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Research Paper

Experimental investigation into the positive effects of a tri-blade-like windbreak wall on small size natural draft dry cooling towers

Yuanshen Lu [a,b,*], Zhiqiang Guan [a,b], Hal Gurgenci [a,b], Abdullah Alkhedhair [a,b], Suoying He [c]

[a] *Queensland Geothermal Energy Centre of Excellence, Qld 4072, Australia*
[b] *School of Mechanical and Mining Engineering, The University of Queensland, Qld 4072, Australia*
[c] *School of Energy and Power Engineering, Shandong University, Jinan 250061, China*

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ABSTRACT

Cooling efficiency of heat exchangers in conventional large natural draft dry cooling towers (NDDCTs) is often affected by crosswind. In our previous work, it was verified that the crosswind influence is more significant on short NDDCTs (height <30 m) with horizontal heat exchangers than on large towers at a same wind speed. A new tri-blade-like windbreak has been proposed in the tower base to improve the cooling performance. In this paper, a following-up experimental study on a 1:12.5 scaled NDDCT equipped with a novel round heat exchanger model is reported. Instrument measurements were made on the air temperatures and velocities as well as the heat rejection rates on the scaled cooling tower model with and without the windbreak wall, and the influences of three wind attack angles (0°, 30°, and 60°) with respect to the windbreak wall were particularly investigated. The overall heat transfer performance of the cooling tower was found sensitive to the attack angles. The study verified that the cooling performance is improved most if the tri-blade-like windbreaks placed in the attack angle of 0°. The experiment results qualitatively agreed with the predictions of the two 3D CFD models, the 15 m-tall prototype and the 1.2 m-tall tower model.

1. Introduction

Any renewable thermal power plants operated by thermal power cycles require cooling facilities for the necessary redundant heat removal in order to maintain their power conversion efficiencies. Geothermal and concentrated solar thermal power plants are two examples of such case. As country rich in solar and geothermal resources, Australia has great interests in seeking advanced technologies for both renewable energies. Potential commercialization of the technologies in Australia prefers distributed small- to medium-scale applications with net capacities from hundreds of kilowatts to a few dozens of megawatts electricity. These power plants will be deployed in remote towns which are scattered in the arid Australia outback, so that the power is supplied locally. While the option of distributed renewable power plants has many advantages, one of the challenges is that the plants require proper and efficient cooling facilities on matching scales. Natural draft dry cooling towers (NDDCTs) with considerably small sizes are considered most cost-effective for such demands [1]. In recent few years, Queensland Geothermal Energy Centre of Excellence (QGECE) has intensively studied small NDDCTs with the heights less than 30 m. The Centre proposed that for such a small size, cooling towers can be pre-fabricated in parts in factories and assembled on sites. As a result, a 20 m-tall steel-polymer pilot NDDCT has been built by QGECE in 2015 [2], registering itself as the world's first experimental cooling tower in its scale.

In NDDCTs, the condensers/heat exchangers are cooled by air. The hot air is less dense and thus lifted by buoyancy. The cooling tower shell forces the hot air to flow upward only, so that a continuous and stable airflow passing through the heat exchanger forms. This working principle implies that the cooling performance of NDDCTs can be heavily influenced by environmental crosswind. A number of researches have been done on the crosswind effect in natural draft cooling towers with either horizontally- or vertically-arranged heat exchanger bundles through numerical and experimental methods, reporting that crosswind reduces the heat rejection rate of the towers [3–11]. Crosswind creates cold inflow at top of any types of tower [12] and disturbs the airflow by adding negative suction effect in tower bottom if horizontal heat exchanger bundles are used. On small cooling towers, the latter is more significant [13].

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[*] Corresponding author at: School of Mechanical and Mining Engineering, The University of Queensland, Qld 4072, Australia.

E-mail address: y.lu7@uq.edu.au (Y. Lu).

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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)
C	discharge coefficient
c_p	specific heat (J kg^{-1} K^{-1})
D	tower diameter (m)
d, d_o, d_f	diameter, tube diameter, and fin diameter, respectively (m)
Eu	Euler number
F	source term for momentum equations
Fr, Fr_D	Froude number and densimetric Froude number, respectively
Gr	Grashof number
H	height, elevation (m)
H_i	tower inlet (base) height (m)
h_r	convective heat transfer coefficient of heat exchanger (W m^{-2} K^{-1})
I	turbulence intensity
K, K_h, K_m	pressure loss coefficient
k	thermal conductivity (W m^{-1} K^{-1})
L_t	tube length (m)
m_a	air mass flow rate (kg s^{-1})
Nu	Nusselt number
n	exponent
P, ΔP_a	pressure and pressure loss (Pa)
Pr	Prandtl number
p_f, p_t	fin pitch and tube pitch, respectively (m)
Q, Q_N	heat transfer rate and heat transfer rate without crosswind, respectively (W)
q_r	heat flux of heat exchanger (W m^{-2})
R	gas constant (J kg^{-1} K^{-1})
Re	Reynolds number
S	modulus of the mean rate-of-strain tensor
S_ϕ	volumetric source term for variable quantity ϕ
T, T_0	temperature, ambient air temperature (K)
T_a, T_a^*	mean air temperature at a certain level (K), and dimensionless temperature
T_{aN}	outlet air temperature without crosswind (K)
T_{avg}, T_r	average air temperature and heater surface temperature, respectively (K)
ΔT_a	air temperature difference (K)
t_f	fin thickness (m)
U, V, W	velocity components in x-, y-, and z-direction (m/s)
V_c	numerical cell volume (m^3)
v	velocity scalar (m/s)
v_a, v_{aN}, v_{cw}	air velocity with crosswind and without crosswind, and crosswind speed (m/s)
x, y, z	Cartesian co-ordinates

Greek letters

α	permeability (m^2)
β	bulk thermal expansion coefficient (K^{-1})
μ	viscosity (kg m^{-1} s^{-1})
ρ, ρ_0	air density and ambient air density (kg m^{-3})

Vectors

$\boldsymbol{V}$	velocity

Subscripts

a	air
cw	cross wind
hx	heat exchanger
i, o	inside or inlet and outside or outlet
m, p	model and prototype
N	pure natural convection
r	radiator or heater
t	tower or tube
0	reference value

To improve cooling tower performance under windy conditions, most methods aim at limiting the crosswind in tower bottoms by introducing wind obstructions. A windbreak wall is an effective example of such obstructions to prevent unfavorable horizontal wind from passing directly through the tower base. Du Preez and Kröger [14,15] had proposed a type of windbreak with two crossed walls installed underneath the horizontal heat exchanger bundles in a 165 m-tall NDDCT. The wall was porous and as tall as the tower inlet and was able to decrease the Approach by up to 8 °C at wind speeds below 18 m/s. This type of windbreak wall was further studied by Al-Waked et al. [16] using a numerical method, and it was found that both the porous wall and the solid wall similarly improved the cooling tower performance. An experiment on a scaled wet cooling tower model with the same type windbreak wall had been run by Chen et al. [17]. Other versions of wind-obstruction have been proposed. Wind shells or deflectors on the periphery of a tower base were investigated by Wang et al. [18] and Zhao et al. [19]. Alternatively, two simple solid walls or radiator-type windbreakers at two opposite lateral sides of towers were investigated by Zhai et al. [11] and Goodarzi et al. [20], respectively.

However, the studies above were all focused on either wet cooling towers or dry towers whose heights and base diameters were more than 100 m and 70 m respectively. There is no existing technical report on the small-size NDDCTs with horizontal heat exchanger arrangement. Because of the shorter heights, the natural convection in small towers is much weaker. Therefore, the crosswind effect on them could be very different from that in large towers.

QGECE has systematically investigated the crosswind-subjected cooling performance on a novel 15 m-tall NDDCT proposed for renewable thermal power plants. The tower is of regular cylindrical shape with a diameter of 12 m. The finned-tube heat exchanger bundles are arranged horizontally 3 m above the ground. A new tri-blade-like windbreak wall has been proposed underneath the heat exchangers to redirect the airflow in the tower bottom. In the first stage of this study, a full-scale CFD model was built and simulated under different wind conditions [13,21]. CFD results preliminarily indicated the effectiveness of this type of windbreak. However, the CFD tower model has not been validated by experimental data yet.

Therefore, a following-up experimental investigation on a scaled natural draft dry cooling tower model (1.2 m-tall tower) with a unique round electric heater was carried out using an open-circuit wind tunnel. In this paper, the experiment procedures are described in detail. The measured results are then compared against the predictions of the corresponding CFD simulations. The comparisons can validate the CFD modeling approach used in our previous work.

2. Experimental method

2.1. Model setup

The scaled laboratory cooling tower model was designed to be geometrically proportional to the full-scale 15 m-tall NDDCT