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Flue gas diffusion for integrated dry-cooling tower and stack system in power plants

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A B S T R A C T

For the integrated dry-cooling tower and stack, the flue gas diffusion characteristics are of great concerns for the pollutant control and tower anticorrosion. In this work, the computational models of flue gas diffusion for the integrated dry-cooling tower and stack system are developed and experimentally validated. By means of numerical simulations, the flue gas diffusions inside and outside the dry-cooling tower are investigated and the flue gas concentrations at different heights of the inner tower shell and on the ground level are obtained. The rising height of flue gas is studied and compared with the separate stack. The total mass flow rate of cooling air and heat rejection of air-cooled heat exchanger for both the dry cooling system with and without the stack inside the dry-cooling tower are also obtained. The results show that not only the thermo-flow performances of the natural draft dry cooling system with the integrated stack can be improved, but also the air pollution alleviation can be guaranteed. At high wind speeds, the inner tower shell faces corrosion risks due to the flue gas deposition, so the anticorrosion measures for the tower should be taken.

1. Introduction

Thanks to the excellent water saving capability, the natural draft dry cooling system has been widely adopted and increasingly developed in power plants [1]. Natural draft dry cooling system mainly consists of the dry-cooling tower and air-cooled heat exchanger bundles vertically arranged around the circumference of the dry-cooling tower or horizontally configured inside the dry-cooling tower. For the former case, the dry-cooling tower is empty, so the integrated dry-cooling tower and stack system can be adopted in practical engineering, in which the flue gas is directly discharged into the tower. As a result, the reheating heat exchanger and stack for the traditional flue gas purification and discharge system can be removed, however it may take a corrosion risk for the tower shell, especially under the windy conditions.

As is well known, the thermo-flow performances of natural draft dry cooling system are vulnerable to the ambient winds, which have been thoroughly investigated in the past decades, and what's more, many measures against the adverse wind effects were also proposed. Yang et al. [2,3] simulated the thermo-flow performances of a natural draft dry cooling system, pointing out that the hot plume penetrates through the rear or lateral finned tube bundles at high wind speeds, and the performances are most deteriorated at a critical wind speed. Su et al. [4] studied the thermo-dynamical performance deterioration of a dry-cooling tower under crosswinds. Zhao et al. [5,6] investigated the cooling performance of a natural draft dry cooling system with vertical deltas around the tower. Ma et al. [7] studied the effects of ambient temperature and winds on the thermo-flow performances of natural draft dry cooling system, concluding that the outlet water temperature is approximately linear with the ambient temperature, whereas nonlinear with the wind speed. Lu et al. [8] experimentally studied the performance of a small natural draft dry cooling tower under windy conditions, and compared with the numerical results. Liao et al. [9] investigated the influence of the tower height to diameter ratio upon the thermo-flow characteristics of natural draft dry cooling system, and recommended a low value for better thermo-flow performances. Goodarzi [10] proposed a changing tower height to reduce the structural wind loads without a big thermal performance drop. Goodarzi and Ramezanpour [11] proposed a dry-cooling tower with an elliptical cross section, by which a higher cooling efficiency under windy conditions can be achieved. Chen et al. [12,13] proposed the windbreaker

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Nomenclature

C	constant in turbulence model
D	Diameter (m)
$D_{i,m}$	mass fraction coefficient for species i (m^2 s^{-1})
D_t	turbulent diffusivity
e	exponent of the wind speed in the power-law equation
H	Height (m)
h	convection heat transfer coefficient (W m^{-2} K^{-1})
h_n	polynomial coefficient for the convection heat transfer coefficient
h_s	enthalpy of the exhaust steam (J kg^{-1})
h_{wa}	enthalpy of the condensate (J kg^{-1})
I	turbulence intensity
k	turbulent kinetic energy (m^2 s^{-2})
k_L	flow loss coefficient
m	mass flow rate (kg s^{-1})
N	number
p	pressure (Pa)
q	heat flux (W m^{-2})
r_n	polynomial coefficient of non-dimensional loss coefficient
S	source term
t	temperature (°C)
Y_i	local mass fraction of species i
u_j	component of velocity (m s^{-1})
u_w	wind speed (m s^{-1})
v_f	frontal velocity (m s^{-1})
x_j	Cartesian coordinate (m)
z	height above the ground (m)

Greek symbols

ε	turbulence dissipation rate (m^2 s^{-3})
μ	dynamic viscosity (kg m^{-1} s^{-1})
μ_t	turbulent viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
Γ	diffusion coefficient (kg m^{-1} s^{-1})
Φ	heat rejection (W)
φ	scalar variable

Subscripts

1	inlet
2	outlet
a	air
avg	average
w	wind
wa	water

configurations inside and outside the dry-cooling tower to improve the thermo-flow performances of the dry cooing system, and suggested the opening degree adjustment of the louvers to prevent the freezing of air-cooled heat exchanger. Al-Waked and Behnia [14] also proposed a layout of windbreakers, finding that the windbreakers can weaken the adverse wind impacts on the thermal performance of natural draft dry cooling system. Goodarzi and Keimanesh [15] suggested a radiator-type windbreaker, pointing out that a higher cooling efficiency can be achieved compared to the solid-type windbreaker.

For the integrated dry-cooling tower and stack system, more emphases have been placed upon the thermal and environmental performances. Klimanek et al. [16] numerically studied the effect of flue gas injection on the wet cooling tower performance, pointing out that the outlet water temperature can hardly be affected due to the low flue gas flow rate, and the recirculation region near the tower outlet leads to flue gas gathering on the tower shell, which will increase the corrosion risk. Jahangiri and Golneshan [17] studied the performance improvement by the flue gas injection to the dry-cooling tower, finding that both the air flow rate and heat rejection are enhanced a little. Han et al. [18] developed a multi-objective optimization model for the dry-cooling tower with flue gas injection, showing that the flue gas injection is an energy efficient method. Eldredge et al. [19] numerically studied the flue gas injection effect on the cooling performance, finding that the buoyancy effect is much bigger than the blockage and momentum transfer caused by the flue gas. Schatzmann et al. [20] experimentally studied the flue gas concentration on the ground level under windy conditions, finding that the flue gas injection to the dry-cooling tower can effectively reduce the local concentrations.

In this work, the computational models for the natural draft dry cooling system with and without flue gas injection to the tower are developed and experimentally validated, by which the flue gas concentrations inside and outside the dry-cooling tower, the flue gas concentration for the separate stack, the thermo-flow performances of the dry cooling system are investigated. The results can contribute to the anticorrosion of the dry-cooling tower and the pollution control of flue gas for the integrated dry-cooling tower and stack system in power plants.

2. Modeling

2.1. Physical model

A natural draft dry cooling system for a 660 MW power generating unit is taken into consideration and the working medium loop and cooling loop are schematically shown in Fig. 1. The conventional layout of a power plant involves the individual natural draft dry cooling system and separated flue gas stack, as shown in Fig. 2(a). The hyperbolic dry-cooling tower and vertically arranged air-cooled heat exchanger bundles basically constitute the natural draft dry cooling system. For the integrated dry-cooling tower and stack system, the flue gas is introduced in the center of the dry-cooling tower by a short steel stack with the height of 60 m and diameter of 8.5 m, and then rises together with the hot air from the air-cooled heat exchanger, which is schematically shown in Fig. 2(a) and (b). Due to the geometric symmetry, the physical model of the integrated system is built in half as shown in Fig. 2(b). The dimensions of the natural draft dry cooling system and the separated and integrated stacks are summarized in Table 1. With the higher temperature flue gas injection to the cooling tower, the buoyancy driving force may be enhanced, which is of benefit to the thermo-flow performances of dry cooling system.

Fig. 3 shows the computational domain. In the absence of winds shown in Fig. 3(a), the dimensions of the computational domain are 1500 × 3000 × 6000 m in the height, width and length. With the winds shown in Fig. 3(b), the computational domain has the size of 1500 × 3000 × 15,000 m in the height, width and length, which is large enough to eliminate the unrealistic effect of the domain boundaries on the flow field. The detailed meshes for the dry-cooling tower and heat exchanger are shown in Fig. 4, where the grid interval size for the radiator and flue gas zone is set as 0.2 m, however for the zone of dry-cooling tower, the grid interval size is set as 3 m. As a result, 4,204,720 cells are created for the simulation.