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Measurements of crosswind influence on a natural draft dry cooling tower for a solar thermal power plant

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HIGHLIGHTS

- A 20 m experimental cooling tower was tested in different crosswind conditions.
- Air temperature distributions and heat exchanger performances are presented.
- The mechanism of the crosswind effect on small cooling tower is discussed.
- Crosswind effect on a small CST power plant is evaluated.

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ABSTRACT

Crosswind is a significant concern for natural draft dry cooling towers. The concern is more serious for shorter towers. Therefore, the crosswind influence is a significant threat to the use of natural draft dry cooling towers in concentrating solar thermal power plants, which are generally built at sizes smaller than conventional fossil-fired plants and employ relatively shorter towers. While some numerical studies and small lab-scale test reports exist, very few full scale experimental studies have been reported for conventional cooling towers and none for relatively short cooling towers suitable for renewable thermal power plants. To address this gap, a 20-m tall fully instrumented natural draft dry cooling tower was built by the University of Queensland. The tower was designed to serve a future 1-MWe concentrating solar thermal plant on the same site. Its performance was tested under different ambient temperatures and crosswind speeds. The detailed experimental data of the crosswind condition, air temperature distribution inside and outside of the cooling tower and the cooling performance are presented. The experimental data demonstrate the substantial yet complex impact of the crosswind on cooling tower performance. Significant non-uniformities in air and hot water temperature distributions and strong air vortices inside the tower were observed in high crosswind speeds. Unlike tall cooling towers used in large conventional plants, the cooling tower performance does not monotonously decrease with the increase of the crosswind speed. In fact, after the tower performance drops to its lowest level at a wind speed around 5 m/s, the trend is reversed and further increases in the crosswind speed help the tower performance. Analysis shows that this reversal occurs because the tower heat transfer mechanism changes. As crosswind rises above the critical speed, the airflow inside the cooling tower becomes increasingly controlled by the crosswind instead of the natural draft.

1. Introduction

The typically arid climates in the likely locations for renewable thermal power plants such as Concentrating Solar Thermal (CST) provide the motivation for dry cooling technology optimized for renewable power generation [1–4]. Due to their low maintenance cost and simple structures, natural draft dry cooling towers (NDDCT) offer a feasible and cost effective option for such applications [5–8]. In a NDDCT, air acts as the cooling medium. The density difference between the hot air inside the tower and the outside ambient air creates the driving force. This driving force makes the outside ambient air move in and pass through the heat exchanger bundles, cooling the tubes inside which the hot fluid flows.

The combination of Australia's dry climate and latitude potentially favours solar energy. The Australian Solar Thermal Research Initiative (ASTRI), which has funded the research described in this paper, is

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Nomenclature

A	area (m^2)
d	diameter (m)
h	heat transfer ($W\,m^{-2}\,K^{-1}$)
H	height, elevation (m)
K	flow resistance
L	length (m)
m	mass flow rate (kg/s)
n	number
P	pressure (Pa)
Pr	Prandtl number
Q	heat transfer rate (W)
q	heat flux ($W\,m^{-2}$)
Re	Reynolds number
T	temperature (°C)
v	velocity scalar (m/s)

Greek letters

ρ	density, mean density ($kg\,m^{-3}$)
μ	viscosity ($kg\,m^{-1}\,s^{-1}$)

Subscripts

a, w	air side, water side
cw	crosswind
i, o	inside or inlet, outside or outlet
t	tube
ref	reference

targeting small supercritical CO_2 (sCO_2) CST power systems (1–25 MWe) for off-grid and fringe-of-grid applications in the of Australian outback. As part of the project, the authors' research group is investigating short NDDCTs for this relatively small CST power plant size.

For such short towers, we expect the crosswind to have a strong influence on the tower performance. Even for tall towers used in conventional thermal power generation, crosswind is recognised as one of the biggest challenges to the performance of NDDCT. Kroger et al. [9,10] summarized how the performance of several industrial cooling towers suffered under windy conditions. The cooling performance was reported to be monotonously decrease with the increasing crosswind speed. Bender et al. [11,12] investigated the wind effects on the air intake flow rate of a cooling tower, using both a numerical model and wind tunnel tests. They also proposed that the wind wall can be used to control the intake flow rate. Su et al. [13] simulated the fluid flow and thermal performance of a dry cooling tower under crosswind conditions. They proposed the possible reasons for the reduction of cooling tower heat diffusion under crosswind conditions as the low-pressure effect at the side of the cooling tower, the formation of the air vortex inside the cooling tower and wind-cover effect at the top of the cooling tower. Wei et al. [14] presented the experimental data of a 125 m NDDCT at the crosswind speed of 6 m/s. Their results indicate the wind reducing the efficiency of the dry cooling tower and increasing the average temperature of the heat exchanger by 5 °C. Al-Waked [15,16] discussed crosswind effects on the performance of both dry and wet towers and found the thermal effectiveness of the cooling towers decrease by more than 30% at crosswind speeds above 10 m/s. Yang et al. [17–20] discussed the dimensional characteristics of wind effects on the performance of an indirect dry cooling system with both vertically and horizontally arranged heat exchanger bundles. The detailed temperature contours of the heat exchangers and the coupled condenser temperature were presented. Zhao et al. [21–23] simulated the changes of cooling performance of a dry cooling tower with vertical two-pass column exchangers under crosswind. They observed water outlet temperatures increasing by 6 °C at a crosswind speed of 12 m/s.

A number of solutions have been proposed to mitigate against the negative crosswind effects on performance of natural draft cooling tower. In the early research, Kroger et al. [10] investigated the arrangement of the heat exchanger and the design of the windbreak wall. According to their result, the A-frame and radially patterned heat exchanger layout could reduce the negative effect of the crosswind. Zhai and Fu [24] tested the performance of the windbreak wall in and around a small scaled cooling tower in the wind tunnel. The relationship between the cooling efficiency recovery and the size of windbreak walls was analysed. Lu et al. [25,26] numerically studied the performance of a tri-blade like windbreak wall for a 15 m cooling tower. The numerical model was validated against tests on a small lab-scale modelling test. They found the windbreak walls enhancing the performance of the cooling tower at certain wind speeds. Ma et al. [27,28] studied the angles of the windbreak wall for a NDDCT with vertical heat exchanger. Their research found that the optimized walls can reduce the interference on airflow at low wind speeds and create a strong secondary flow at high wind speeds. Yang et al. [29] proposed a novel bilaterally arranged air-cooled heat exchanger configuration. They found the performance of the cooling tower being enhanced by this arrangement. Wang et al. [30,31] investigated an enclosure approach to improve the cooling tower efficiency in wind. Their results showed the enclosure greatly improving the mass flow of the air inside the tower. Sun et al. [23] studied the thermal performance of the NDDCT and NDWCT with inlet airflow guiding channels under crosswind conditions. According to the results, the mass flow rate of the air stream greatly increased by applying this method. Li et al. [32] proposed the waterside optimization method to enhance the cooling performance. By applying this method, the performance of the cooling tower was found to improve by up to 18.5%, the degree of improvement varying with the wind speed.

There are convincing evidences in the past literatures on the significance of the crosswind effect on NDDCT performance. The experimental study of the off-design performance of the cooling tower is a very important preparation for the future design and operation [33–35]. However, most of previous full scale experimental studies of the crosswind effect didn't provide enough details, such as the detailed experimental data of wind direction, changes in ambient temperature, detailed heat exchanger temperature and the air temperature distribution within the cooling tower [9,14,36–38]. On the other hand, the experiments on lab-scale cooling tower models can offer controlled conditions and reliable data, but most of the Reynolds numbers for such small towers are much lower than those for full scale towers, which may result in erroneous results [9,11,24,25,39]. In addition, most of the lab-scale cooling towers used electrical heaters or mechanical fans to simulate the air-cooled heat exchanger in the test model, which could also make the outcomes inaccurate.

This paper reports on the results obtained on a 20-m NDDCT. This tower was built on the Gatton campus of the University of Queensland in anticipation of a future 1 MWe CST power plant using a sCO_2 Brayton cycle to be built next to it. It is a tower expressly built for research purposes and is equipped with a comprehensive instrumentation system. Its performance was tested under different ambient conditions. Detailed experimental data of the wind speed, wind direction, heat exchanger performance, and the air temperature distribution inside the cooling tower are presented in this paper. Based on the experimental data, the previous CFD modelling of the same cooling tower is validated. The crosswind effect on the overall performance of this small cooling tower as well as the crosswind effect on the power system is shown and the mechanism is discussed below.