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FAN INLET TEMPERATURE CONSIDERATIONS AT AN ACC

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Abstract

Current plant operating standards see the cooling performance of an air-cooled condenser (ACC) being calculated based on a reference air temperature measured near ground level (typically at $z = 1.2$ m). An increase in fan inlet temperatures above this reference temperature will result in a decrease in the ACC performance below its design value, and a subsequent reduction in turbine performance. Localised fan inlet temperature increases have traditionally been attributed to the presence of plume recirculation. A comparison of test data collected at an existing ACC and numerical data, generated during a CFD analysis of the flow around the same ACC, shows a discrepancy in the predicted effects of wind on fan inlet temperature. Careful analysis of the test data indicates the potential involvement of atmospheric temperature distributions in fan inlet temperature deviations. A numerical case study is conducted considering four differing atmospheric temperature distributions. It is found that such distributions, and atmospheric temperature inversions in particular, can cause measurable deviations of the fan inlet temperature from the $z = 1.2$ m reference value; and subsequently measureable deviations in plant behaviour from design. Selecting fan platform height as the reference elevation is shown to result in a better prediction of actual ACC performance for all atmospheric temperature distributions and wind conditions considered.

Keywords: Air-cooled steam condensers; recirculation; temperature distributions.

1. Introduction

Air-cooled condensers use ambient air to cool and condense a process fluid. Mechanical draft air-cooled steam condensers (ACCs) are finding increasing application in direct cooled thermoelectric power plants due to economic and environmental considerations.

Since ambient air is used as the cooling medium in an ACC: the achievable heat transfer rate is susceptible to influence from the ambient conditions such as wind, temperature and atmospheric instabilities. Wind effects in particular have been the focus of many recent studies and it is well documented that wind has a negative effect on ACC performance. Duvenhage and Kr□ger [1] identify reduced fan performance and plume recirculation as the causes of reduced ACC heat transfer rates under windy conditions. These findings are confirmed by Van Rooyen [2] and Owen and Kr□ger [3] amongst others. Several studies have attempted to identify, quantify and mitigate the reduction in fan performance (see for example references 1-10) as well as plume recirculation (references 3, 4, 6, 7, 11 and 12 for example), experienced by ACC installations under windy conditions.

Plume recirculation results in an increase in the temperature of the air being drawn into the ACC fans. The driving force for heat transfer in an ACC is the difference between the temperature of this inlet air and that of the steam flowing through the ACC heat exchanger tubes. An increase in this inlet air temperature will therefore result in a reduction in the ACC heat transfer rate.

During operation, the ACC heat transfer rate is calculated assuming a uniform temperature at the inlet to all the fans. This reference temperature is typically measured near ground level ($z_{ref} = 1.2$ m is common). Any increase in the actual air temperature at the fan inlets from this reference value will result in the ACC performance deviating from the design value.

Localized increases in fan inlet temperature have traditionally been attributed to the recirculation of hot plume air. Owen and Kr□ger [3], in their numerical study of an ACC, show that plume recirculation increases with wind speed. In an experimental investigation of the same ACC, Maulbetsch and DiFilippo [6] indicate that increased fan inlet temperatures are most severe at moderate wind speeds but tend to decrease and level-off at higher wind speeds. The discrepancy between these results has prompted this investigation into a possible alternative contributor to increased fan inlet temperature at an ACC: the presence of atmospheric temperature inversions. The numerical model presented in Owen and Kr□ger [3] was used for the purpose of this investigation. Figure 1 illustrates the layout of the ACC in question and the fan numbering scheme used throughout this document.

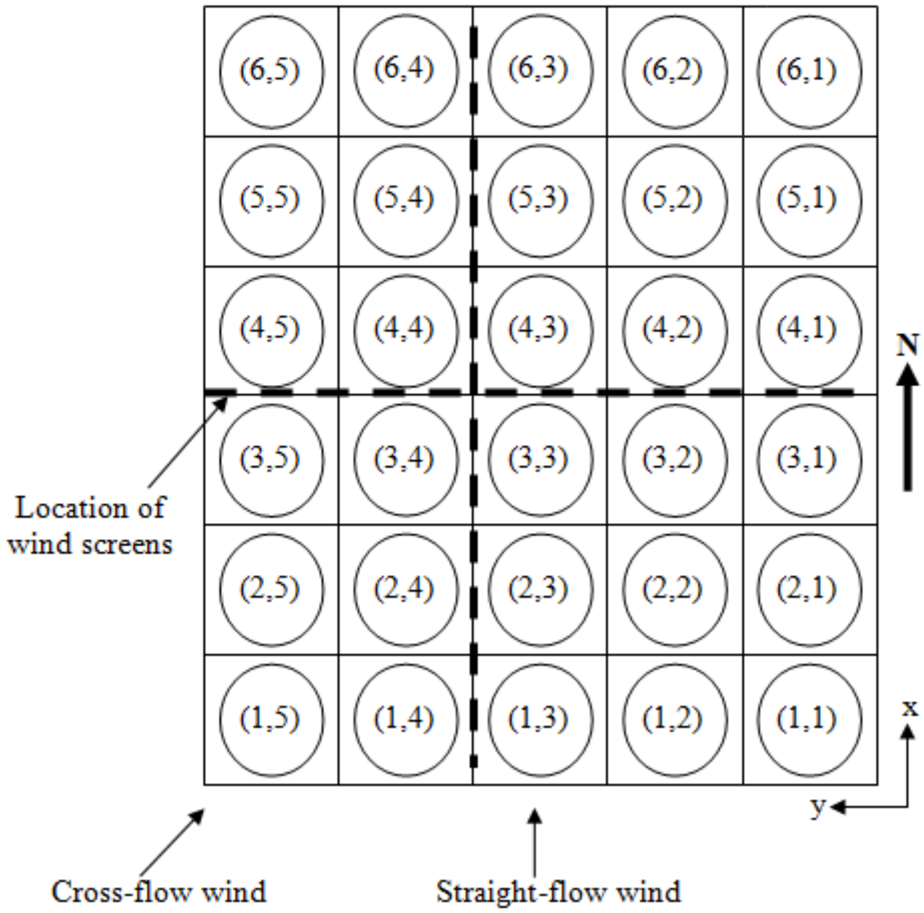


Fig. 1. ACC layout and fan numbering scheme

2. Plume recirculation

Plume recirculation occurs when hot plume air leaving the ACC heat exchangers is entrained in vortices formed from the leading edge of the ACC. The vortices form due to the presence of wind. Figure 2 illustrates the nature of such vortices formed under straight-flow conditions (see Figure 1) for a wind speed of v_w = 9 m/s at fan platform height.

The vortices expand in the downstream direction resulting in increased entrainment of the plume along the ACC wind-aligned axis. Eventually the vortex diameter grows sufficiently large to force plume air into the region from which the fans draw their air. The downstream ACC fans are located in this region of large vortex diameter and are subsequently the worst affected by plume recirculation, as illustrated in Figure 3.

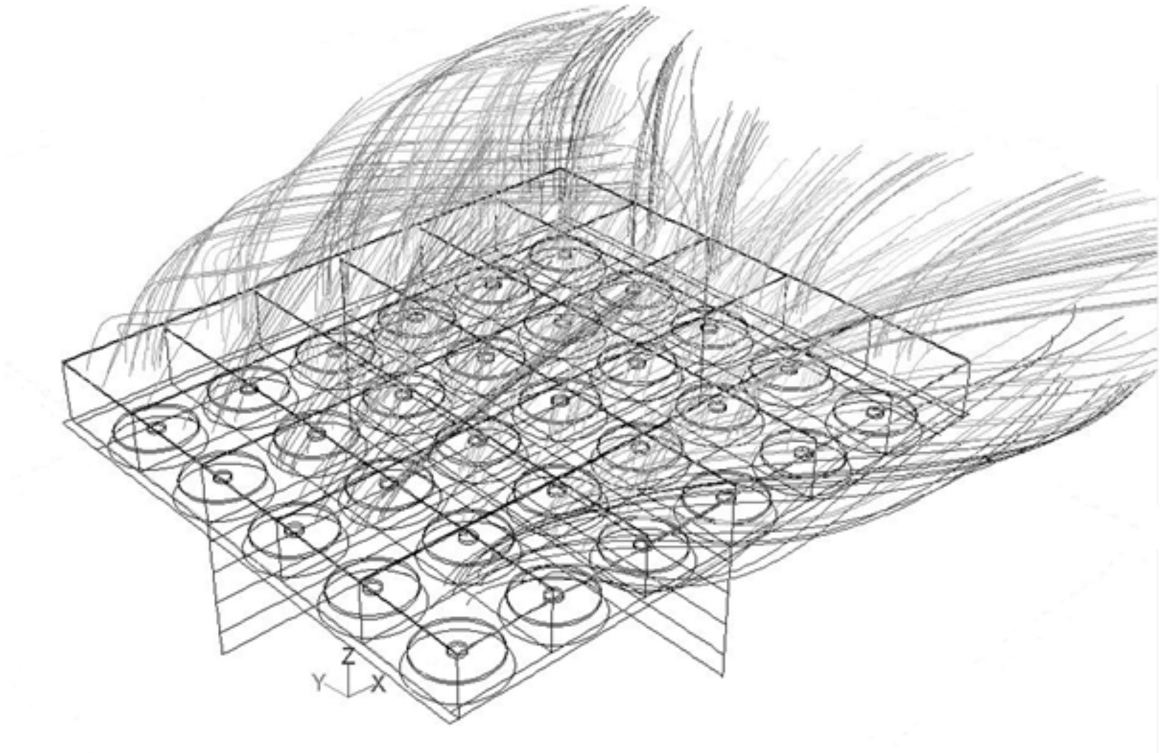


Fig. 2. Vortices formed due to the presence of a straight-flow wind of v_w = 9 m/s

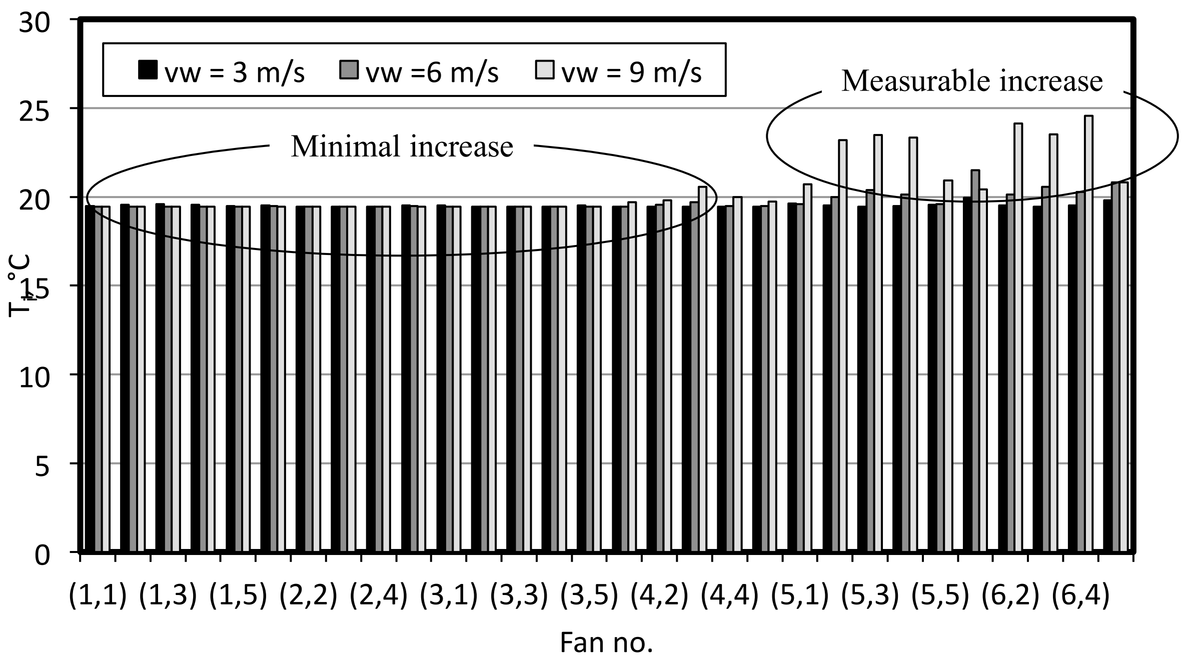


Fig. 3: Numerically predicted fan inlet temperatures under straight-flow wind conditions

Numerical results [3] indicate that the severity of the vortices, as well as the horizontal component of the plume velocity, increases with wind speed. Subsequently, recirculation increases with increasing wind speed. This relationship between wind speed and recirculation can be seen clearly in Figure 4 where the temperatures under the downwind fans are measurably higher at v_w = 9 m/s than at the lower wind speeds.

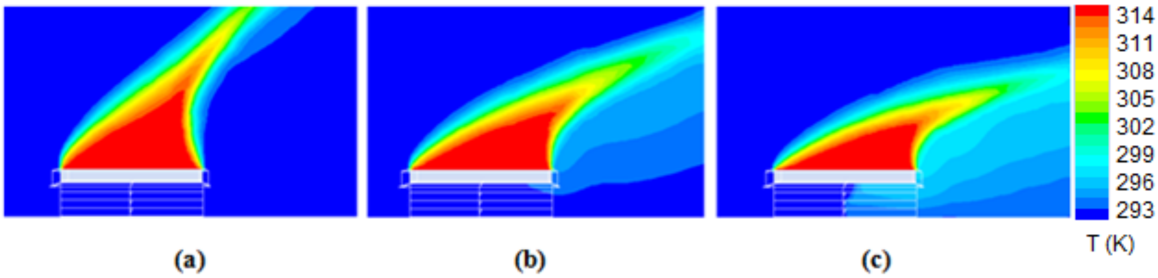


Fig. 4: Contours of temperature for straight-flow wind speeds of (a) v_w = 3 m/s, (b) v_w = 6 m/s and (c) v_w = 9 m/s on a mid-plane through the ACC

An analysis of the test data [6] also indicates an increase in the fan inlet temperature at the downwind fans associated with winds. This trend is evident in Figure 5, adapted from Maulbetsch and DiFilippo [6]. Note that in Figure 5 the ambient temperature at the higher wind speed was approximately 1.5 °C higher than at the lower wind speed. This accounts for the difference in inlet temperature at the upstream fans.

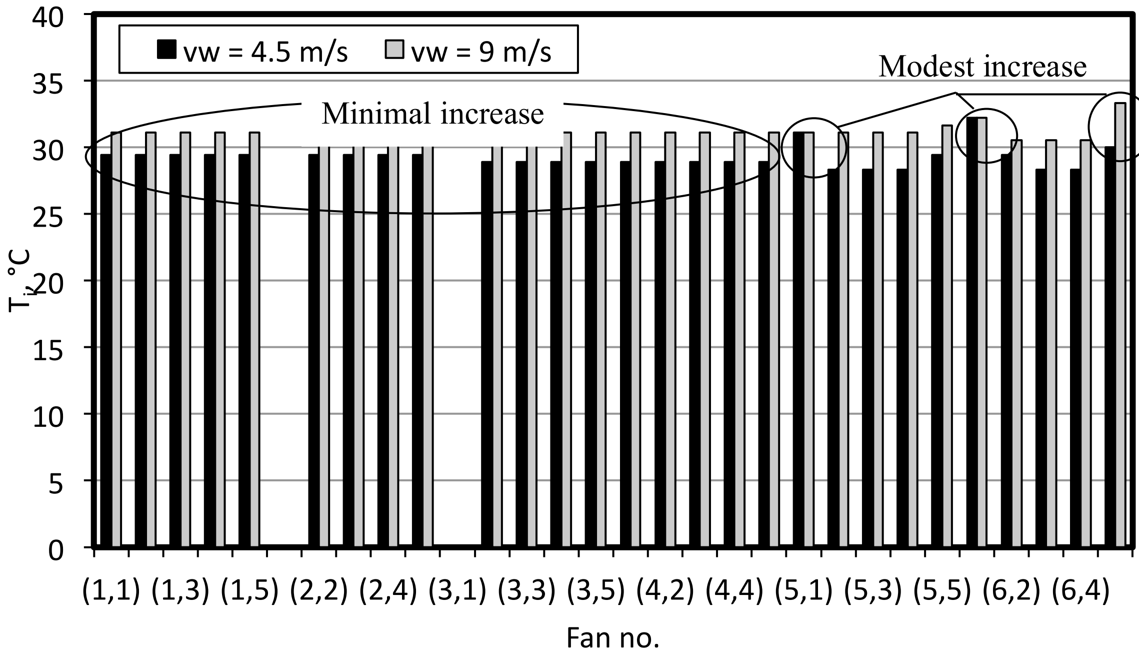
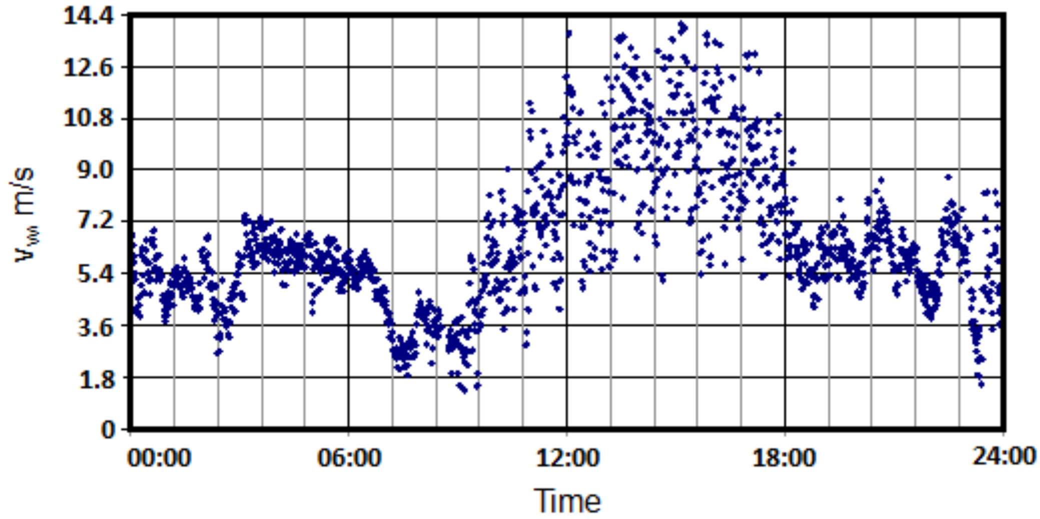


Fig. 5: Measured fan inlet temperatures under straight-flow wind conditions

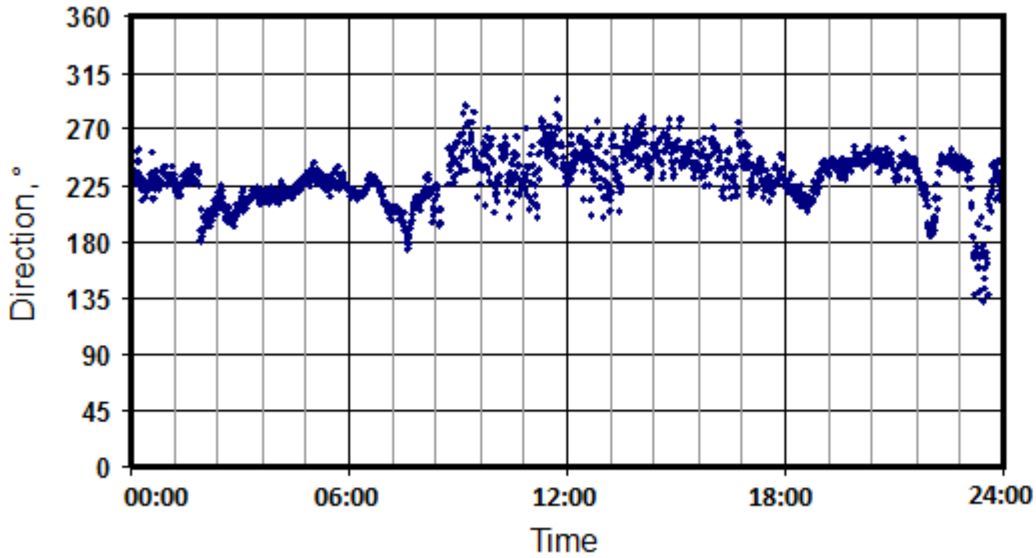
To confirm the effect of wind speed on the magnitude of recirculation, an analysis of a set of test data was conducted. The data was collected over a 24 hour period (00:00 – 24:00) on 13 September 2007. The wind speed and direction for this test period is illustrated in Figure 6. Figure 6(b) illustrates that the wind direction was largely consistent at or near 225° (South-Westerly) for the entire test period. This direction is analogous to the cross-flow wind direction in the numerical model as illustrated in Figure 1.

The effect of wind speed on fan inlet temperature determined from the test data is illustrated in Figure 7. The data appears to contradict the numerical results since it indicates that the maximum increase in fan inlet temperature above a reference temperature occurs at moderate wind speeds (3 m/s ≤ v_w ≤ 7 m/s). The fan inlet temperature increase then drops off to a lower level at higher wind speeds, although always remaining above the low-wind-speed level. Note that in Figure 7 the reference temperature is defined as the minimum temperature measured at the inlet of all the ACC fans.

Figure 7 cannot be considered in isolation however and must be considered in conjunction with Figure 6(a) where it can be seen that the moderate wind speeds, for which the difference between the inlet and ambient temperatures is a maximum, occur during the night time (18:00 – 06:00). Furthermore, the high wind speeds are isolated to the day time (12:00 – 18:00). This diurnal wind speed distribution points to the potential involvement of diurnal variations in the atmospheric temperature profile in the measured increase of the fan inlet temperatures.



(a)



(b)

Fig. 6: Wind conditions for a 24 hour period on 13 September 2007 (a) Wind speed, (b) Wind direction [6]

3. Contribution of temperature inversions

The lower portion of the atmosphere is called the atmospheric boundary layer (ABL) and is characterised by large vertical gradients in wind speed and temperature. Significant diurnal temperature variations exist near the ground in the ABL due to radiative heating and cooling of the earth's surface [13]. A typical example of these diurnal variations is illustrated schematically in Figure 8. It can be seen that at night time a temperature inversion (increasing temperature with elevation in the lower ABL) occurs due to radiative cooling of the air by the ground.

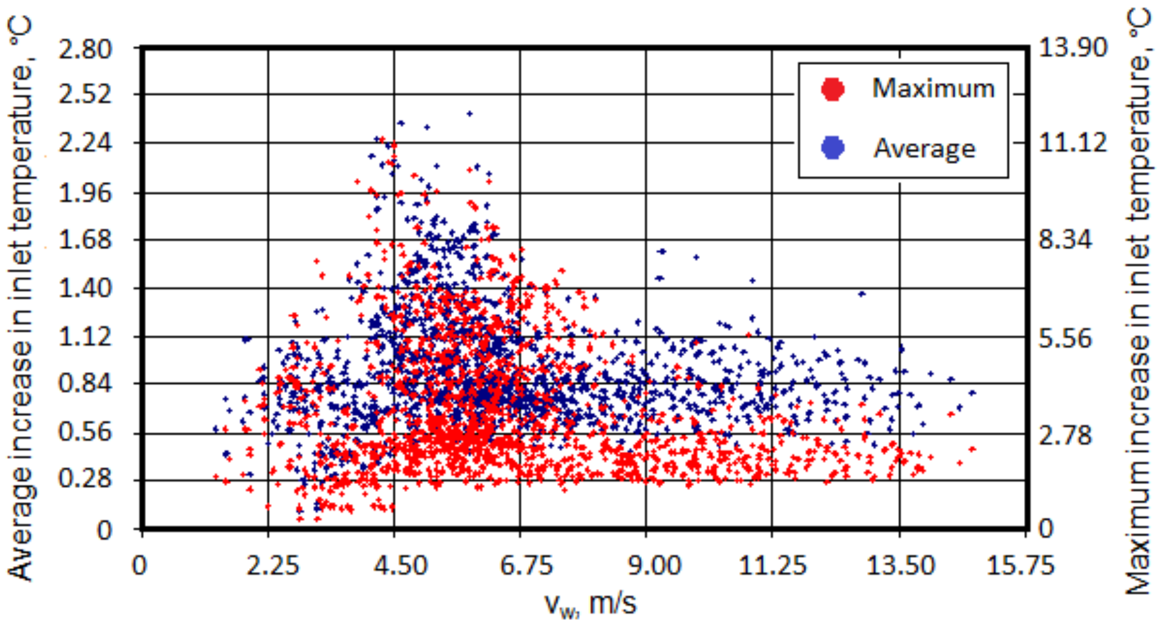


Fig. 7: Fan inlet temperature vs wind speed for a 24 hour period on 13 September 2007 [6]

These variations in atmospheric temperature distribution become important when considering the regions from which the ACC fans source their inlet air. Figure 9 illustrates the numerical prediction of the regions from which the fans draw air and the effect of wind speed on the location of these regions. At low wind speeds the upstream fans draw air from an elevation greater than fan platform height while the downstream fans draw air from near ground level. As the wind speed increases the fans begin to draw air from a more uniform elevation near the fan platform height.

The trends presented in Figure 9 indicate that at high wind speeds the effect of atmospheric temperature distributions on the measured increase in fan inlet temperature, as presented in Figure 7, is negligible since all the fans draw air from a similar mean elevation. Furthermore, the turbulence associated with high wind speeds enhances mixing in the ABL resulting in a subdued temperature distribution [13]. Golder [14] states that a wind speed in excess of v = 8 m/s will result in an adiabatic or neutral atmosphere. Any increase in fan inlet temperature at high wind speeds can therefore be attributed almost completely to plume recirculation.

At low and moderate wind speeds however, fans draw air from a wide range of elevations and as such atmospheric temperature distributions can contribute significantly to any measured increase in fan inlet temperature. Consider Figure 10 where a measured atmospheric temperature distribution is superimposed on the results of Figure 9(a). This distribution is sourced from data collected on a 96 m weather mast over a calm 24 hour period and is an example of an inversion recorded at approximately midnight [13]. In this case the conservative maximum temperature drawn into the ACC as a result of the atmospheric temperature distribution would be approximately 22 °C at fan (3,1). In contrast, the lowest temperature drawn into the ACC would be approximately 9 °C at fan (6,3). The contribution of the temperature inversion to the measured increased fan inlet temperature would therefore be 13 °C based on Maulbetsch and DiFilippo's [6] definition.

Considering the information presented in Figures 6(a), 7 and 10 together, it would appear as if a large portion of the increased fan inlet temperature in Figure 7 for moderate wind speeds could be attributed to the presence of a temperature inversion being present. If the effect of the inversion is subtracted from Figure 7 it is likely that the data would indicate an increase in the measured fan inlet temperature with wind speed, as illustrated in Figure 11. This would then be consistent with the findings from the numerical analysis of Owen and Kröger [3].

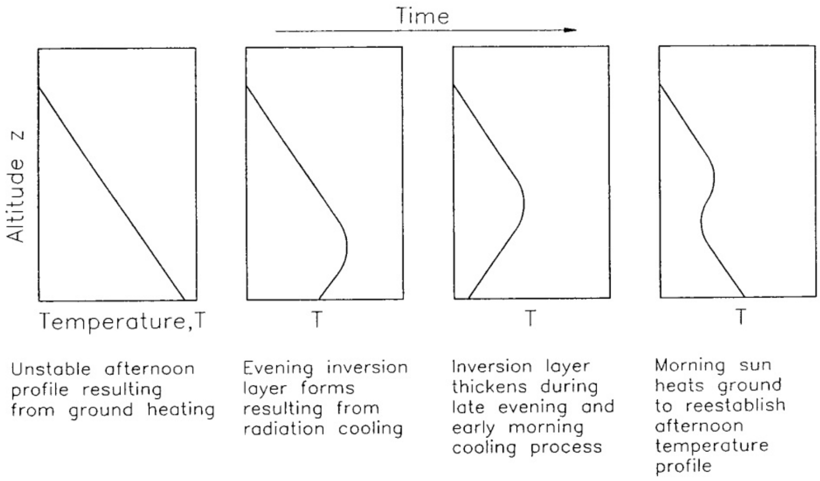


Fig. 8: Typical diurnal variation in atmospheric temperature profile [13]

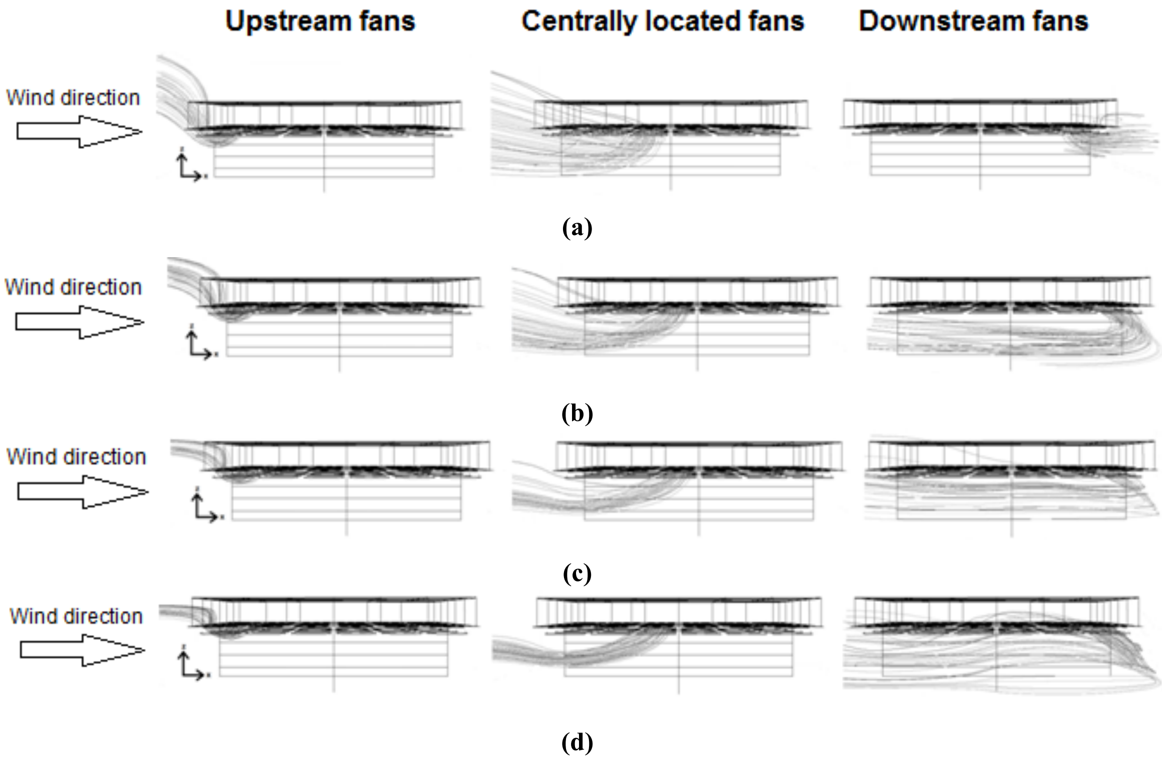


Fig. 9: Source elevation of the air for ACC fans under straight-flow winds of (a) v_w = 1 m/s, (b) v_w = 3 m/s, (c) v_w = 6 m/s, and (d) v_w = 9 m/s (pathlines leading into fans)

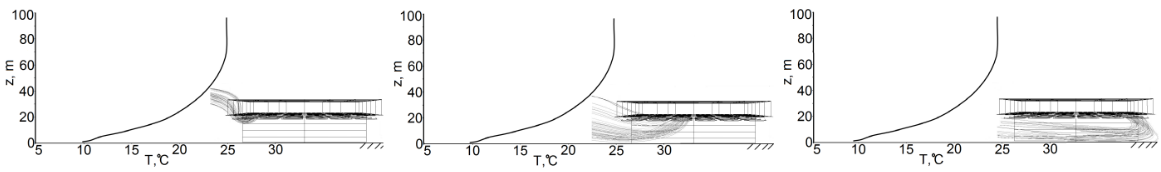


Fig. 10: Illustration of the effect of a temperature inversion on fan inlet temperature for straight-flow wind speed of v_w = 3 m/s

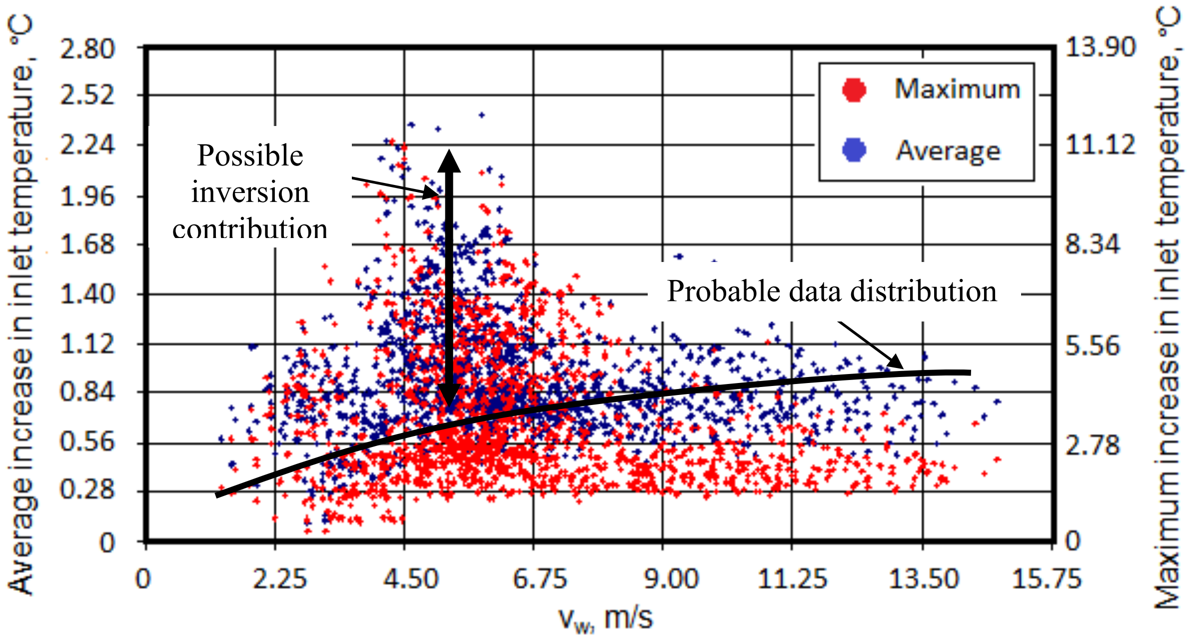


Fig. 11: Hypothesized fan inlet temperature vs wind speed if inversion effects are ignored on 13 September 2007

4. Numerical case study

In order to verify the above hypothesis a numerical case study was conducted (a detailed description of the numerical model is given in [3]). Four atmospheric temperature distributions; sourced from data that was collected at an existing ACC site (at 12:00, 17:00 18:00 and 00:00 respectively) and presented in Kröger [13]; were simulated for straight flow wind speeds of $v_w = 3$ m/s and $v_w = 6$ m/s at fan platform height. Figure 12 illustrates the temperature profiles in question. A power law profile, $T(z) = T_{ref}(z/z_{ref})^b$, is fitted through the data. In this equation T_{ref} is the ambient temperature measured at the reference elevation z_{ref}. The power law coefficients and exponents for each of the distributions are listed in Table 1.

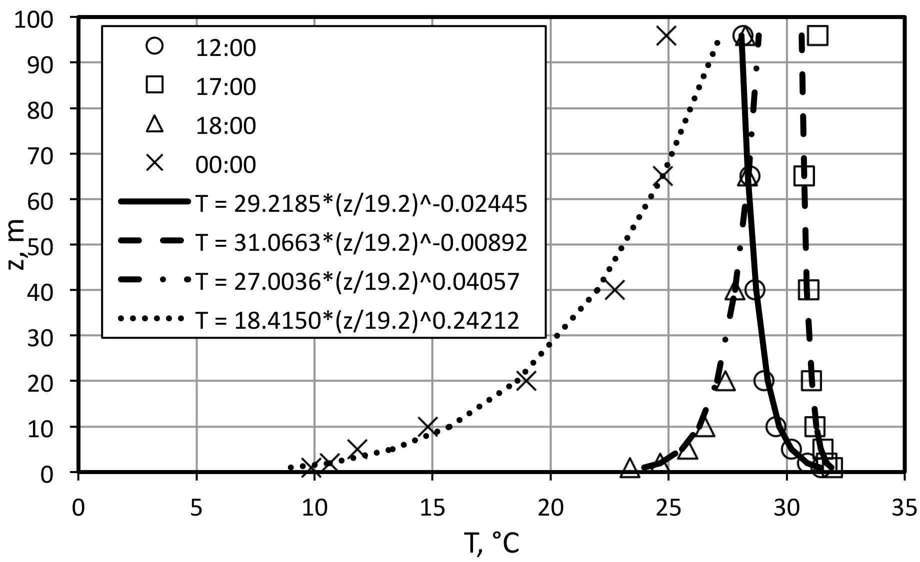


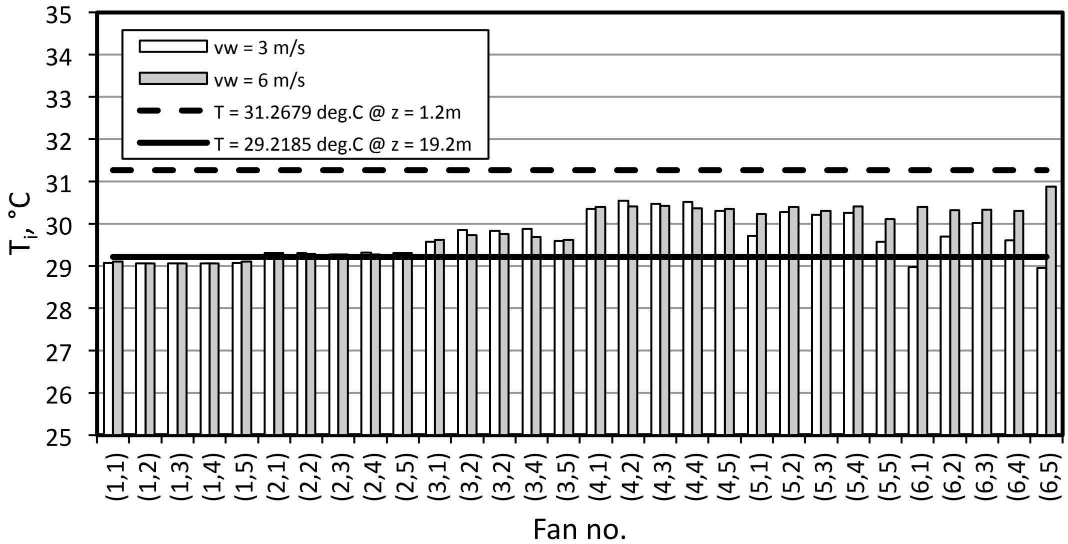
Fig. 12: Atmospheric temperature distributions

	12:00	17:00	18:00	00:00
T_{ref}, °C	29.2185	31.0663	27.0036	18.4150
b	-0.02445	-0.00892	0.4057	0.24212

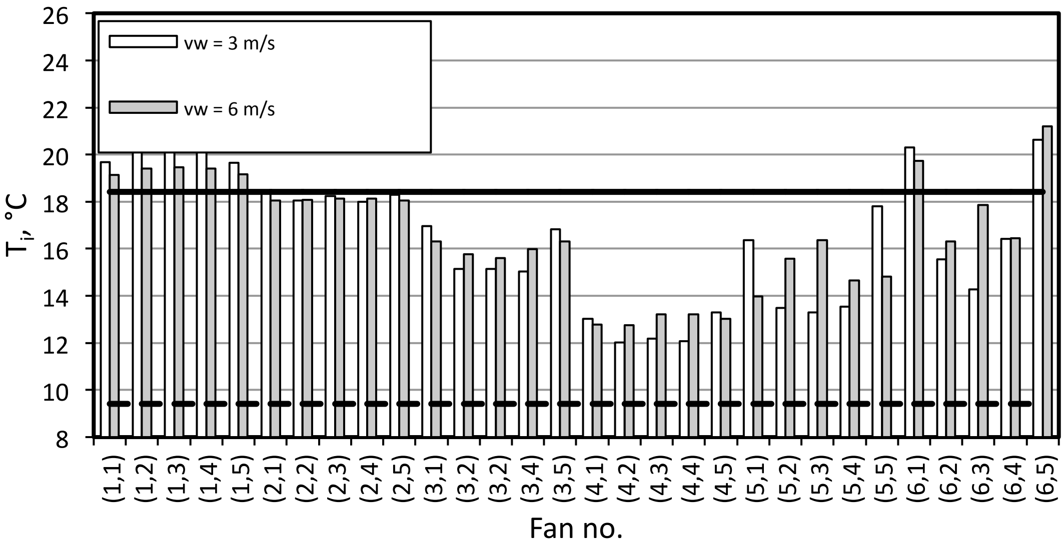
Table 1: Atmospheric temperature distribution coefficients and exponents

At 12:00 and 17:00 the atmospheric temperature distributions conform to a dry air lapse rate (DALR) type profile where the temperature decreases with increasing elevation. At 18:00 a temperature inversion has developed with the atmospheric temperature increasing with elevation. This inversion effect is more pronounced at 00:00.

The numerically predicted fan inlet temperatures for wind speeds of $v_w = 3$ m/s and $v_w = 6$ m/s associated with the 12:00 and 00:00 atmospheric temperature distributions is illustrated in Figure 13 along with the atmospheric temperature at elevations of $z = 1.2$ m and $z = 19.2$ m.



(a)



(b)

Fig. 13: Numerically predicted fan inlet temperatures at (a) 12:00 and (b) 00:00

For the DALR temperature distribution at 12:00 the inlet temperatures at the upstream fans, shown in Figure 13(a), are largely uniform and similar to the ambient temperature at fan platform height. The inlet temperatures at the downstream fans are higher than that of the upstream fans. The difference in the upstream and downstream fan inlet temperatures is greater at the higher wind speed indicating the presence of recirculation.

At 00:00 where a temperature inversion is present a measurable degree of variability exists in the fan inlet temperatures, as shown in Figure 13(b). The inlet temperatures at the upstream fans are higher than the ambient temperature at fan platform height. At the central fans the inlet temperatures are lower than at the upstream fans and tend towards the ambient temperature at z = 1.2 m. The downstream fans exhibit higher inlet temperatures than the centrally located fans and there is evidence of recirculation with higher inlet temperatures in general at the higher wind speed. Considering these results along with Figure 10 it would appear that the temperature inversion is affecting the fan inlet temperatures in this case.

The inlet temperatures illustrated in Figure 13 will be influenced by both recirculation and the potential effects of the atmospheric temperature distribution. In order to isolate the effects of each of these, a second set of simulations was carried out using a constant atmospheric temperature corresponding to that measured at fan platform height. Any increase in the fan inlet temperatures above ambient in these results can be attributed solely to recirculation. Figure 14 illustrates a comparison of the numerically predicted fan inlet temperatures for straight-flow wind speeds of v_w = 3 m/s and v_w = 6 m/s, considering both a constant atmospheric temperature as well as a temperature distribution at 12:00 and 00:00.

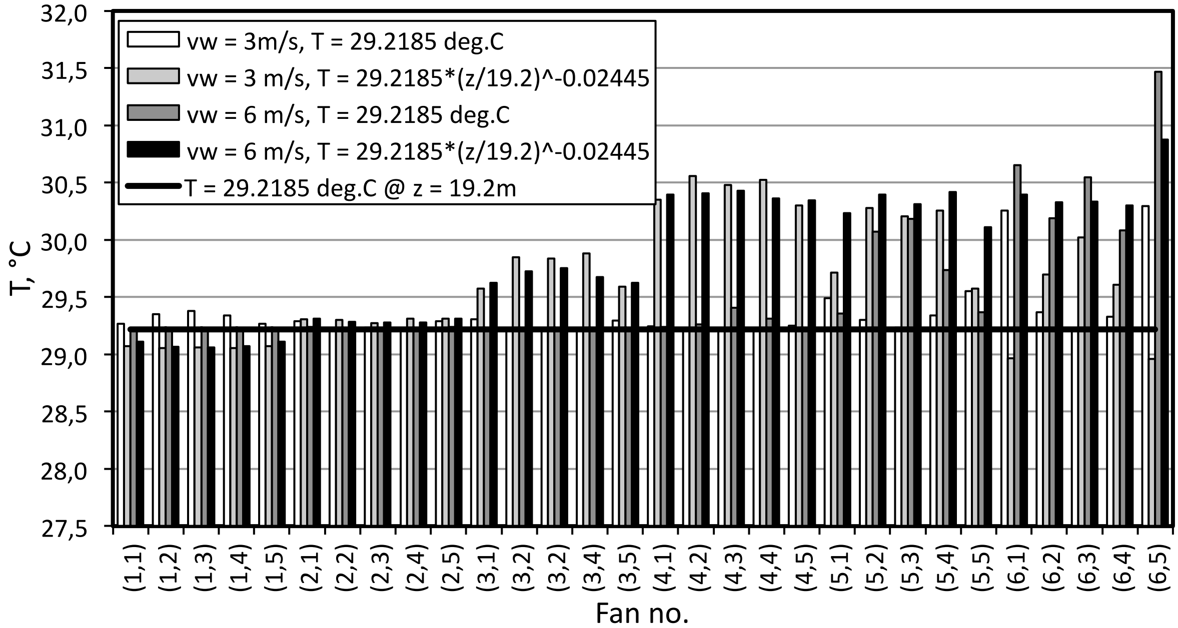
Considering Figure 14 it can be noted that any deviation in the temperature at the upstream fans from a constant reference temperature is exclusively due to the presence of an atmospheric temperature distribution. The influence of the distribution on the inlet temperature at these upstream fans is less pronounced at higher wind speeds. This is due to the convergence of the fan air source elevation with increasing wind speed as illustrated in Figure 9. Variations in the inlet temperatures at the centrally located fans can also be attributed almost solely to the presence of an atmospheric temperature distribution.

At the downstream fans, Figure 14 illustrates the influence of recirculation and the increasing severity of recirculation with increasing wind speed. In Figure 14(a), for a DALR temperature distribution, it can be seen that recirculation is the primary cause of increased inlet temperatures at the downstream fans. When an inversion is present, such as in Figure 14(b), the atmospheric temperature distribution contributes significantly to increased inlet temperatures at these fans and may be a more dominant contributor for severe inversions at low wind speeds.

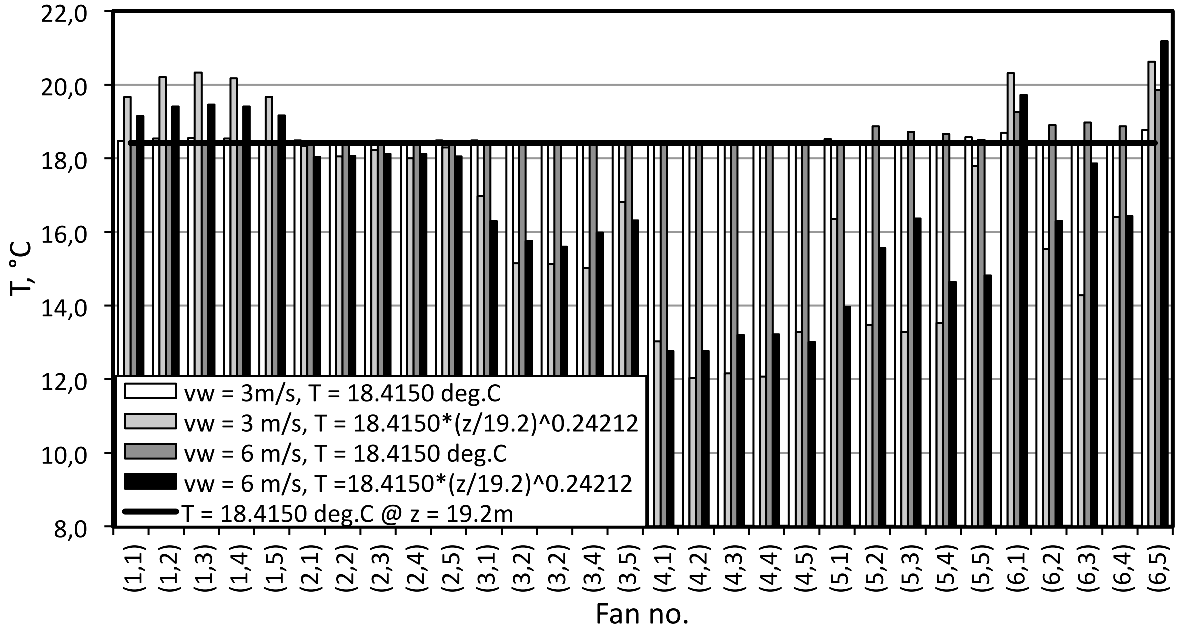
5. Recommended temperature reference elevation

Both temperature distributions and recirculation can lead to a significant deviation of the performance of the ACC from that predicted based on an assumed constant fan inlet temperature measured at some reference elevation. Such errors are unavoidable but can be reduced through the selection of an appropriate reference elevation. In industry z_{ref} = 1.2 m is commonly used while Owen and Kr□ger [3] recommend using the fan platform height as the reference elevation. In order to test the suitability of these reference elevations the ACC heat transfer rates for the four atmospheric temperature distributions, described in Table 1, were calculated based on constant fan inlet temperatures corresponding to the ambient temperature at z_{ref} = 1.2 m and z_{ref} = 19.2 m. These heat transfer rates are compared, in Figure 15, to the actual heat transfer rates calculated based on the numerically predicted fan inlet temperatures when an atmospheric temperature distribution is present.

At 12:00 and 17:00, when a DALR temperature distribution prevails, the vertical temperature gradient is relatively small. The predicted ACC heat transfer rates are therefore largely similar to the actual rate and the prediction error is nominal. Nonetheless, Figure 15 indicates that the error is slightly smaller when using the fan platform height (z_{ref} = 19.2 m) as the reference elevation as opposed to z_{ref} = 1.2 m. This can be attributed to the fact that the fans located on the leading and side edges of the ACC (18 out of the 30 fans in this case) source their air from an elevation similar to, or greater than, the fan platform height as shown in Figure 9.



(a)

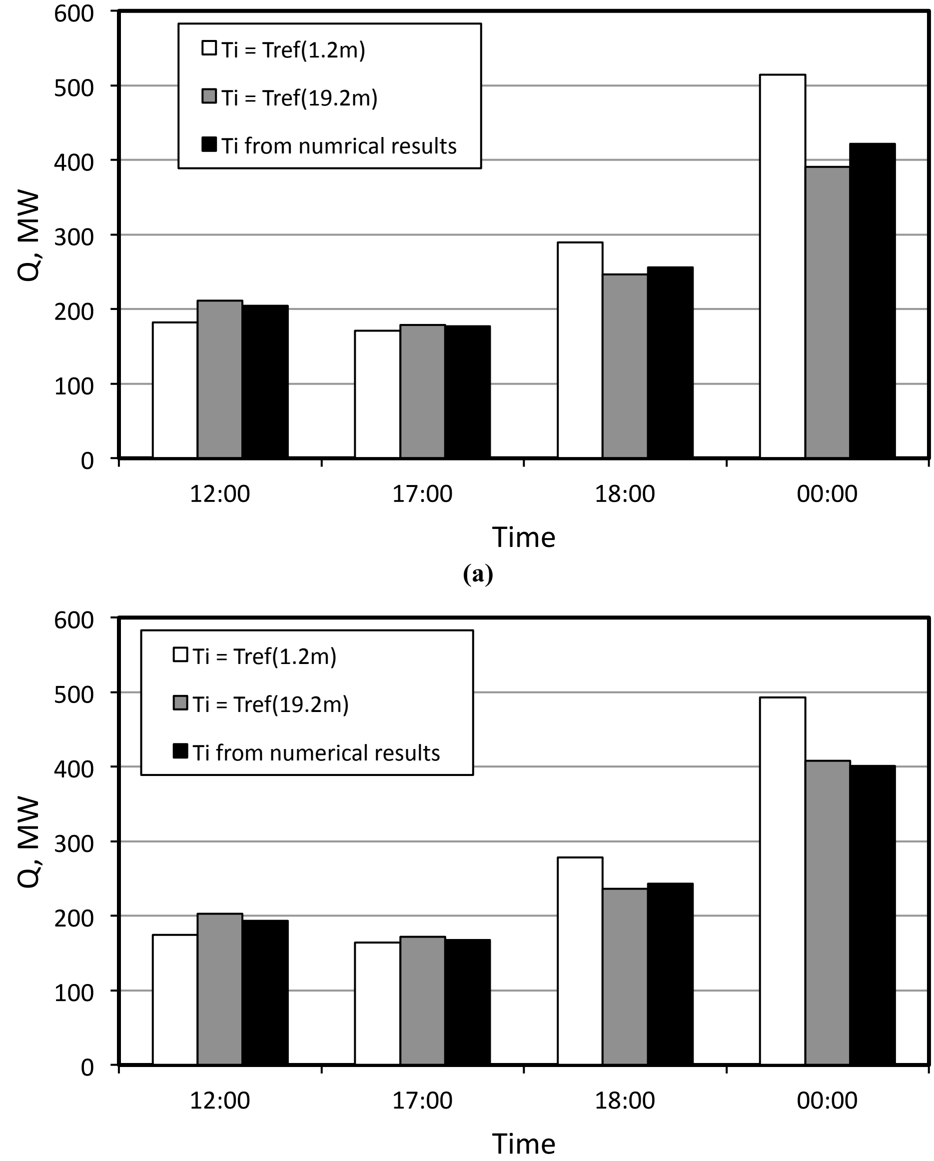


(b)

Fig. 14: Numerically predicted fan inlet temperatures at (a) 12:00 and (b) 00:00

The remaining fans draw air from an elevation ranging from approximately fan platform height to near ground level. The upper and lower limits of the source elevation converge towards the fan platform height with increasing wind speed. The heat transfer prediction based on the fan platform temperature should therefore, notwithstanding the effects of plume recirculation, improve in accuracy with increasing wind speed.

At 18:00 and 00:00, when a temperature inversion is present, it can be seen that the prediction error for $z_{ref} = 1.2$ m is considerably larger than for $z_{ref} = 19.2$ m. Similar reasoning as for 12:00 and 17:00 can be applied to describe why the fan platform height reference temperature provides a more accurate prediction. The reason for the increased magnitude of the discrepancy must lie in the nature of the atmospheric temperature distribution. Figure 12 reveals that the vertical temperature gradients at 18:00 and 00:00 are more severe than for 12:00 and 17:00. The effects of atmospheric temperature distributions on the fan inlet temperature will therefore be more pronounced for the inversion cases. While this is a specific case, it is not unusual for the vertical temperature gradients associated with periods where inversions are present to be greater than for those when a DALR profile is approached.



(a)

(b)

Fig. 15: Comparison of predicted and actual ACC heat transfer rates for straight flow wind speeds of (a) v_w = 3 m/s and (b) v_w = 6 m/s

6. Conclusion

Atmospheric temperature distributions can have a measureable effect on the ACC fan inlet temperatures and subsequently the ACC heat transfer rate. As a result, and even with no plume recirculation present, calculating the ACC performance using a single reference fan inlet temperature will result in an erroneous prediction. This temperature distribution induced error is more pronounced at lower wind speeds where ACC fan source elevation extends over a greater range. It does however appear that using a reference elevation corresponding approximately to fan platform height can provide useful results regardless of the nature of the atmospheric temperature distribution. It is therefore recommended that the fan platform height be used as the reference elevation when calculating ACC performance as opposed to z_{ref} = 1.2 m which is currently common practice.

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