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Anti-freezing water flow rates of various sectors for natural draft dry cooling system under wind conditions

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ABSTRACT

Freezing risk of air-cooled heat exchangers for natural draft dry cooling system is a key concern in power plants during cold days, so it is beneficial to the safe and economic operation of natural draft dry cooling system to propose the anti-freezing measures at various ambient conditions. As a main issue, the anti-freezing water flow rate of air-cooled heat exchanger is investigated by using the macro heat exchanger model based on the heat load balance between the circulating water and ambient air. The detailed thermo-flow characteristics of the cooling deltas and the anti-freezing water flow rate for each sector at various wind speeds are obtained with reference to the water freezing temperature, and the residual anti-freezing coefficient is introduced to describe the affluent anti-freezing capacities of each sector and cooling delta at the anti-freezing water flow rate. The results show that the anti-freezing water flow rate is highest and the residual anti-freezing coefficient is lowest for the frontal sector compared with those for other sectors. For the middle and middle-rear sectors, even with small anti-freezing water flow rates, the residual anti-freezing coefficients can be high because of the reduced heat rejection to the deteriorated air flows.

1. Introduction

With the delta-type heat exchanger vertically arranged around the circumference of the dry-cooling tower, the natural draft dry cooling system rejects the waste heat of the circulating water to the ambient air [1], so the ambient conditions could play important roles in the operation of natural draft dry cooling system. In extremely cold days, the air-cooled heat exchanger is even faced with the freezing risks that the finned tube bundles may encounter great damages. So it is critical to investigate the anti-freezing of air-cooled heat exchangers for the safe and energy-efficient operation of natural draft dry cooling system in power plants.

As the key issues of ambient conditions, ambient winds have been thoroughly studied involving the unfavorable impacts on the natural draft dry cooling system. Yang et al. [2,3] numerically investigated the performance of a dry-cooling tower incorporating vertically arranged heat exchanger bundles, finding that the hot plume penetration through the rear or side finned tube bundles occurs at high wind speeds, and there exists a critical wind speed at which the performance of natural draft dry cooling system is most deteriorated. Su et al. [4] studied the deterioration of the thermo-dynamical performances of a dry-cooling tower under crosswinds by numerical simulations. Liao et al. [5] investigated the influence of the height to diameter ratio of dry-cooling tower upon the thermo-flow characteristics of natural draft dry cooling system, proposing a low height to diameter ratio for better thermo-flow performances at strong ambient winds. Al-Waked and Behnia [6] investigated the effects of the crosswinds and windbreakers on the natural draft dry cooling system performance, and pointed out that the windbreakers can weaken the adverse impacts of crosswinds. Zhao et al. [7,8] studied the cooling performance of a natural draft dry cooling system with vertically arranged heat exchanger bundles around the circumference of a dry-cooling tower. Ma et al. [9] studied the effects of the ambient temperature and crosswind on the thermo-flow performances of natural draft dry cooling system, concluding that the outlet water temperature of air-cooled heat exchanger is approximately linear with ambient temperature, whereas nonlinear with wind speed. Lu et al. [10] experimentally studied the wind effects on the performance of small cylindrical natural draft dry cooling towers, the comparisons against CFD models showed a good agreement between the experimental and numerical results. Goodarzi [11] suggested a variable tower height to reduce the structural wind loads without a considerable thermal performance reduction. Du Preez and Kroger [12] initially recommended the windbreakers, and presented a cooling

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Nomenclature

a	core friction coefficient
A	heat transfer surface area (m^2)
b	core friction exponent
c_p	specific heat ($JKg^{-1}\,K^{-1}$)
C	heat capacity rate ($W\,K^{-1}$)
C_r	ratio of air to water heat capacity rate
D	diameter (m)
e	exponent in the power-law equation of wind speed
f	pressure loss coefficient
f_c	core friction factor
g	gravitational acceleration ($m\,s^{-2}$)
h	convection heat transfer coefficient
H	height (m)
I	turbulence intensity
k	turbulent kinetic energy ($m^2\,s^{-2}$)
K	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
L	length (m)
m	mass flow rate ($kg\,s^{-1}$)
n	number
Nu	Nusselt number
NTU	number of transfer unit
p	pressure (Pa)
Pr	Prandtl number
Q	heat rejection (W)
Re	Reynolds number
S	source term in generic equation
t	temperature (°C)
u	velocity ($m\,s^{-1}$)
v	specific volume ($m^3\,kg^{-1}$)
V	volume (m^3)
x_j	coordinate in j direction (m)
z	height above the ground (m)

Greek symbols

δ	residual anti-freezing coefficient
δ_f	fin thickness (mm)
ε	turbulence dissipation rate ($m^2\,s^{-3}$)
ε_Q	heat exchanger effectiveness
λ	heat conductivity ($W\,m^{-1}\,K^{-1}$)
Γ	diffusion coefficient ($m^2\,s^{-1}$)
φ	scalar variable
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
μ_t	turbulent viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	minimum flow to face area ratio

Subscripts

a	air
A_{min}	minimum flow area
b	base
d	cooling delta
e	exit
he	heat exchanger
i	inlet
m	mean
min	minimum
max	maximum
s	sector
t	tower
w	water
wd	wind
1	inlet
2	outlet

efficiency increase of 16% compared with the original model at the wind speed of 10 m/s. Goodarzi and Keimanesh [13] studied the effect of a radiator-type windbreaker on natural draft dry cooling system, pointing out that a higher cooling efficiency can be achieved than the solid-type windbreaker. Goodarzi and Ramezanpour [14] proposed an elliptical geometry of dry-cooling tower to bring on a higher cooling efficiency under windy conditions.

The aforementioned works show that more attentions have been attracted to the air-side flow and heat transfer characteristics, and no interest is expressed to the water-side. As is well known, the big thermal resistance of air-cooled heat exchanger exists in the air side, so the thermo-flow performances of air-cooled heat exchanger mainly depend on the air-side conditions. However, the water will face with the freezing risk once the ambient temperature is reduced to below 0 °C at a normal atmosphere. In this case, the water flow and heat transfer characteristics become an important concern also, and the air-side and water-side thermal-flow performances should be simultaneously taken into account. But unfortunately, more emphases were placed only on the freezing mechanism of water and other fluids in the past years, such as the works by Seeniraj and Hari [15], Habeebullah [16], Tay et al. [17], Amin et al. [18], Conde et al. [19] and so on. How the air-side flow and heat transfer characteristics affect the water freezing process is rarely mentioned. Although Yang et al. [20] studied the anti-freezing flow rate of exhaust steam, turbine back pressure and flow rate of axial flow fan for air-cooled condensers, the effects of ambient winds were not considered in detail.

When considering the air-cooled heat exchanger freezing, the thermo-flow performances of circulating water and cooling air should be simultaneously modeled. In this paper, the heat exchanger model is applied to the air-cooled heat exchanger, by which the anti-freezing circulating water flow rate at various wind speeds with reference to the water freezing point is obtained. Based on the anti-freezing water flow rates of the cooling deltas and sectors, the anti-freezing approaches such as the water redistribution and also the louver adjusting can be suggested in practical engineering.

2. Models

2.1. Physical models

For the typical natural draft dry cooling system, the geometries of the dry-cooling tower and air-cooled heat exchanger are shown in Fig. 1, with the detailed sizes listed in Table 1. Besides, in practical engineering, the heat exchanger system is basically divided into ten air-cooled sectors for easily distributing the circulating water. Owing to the symmetric geometry of the natural draft dry cooling system, only five air-cooled sectors ranging at 0–180° are studied for the anti-freezing issues, as shown in Fig.1.

The computational domain shown in Fig. 2 is large enough compared with the heat exchanger and tower so as to eliminate the unrealistic impacts of the domain boundaries on the cooling air flows. Moreover, Fig. 2 also shows the local grids of the cooling deltas and dry-cooling tower. The structured hexahedron meshes are applied to the cooling deltas and the tower body, while the unstructured hexahedron/tetrahedron hybrid meshes are adopted for the part between the heat exchanger and cooling tower. The mesh interval sizes for the heat exchanger surface and the cooling tower are set 0.2 m and 2 m, respectively [3,5]. The multi-block