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The influence of windbreak wall orientation on the cooling performance of small natural draft dry cooling towers

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ABSTRACT

While crosswind has a negative influence on natural draft dry cooling towers (NDDCTs) of all sizes, the influence may be fatal for short towers (height < 30 m) proposed for geothermal or solar thermal power plants. In a previous paper, the authors demonstrated the potential for tri-blade-like windbreak walls not to only maintain but significantly improve the short tower cooling performance. The effect of crosswind attack angle (windbreak walls orientation) was not examined in that paper. The present paper investigates that effect for a 15 m-high small-size NDDCT with horizontally-arranged heat exchangers. 3D CFD models with different wind attack angles (0°, 10°, 20°, 30°, 40°, 50°, and 60°) are set up and computed at different crosswind speeds. The results indicate that the way the cooling tower performance varies with the crosswind speed is highly sensitive to the wind attack angles. At attack angles of 0° and 60° the cooling performance is improved by windbreaks over the entire crosswind speed range investigated. Other attack angles lead to unfavourable effects at certain wind speeds. The differences are related to the turbulent airflow field in the tower bottom. The results suggest that the tri-blade-like windbreaks placements always with one symmetry axis alignment with the dominant crosswind direction. The findings could be used to determine the windbreak installation angles with respect to the most frequent direction(s) of the ambient wind in a given district.

1. Introduction

Thermal power plants based on Rankine cycles, no matter what heat sources they use, produce nearly 90% of electric power in today's world [1]. In these power plants, the redundant heat needs to be removed through condensers or heat exchangers [2], which usually work with cooling towers of various types. Natural draft dry cooling towers (NDDCTs) feature no water loss and no parasitic power consumption and therefore are widely used in thermal power plants in arid areas around the world [3]. Geothermal and solar-thermal power plants, two types of renewable thermal power plants, are more likely to be located in arid areas. The Queensland Geothermal Energy Centre of Excellence (QGECE) has been developing small-scale geothermal and solar thermal power plants with net power generation up to a few megawatts for remote Australian communities [4]. The NDDCTs proposed for these plants are considerably shorter than towers designed for conventional fossil-fired or nuclear power plants. One proposed NDDCT for a 100 kW geothermal power plant is a 15-m tall cylindrical steel tower with a diameter of 12 m [5]. This tower is equipped with horizontally arranged finned-tube heat exchangers and has a heat rejection capacity around 578 kW at the free convection air speed of less than 0.5 m/s (i.e. the mean velocity of the hot air rising in the tower in still ambient air), predicted by the 1D model developed by the authors.

While crosswind is not considered in the traditional design fundamentals of NDDCTs [6], its effects on the cooling performance of conventional towers have been widely investigated experimentally as well as numerically (CFD) in recent decades [7–15]. These studies reported that crosswind had a negative influence on the NDDCTs with either horizontally or vertically arranged heat exchanger bundles; for example, the approach temperature increases by 4–7 °C [8,11] or the heat rejection rate decreases by 25–34% [7,10,15] when the crosswind speed is 10 m/s.

Methods of mitigating the crosswind effect have been proposed using windbreak walls or wind shells. A cross-shape windbreak wall installed underneath the horizontally arranged heat exchangers in a 165 m-high NDDCT was proposed and investigated by Du Preez and Kröger [16,17]. The wall was porous and as high as the tower inlet and was able to decrease the approach by up to 8 °C

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Nomenclature

A	area (m^2)
A_a, A_{fr}, A_r	air-side area, front area and fin-root area of heat exchangers, respectively (m^2)
A_c	surface area of numerical cell (m^2)
a	constant
C	inertial resistance factor
c_p	specific heat (J kg^{-1} K^{-1})
d_r	outer diameter of finned tube (m)
F	source term for momentum equations
F_T	temperature correction factor
H	height, elevation (m)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
G_k, G_{kb}	generation term of k due to mean velocity gradients and buoyancy, respectively
G_ω, $G_{\omega b}$	generation term of ω due to mean velocity gradients and buoyancy, respectively
K_r	pressure loss coefficient
K, K_e, K_t	laminar, effective, and turbulent thermal conductivity, respectively (W m^{-1} K^{-1})
k	turbulent kinetic energy (m^2 s^{-2})
m	mass flow rate (kg s^{-1})
n	iteration number in CFD calculation
P	pressure (Pa)
Pr, Pr_t	laminar and turbulent Prandtl number, respectively
p_t, p_d	fin pitch and tube diagonal pitch, respectively (m)
Q	heat transfer rate (W)
q	heat flux (W m^{-2})
Re_t	turbulence Reynolds number
S	modulus of the mean rate-of-strain tensor
S_ϕ	volumetric source term for variable quantity ϕ
T	temperature (K)
ΔT_{lm}	logarithmic mean temperature difference (K)
U, V, W	velocity components in x-, y-, and z-direction (m s^{-1})
V_c	numerical cell volume (m^3)
v	velocity scalar (m s^{-1})
x, y, z	Cartesian co-ordinates

Greek letters

α, α^*	constants in generation terms of ω
β	bulk thermal expansion coefficient (K^{-1})
Γ_ϕ	diffusion coefficient for variable quantity ϕ
γ^*, γ	constants in dissipation terms of k and ω, respectively
δ	velocity ratio
μ, μ_e, μ_t	laminar, effective, and turbulent viscosity, respectively (kg m^{-1} s^{-1})
ρ, $\bar{\rho}$	density and mean density (kg m^{-3})
σ_k, σ_ω	turbulent Prandtl number for k and ω, respectively
σ_ρ	constant in generation terms of k
ϕ	scalar quantity (u, v, w, T, k, ε...)
φ	permeability (m^2)
ω	turbulence energy specific dissipation rate (s^{-1})

Vectors

$\vec{v}$	velocity

Subscripts

a, l	air side, liquid (water) side
cw	cross wind
e	effective
hx	heat exchanger
i, o	inside or inlet and outside or outlet
r	radiator
t	tower
u	overall
0, ref	reference value

at wind speeds below 18 m/s. This conclusion was verified by Al-Waked et al. [18], who numerically studied the effect of this type of windbreak wall on the thermal performance of NDDCT and they further reported that either porous walls or solid walls have similar favourable effects on cooling tower. Chen et al. [19] ran experiments on a scaled wet cooling tower model installed with the same windbreak walls and found that improvement in the cooling performance of the tower due to windbreak walls depended on the setting angles of the walls. Alternative wind shells on the periphery of the tower base were investigated by Wang et al. [20] using a scaled model tower in the laboratory. They found that the air flow rate and the cooling efficiency increased remarkably after the inlet air was directed by the wind shells with various installation angles. Zhai et al. [15] proposed a similar but much simpler version of outer shells—the placement of two walls at two opposite lateral sides of towers, which was found to improve the cooling efficiency by about 50% by hindering the cross-airflow and forcing the air flowing into the towers.

All these past studies focused on natural draft cooling towers or their prototypes with heights usually over 100 m under crosswind speeds up to 20 m/s. Compared to these tall towers employed in conventional power plants, the effect of crosswind on the cooling performance of short towers is much more complicated since small towers are more sensitive to the ambient conditions. The reason is related to the relative magnitude of the crosswind with the natural air flow through the heat exchanger for a particular tower, which can be defined by a ratio of the crosswind speed to the free convection air speed—the velocity ratio δ [9] as Eq. (1)

$$\delta = \frac{v_{cw}}{v_{ao}} \tag{1}$$

where v_{cw} is the crosswind speed at the tower height and v_{ao} stands for the net upward air speed inside the cooling tower.

Since tall towers provide high air draft speeds, the velocity ratios were generally limited to below 10 in these past studies, while for shorter towers, δ can easily exceed 10. In a previous study, the present authors considered crosswind effects on a short NDDCT at velocity ratios up to 47 (corresponding to a wind speed of 18 m/s) [21]. They found that the heat rejection performance of the short tower kept declining along with the increasing of the velocity ratio until reaching the maximum reduction of 37% at the velocity ratio of around 13, which corresponded to an actual crosswind speed of 5 m/s, only a slightly annoying speed on most large NDDCTs [21]. It was proposed that, by introducing tri-blade-like windbreak walls in small NDDCTs, the negative effect of the crosswind in a wide range of velocity ratios (up to 40) could be effectively converted into a significant performance boost. But that paper did not consider the performance differences of the windbreak walls when the crosswind approached in different angles.

Therefore in this follow-up study, investigations are made on the effects of the wind attack angles on the cooling tower performance. 3D CFD models with different wind attack angles are built and computed at different crosswind speeds. The variation of the heat transfer rates of the heat exchanger are examined and explained by considering the vortices in the airflow. The results provide further assistance to designers who need to design