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Performance improvement of natural draft dry cooling system by water flow distribution under crosswinds

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ABSTRACT

The cooling performance of natural draft dry cooling system may be deteriorated by ambient winds, so effective measures need to be taken against the adverse wind effects. In this work, a three-dimensional numerical model of a typical natural draft dry cooling system coupled with the condenser is developed to investigate the thermo-flow performance improvement of natural draft dry cooling system by circulating water flow distribution, in which the finned tube bundles are dealt with the heat exchanger model to take both the air and circulating water into account. The flow and temperature fields, heat rejection of each sector, outlet water temperature of air-cooled heat exchanger and the corresponding turbine back pressures are obtained. The results show that appropriate water flow distribution can significantly improve the thermo-flow performances of natural draft dry cooling system, while the improper one may deteriorate the cooling performance more seriously at low wind speeds. Based on the entransy dissipation theory, the optimized heterogeneous water distributions are provided under five certain wind conditions by using the numerical-theoretical iterative method.

1. Introduction

Owing to the urgent water resource issue, the natural draft dry cooling system (NDDCS) with the air-cooled heat exchanger vertically arranged around the circumference of dry-cooling tower or horizontally installed inside cooling tower is widely used in arid regions where the cooling water is not available or is very expensive [1]. Ambient air is driven by the dry-cooling tower generated buoyancy force to cool the circulating water in the air-cooled heat exchanger, so the thermo-flow performances of NDDCS are easily influenced by the ambient conditions. More and more attentions have been paid to the unsatisfactory performance of NDDCS under crosswinds, and various measures against the adverse wind impacts.

He et al. [2] developed three mathematical models and the iterative algorithms to investigate the annual performances of a natural draft dry cooling tower (NDDCT), a pre-cooled NDDCT and a natural draft wet cooling tower (NDWCT), finding that the pre-cooling system can increase the heat rejection and save 70% water consumption in hot months. Hooman investigated the convective heat transfer performance of the air-cooled heat exchanger and dry-cooling tower by using CFD methods [3], and predicted the wind effects on the performance of natural draft dry cooling towers by theoretical analysis, which just lead to a maximum error of 15% compared to the numerical and experimental results [4]. Ma et al. [5] studied the effects of ambient temperature and crosswinds on the performance of NDDCS and found that the outlet water temperature of the air-cooled heat exchanger is approximately liner with ambient temperature whereas nonlinear with wind speed. Yang et al. [6,7] investigated the wind impacts on the thermo-flow performances of NDDCS, finding that the performances are deteriorated with increasing the wind speed at low wind speeds and then get improved at high wind speeds. Zhao et al. [8–10] developed a three-dimensional numerical model for both the natural draft dry cooling tower and cooling columns, and studied the crosswind impact mechanism by introducing the inflow air deviation angle, obtained the exit water temperature distribution of cooling columns.

Based on the wind effects on the thermo-flow performances of NDDCS, Al-Waked and Behnia [11] suggested the windbreaker configuration and found that the windbreakers can significantly weaken the adverse wind effects. Lu et al. [12] numerically analyzed a small dry-cooling tower, pointing out that the windbreakers installed at the bottom of dry-cooling tower can effectively improve the cooling performance of NDDCS. Following this numerical investigation, Lu et al. [13] used a scaled cooling tower model

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Nomenclature

a	core friction coefficient
A	heat transfer surface area (m^2)
b	core friction exponent
c_p	specific heat (J kg^{-1} K^{-1})
C	heat capacity rate (W K^{-1})
C_r	the ratio of air and 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	height (m)
I	turbulence intensity
k	turbulent kinetic energy (m^2 s^{-2})
K_Q	overall heat transfer coefficient (W m^{-2} K^{-1})
K	friction loss coefficient
L	length
m	mass flow rate (kg s^{-1})
n	number
NTU	number of transfer unit
p	pressure (Pa)
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})
x_j	coordinate in j direction (m)
z	height above the ground (m)

Greek symbols

Γ	diffusion coefficient (m^2 s^{-1})
δ	residual anti-freezing coefficient
ε	turbulence dissipation rate (m^2 s^{-3})
ζ	water flow rate propotion
η	performance improvement degree
ε_Q	heat exchanger effectiveness
μ	dynamic viscosity (kg^{-1} 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
φ	scalar variable

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
pb	turbine back pressure
s	sector
t	tower
w	wind
wa	water
1	inlet
2	outlet

with horizontally arranged heat exchanger to investigate the cooling efficiency of natural draft dry cooling tower (NDDCT), finding that the total heat transfer rate was a combination of a natural convective heat transfer term and a forced convective one. Zhai and Fu [14] experimentally and numerically investigated the airflow and thermal performance of NDDCS, pointing out that about 50% of cooling capacity can be recovered by placing the windbreakers at the lateral sides of cooling tower. Goodarzi and Keimanesh [15] numerically studied the impacts of a radiator-type windbreaker, showing that a better performance can be achieved than the solid-type windbreaker. Goodarzi [16,17] also investigated different types of cooling tower, pointing out that the dry-cooling tower with an elliptical cross section or a loxotic exit has a better performance at high wind speeds. Liao et al. [18] investigated the influence of the height to diameter ratio of dry-cooling tower, pointing out that a lower height to diameter ratio can help NDDCS achieve better performances at strong ambient winds.

The aforementioned works show that the thermo-flow performance improvement of NDDCS mainly focuses on the windbreaker and cooling tower configurations. Few researches pay attention to the circulating water distribution under crosswind conditions. Goodarzi and Amooie [19,20] combined the Genetic Algorithm with CFD computational model to optimize the distribution of circulating water. However, they utilized a simplified physical model and merely investigated the water distribution at a certain wind speed.

By changing or integrating the geometric structure of NDDCS, the measures of windbreakers and unusual tower geometry undoubtedly lead to a satisfactory improvement of the thermo-flow performances of NDDCS in a certain wind direction, but they may not work well when the wind direction or speed changes. The approach of circulating water distribution needn't change the configuration of NDDCS, so it can be easily used in practical engineering with a low cost [20]. Moreover, the water distribution can be flexibly adjusted with the changing wind direction and speed, which may improve the energy efficiency of the power generating unit under different wind conditions.

In this study, a typical natural draft dry cooling system coupled with the condenser will be investigated, which works under a constant heat load. A three-dimensional physical model is developed for both the tower shell and each cooling delta of air-cooled heat exchanger. For the cooling delta, the heat exchanger model is applied, which takes both the flow and heat transfer on the air side and the heat rejection on the water side into consideration. Because the water flow rate of each sector can be artificially controlled, the circulating water flow distribution of each sector under wind conditions will be investigated. Different from the coupled numerical-theoretical procedure with Genetic Algorithm provided by Goodarzi and Amooie, the theory of entransy dissipation [21] will be integrated with the numerical-theoretical iteration procedure to find the optimized water distribution under various wind conditions.

2. Numerical model

2.1. Physical model

A typical natural draft dry-cooling tower of a 200 MW power generating unit, which adopts a hyperbolic tower shell and incor-