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Comparative study on the cooling characteristics of high level water collecting natural draft wet cooling tower and the usual cooling tower

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ABSTRACT

With the rapid development of large capacity power units, high level water collecting natural draft wet cooling towers (HNDWCTs) are now attractive. To study the cooling characteristics of HNDWCT, a three-dimensional (3D) numerical model for a HNDWCT was established and validated. Combining with the verified 3D numerical models for usual natural draft wet cooling towers (UNDWCTs), the parameters such as air pressure drop, air mass flow rate, exit water temperature, cooling load percentage of each zone, air velocity, air temperature and H_2O mass fraction were elaborated for HNDWCT and UNDWCTs under the same work conditions. Comparing with UNDWCTs, the cooling characteristics of HNDWCT were analyzed and highlighted. The cooling load percentage of fill zone in HNDWCT is far larger than those in UNDWCTs for the large air mass flow rate and large heat transfer potential. Under high velocity crosswind impacts, blocking the cross ventilation through HNDWCT is favorable to its cooling performance. Suggestions concerning the orientations of water collecting gutter and cross wall are presented.

1. Introduction

As large-scale cooling equipments with high effectiveness, natural draft wet cooling towers (NDWCTs) are widely used to provide cooling water for nuclear power plants or thermal power plants. According to the characteristics of the water collecting mode, NDWCTs can be classified into the usual natural draft wet cooling towers (UNDWCTs) [1] and the high level water collecting natural draft wet cooling towers (HNDWCTs) [2,3]. Fig. 1 schematically shows both the UNDWCT and HNDWCT. As illustrated in Fig. 1, except for the high level water collecting devices (HWCDs), both the UNDWCT and HNDWCT are very similar in structure.

In UNDWCT or HNDWCT, hot water is pumped into tower via the vertical shaft and sprayed downward by nozzles. Colliding on the inherent surfaces of fill, especially film fill, water droplets cling to the film media and flow downward as water film. Below fill, water becomes droplets again and collects in water basin or HWCDs. Ambient air is drawn into tower by tower draft and flows upward. Both UNDWCT and HNDWCT have three heat and mass transfer zones, i.e., the spray zone, the fill zone and the rain zone from spray nozzles to water basin or HWCDs, where the heat and mass transfer from water to air occurs.

The HWCDs are composed of multi parallel water collecting units. A water collecting unit consists of a sloping plate and the following U-type channel. The sloping plates and corresponding U-type channels collect the falling water droplets from fill and drain into the high level water collecting gutter below. So a high water level is formed in the water collecting gutter, which can reduce the pumping power required for circulating water between the HNDWCT and condenser. Because the HWCDs are just beneath the cooling fill of HNDWCT, the falling distances of water droplets from fill bottom are correspondingly very small, so both the noise level and air flow resistance are also very small [4].

With the advantages of small air flow resistance, low noise level and reduced pumping power [4], HNDWCTs are becoming a research hot spot, along with the rapid development of large capacity power plants [5] especially in China. The HWCDs only shorten the rain zone of HNDWCT, but do not change the water flow form in a wet cooling tower. So the transfer mechanisms of momentum, heat and mass between water and air in HNDWCT are as same as those in UNDWCT. The cooling characteristics comparison between HNDWCT and UNDWCT can promote the

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Nomenclature

A_d	surface area of droplet, m^2
A_f	experimental correlation coefficient
c_{pv}	constant pressure specific heat of water vapor, kJ/(kg K)
c_w	constant pressure specific heat of water, kJ/(kg K)
D_m	water vapor diffusion coefficient in the bulk moist air, m^2/s
g	gravitational acceleration, 9.8 m/s^2
g_a	mass flow velocity of air, $kg/(m^2\,s)$
h	heat transfer coefficient, $W/(m^2\,K)$
h_m	mass transfer coefficient, m/s
k	turbulent kinetic energy per unit mass, J/kg
k_∞	thermal conductivity of moist air, W/(m K)
K_a	volumetric mass transfer coefficient, $kg/(m^3\,s)$
K_h	volumetric heat transfer coefficient, $W/(m^3\,K)$
Le_f	Lewis factor
m_a	air mass flow rate, kg/s
m_w	mass of a falling water droplet, kg
M_w	molecular weight of moist air, kg/kmol
N_d	water droplet number per unit volume
n_f	experimental correlation index
p_a	ambience pressure, Pa
p	local air pressure, Pa
Pr	Prandtl number of moist air
p_v	partial pressure of water vapor in air
P''_v	saturated vapor pressure, Pa
q	the local water mass flow rate, $kg/(m^2\,s)$
Q_w	water volume flow rate, m^3/h
R	the universal gas constant, 8314 J/(kmol K)
Re_d	Reynolds number based on the relative velocity between water droplet and moist air
r_w	latent heat of water evaporation, kJ/kg
Sc	Schmidt number
$S_{\varphi i}$	internal source term for the governing equation of air variable φ
μ	dynamic viscosity, N s/m^2
v	kinematic viscosity, m^2/s
ρ	local air density, kg/m^3
ρ_w	water density, kg/m^3
τ	atmospheric wet-bulb temperature, °C
φ	evaluated variable for air flow
ω_v	mass fraction of H_2O, kg/kg(moist air)
d	water droplet diameter, m
dS	micro area, m^3
$d(-z)$	micro height, m
f_i	interactive force between water droplet and air in the i-direction
F_i	air flow resistance in the i-direction
S_φ	source term for the governing equation of air variable φ by the air–water interaction
S_m	volumetric water evaporation rate, $kg/(m^3\,s)$
S_{we}	volumetric energy reduction rate of water, $kJ/(m^3\,s)$
S_{ae}	volumetric heat increase rate of air, $kJ/(m^3\,s)$
T	local air temperature, °C
T_w	local water temperature, °C
T_{w1}	entry water temperature of tower, °C
T_{w2}	exit water temperature of tower, °C, based on the 3D numerical model
T_{w2e}	exit water temperature of tower, °C, based on the 1D enthalpy difference method
T_{w2r}	real test exit water temperature of tower, °C
$\vec{u}$	local air velocity vector, m/s
u_c	ambient natural crosswind velocity, m/s
u_i	the i-direction velocity component of air, m/s
u_{ref}	reference crosswind velocity, m/s
u_{wz}	vertical falling velocity of water droplet, m/s
x_a	humidity ratio of moist air, kg/kg
x''_w	humidity ratio of saturated moist air, kg/kg
x, y, z	coordinates, m

Greek symbols

α	profile index of ambient crosswind speed
Γ_φ	diffusion coefficient for air variable φ
Δp	air pressure drop, Pa
ΔT_w	water temperature drop, °C
δT_{w2}	computed error between T_{w2} and T_{w2e}
ε	turbulent dissipation rate, m^2/s^3
θ	atmospheric dry-bulb temperature, °C

Subscripts

0	windless condition
a	air
d	water droplet
i	coordinates of x, y and z
w	water

intensive study of HNDWCT and lay a good foundation for its thermal performance optimization.

Unlike the recent popularity of HNDWCT in China, the UNDWCT has been used widely around the world for about 100 years [6], and then there have been a lot of studies about the cooling performances of UNDWCTs, especially about the heat and mass transfer processes from water to air. In 1923, Walker et al. [7] first described the heat and mass transfer processes in a wet cooling tower. In 1925, Merkel [8] rearranged the heat transfer equations from water to air and obtained the enthalpy difference method. Using the enthalpy difference method, Merkel presented the widely used Merkel number, which could reflect the cooling capacities of UNDWCT and its adopted fill. Using rigorous differential equations of moist air enthalpy and humidity ratio versus water temperature, Poppe and Rögener [9] presented the Poppe Merkel number, which could accurately calculate the outflow air state as well as the tower cooling capacity. But both the above Merkel numbers [8,9] evaluate the heat transfer coefficients from water to air, without considering the outflow air temperature [10,11].

For cross-corrugated film fills with separate depths of 0.6 m, 0.9 m and 1.2 m, Kloppers [12] tested their performance characteristics and obtained the relevant Merkel number correlations based on the Merkel method [8], the Poppe method [9] and the e-NTU method [12]. Using the fill Merkel number and its loss coefficient correlation [11], the total performance of a cooling tower can be evaluated [13,14]. Combining with the local mass flow rates of air and water, the heat and mass transfer intensities can also be locally evaluated so as to reflect their differences across fill. Kloppers and Kröger [10] stated that the Merkel method [8] can provide accurate results for the cooling performance calculation of a wet cooling tower, if the same method is used when deriving its fill performance correlations. Also with the advantage of relative concision, the Merkel method was recommended as the standard approach [13,14] for determining tower cooling performance.

Using the Merkel number given by the Merkel method [8], Reuter and Kröger [15] numerically studied the cooling performance of a UNDWCT and indicated that the tower cooling performance can be improved by maximizing the fill height in the annulus and