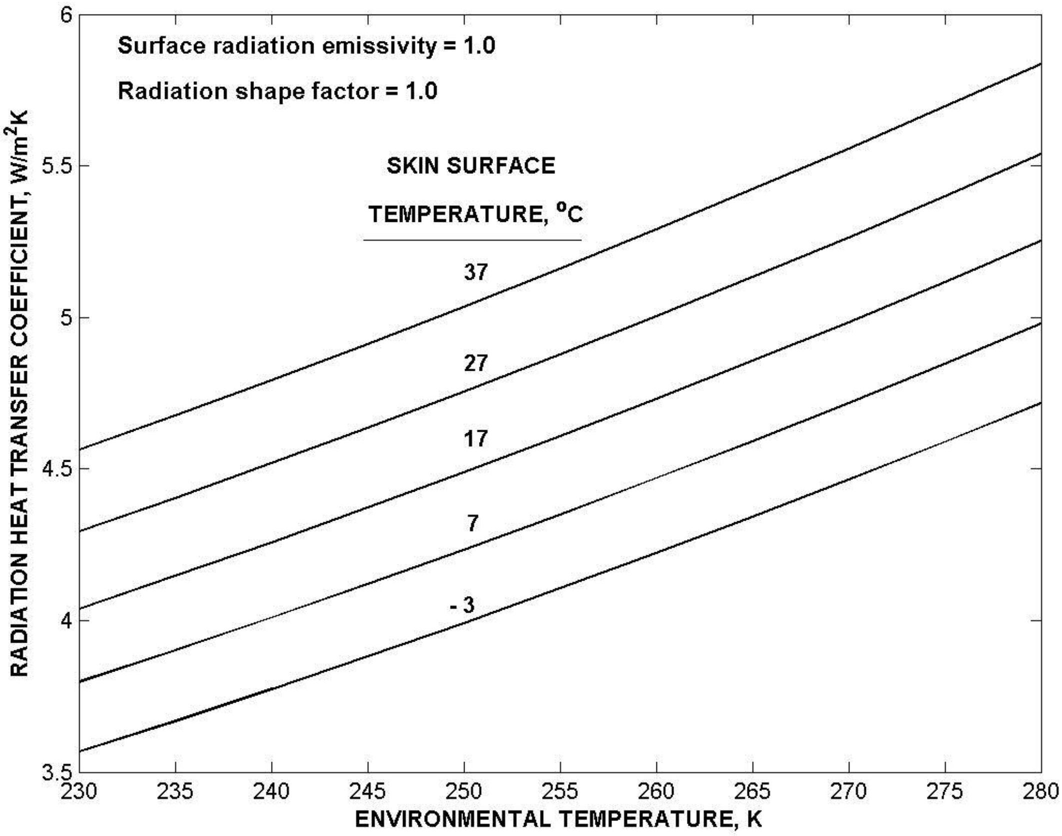
Figure 1: Radiation heat transfer coefficient

Figure 2: Wind-driven convection and upper and lower bounds of the combined convection-radiation heat transfer coefficients

Figure 3: Upper and Lower bounds of the radiation-modified wind speeds

Figure 4: Wind chill equivalent temperatures calculated by wind-driven convection and by maximal and minimal combined effects of environmental radiation

Figure 5: Wind chill equivalent temperatures calculated by wind-driven convection and by maximal combined convection-radiation compared to "new" wind chill formula (Environment Canada 2001)



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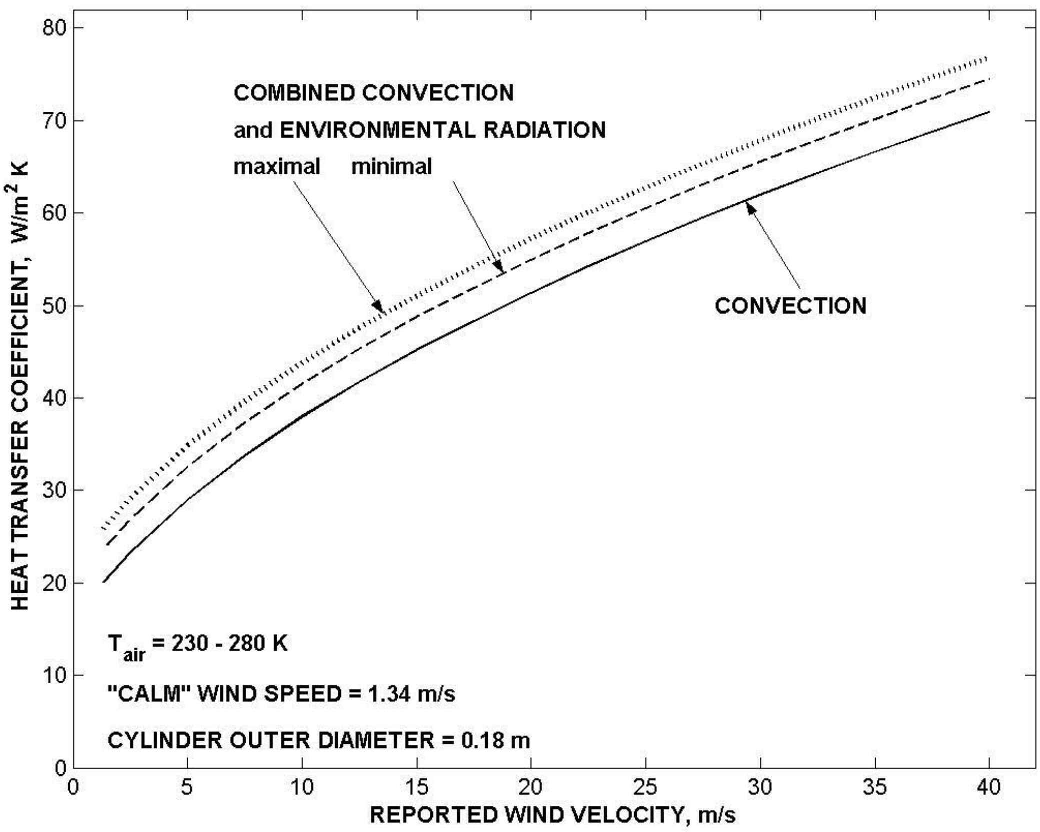


Figure 2: Wind-driven convection and upper and lower bounds of the combined convection-radiation heat transfer coefficients

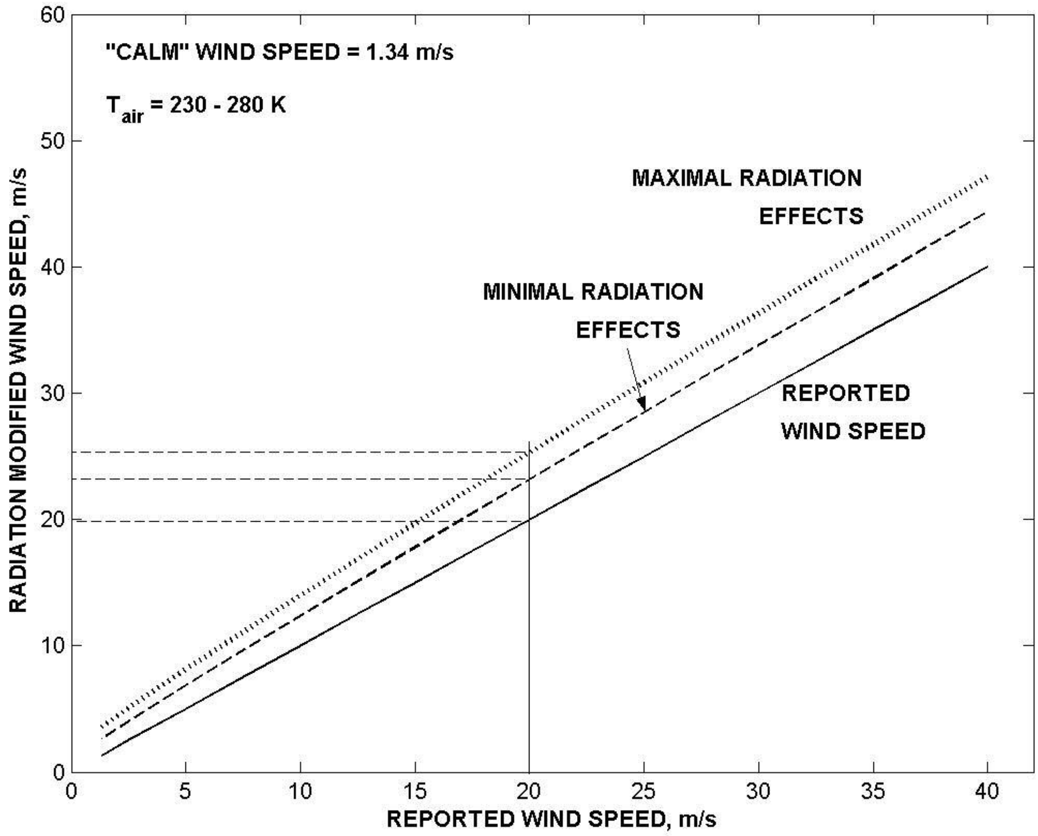


Figure 3: Upper and Lower bounds of the radiation-modified wind speeds

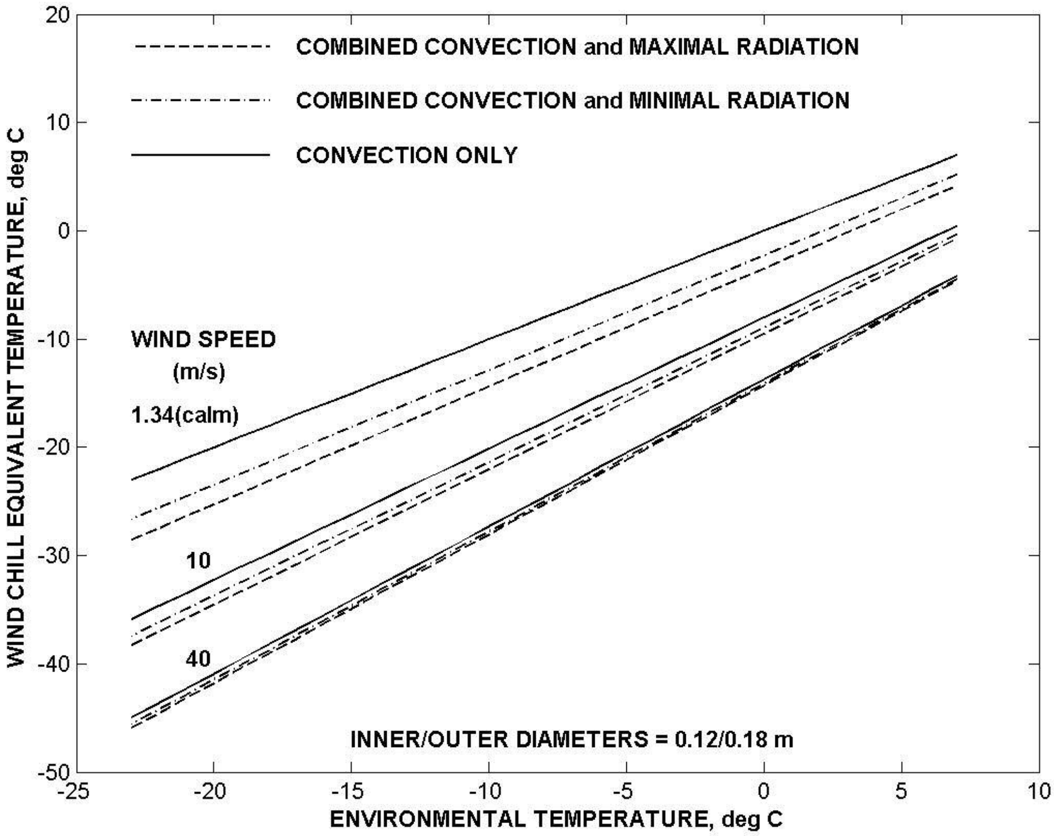
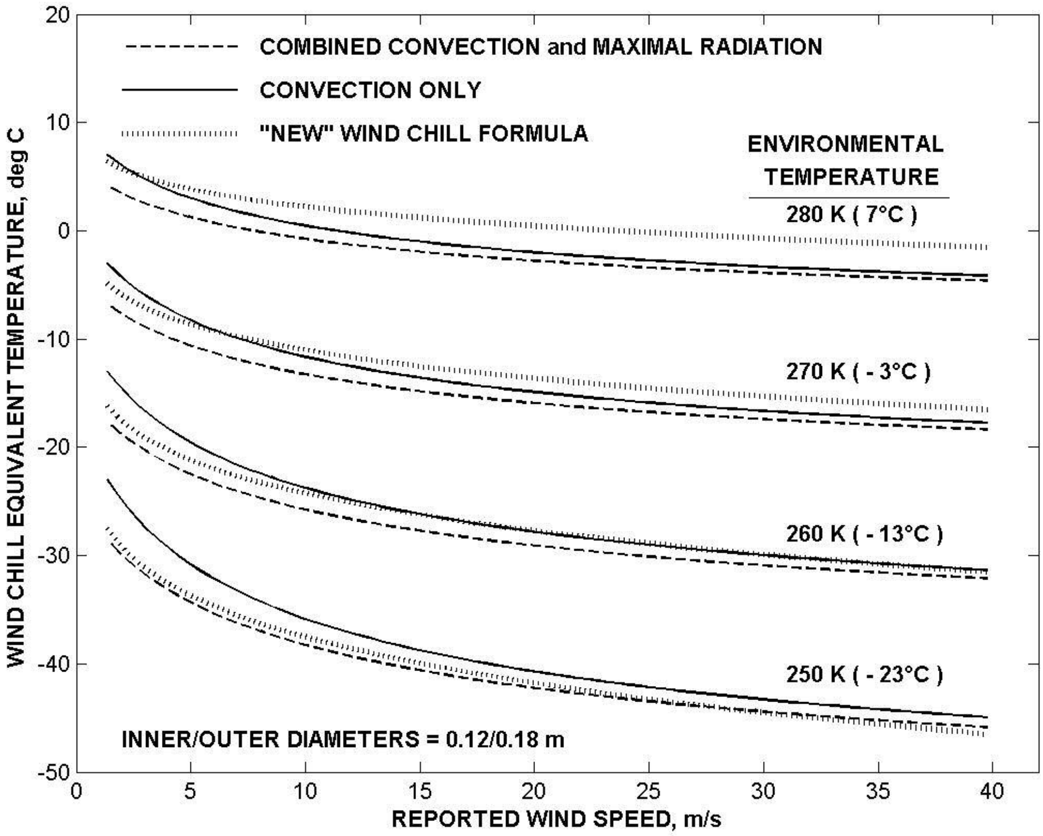


Figure 4: Wind chill equivalent temperatures calculated by wind-driven convection and by maximal and minimal combined effects of environmental radiation



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