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Investigation on the influence of injection direction on the spray cooling performance in natural draft dry cooling tower

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ABSTRACT

In arid areas, natural draft dry cooling tower (NDDCT) has become the primary choice in concentrating solar thermal power plants due to its advantages of low water consumption, low maintenance cost and little parasite loss. However, NDDCT suffers from deteriorated cooling performance in hot summer days, causing net power loss for power plants. To solve this problem, we propose a pre-cooling technology by introducing a spray of controlled and small quantity of fine water droplets to cool the inlet air and thus improve the cooling tower performance when ambient temperature is high. The effective pre-cooling requires the careful arrangement of spray nozzles. Here the optimal injection for a hollow cone nozzle has been identified based on CFD study. This study shows that pre-cooling performance heavily depends on the injection direction of nozzle. For a single nozzle with the water flowrate of 5 g/s, the largest temperature drop is 1.27 °C, corresponding to the radiator temperature of 38.73 °C. It is found that the injection angle varies with the height of nozzle location to achieve full evaporation.

1. Introduction

Thermal power plants, from a thermodynamic point of view, exhaust substantial waste heat to the surrounding environment and need a low-temperature reservoir for cooling purpose. In this sense, the performance of cooling system is significant for the power plant operations and have an important impact on the performance of the entire power cycle. A defective cooling system, failing to provide adequate cooling for the power generation process, would lead to decreased electricity production as well as serious economic consequences. An approximate 0.3 GW h annual electrical generation loss in the U.S. was caused by the cooling towers' operating at their off-design points. Economically speaking, this power loss corresponds to a reduced benefit of US$20 million per year [1]. In order to avoid such disadvantage, an efficient cooling system becomes a necessary part for power plants.

In practice, mechanical draft and natural draft cooling towers are most commonly used. Mechanical draft cooling towers use motor-driven fan to force or draw air through the towers and the energy consumption by the fans increases the running costs, therefore many power plants prefer to build the more economical natural draft cooling towers. Broadly speaking, both natural and mechanical-draft draft cooling towers can be categorized into two types: wet and dry cooling towers. Wet cooling towers use water as the heat transfer medium and rely on the latent heat of water to provide significant cooling to the process. Theoretically, wet cooling enables the hot water to be cooled to the atmospheric wet bulb temperature and is more efficient than dry cooling. However, they consume large quantities of freshwater due to evaporation, drift and draining losses. Therefore, supplemented water should be continuously supplied to guarantee the normal operation of towers. The large water consumption as well as the environmental concerns such as thermal pollution, which would result in the degradation of water quality, visible plume and entrainment and impingement issues makes them unsuitable for the regions suffering from water shortage [2].

In arid areas, dry cooling towers with the advantages of low water consumption, low maintenance cost and little parasitic loss, become the primary choice for some thermal power plants to release the waste heat to the atmosphere by cooling down hot fluid to a lower temperature. Despite these advantages, dry cooling towers suffer from low performance relative to wet cooling towers as they rely mainly on convective heat transfer into the air to dissipate heat rather than evaporation of water [3]. The cooling efficiency loss becomes remarkable during high ambient temperature periods and/or under strong crosswind conditions [4].

As to the tower performance loss caused by the crosswind, numerous results have been published. Wei et al. [5] conducted full scale measurements and wind tunnel modelling to

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Nomenclature

$\vec{A}_i$	local areas at the radiator surface
C_D	drag coefficient
C_{pa}	specific heat of air (J/kg·K)
C_{pw}	specific heat of water (J/kg·K)
D_d	droplet diameter (μm)
D_f	diffusion coefficient (m^2/s)
g	gravitational acceleration (m/s^2)
E	total energy (J)
F	forces acting on droplet (N)
F_d	drag force (N)
F_G	gravity force (N)
G_k	production of turbulent kinetic energy
h_c	heat transfer coefficient ($W/m^2/K$)
h_d	mass transfer coefficient (m/s)
h_{fg}	latent heat of water vaporization (J/kg)
h_r	heat transfer coefficient for radiator
K	thermal conductivity (W/(m·K))
L_f	loss coefficient
L_c	characteristic length (m)
$\dot{m}_a$	air flow rate (kg/s)
$\dot{m}_e$	evaporative mass flux (kg/s)
$\dot{m}_w$	water flow rate (kg/s)
$\dot{m}_d$	droplet mass (kg)
Nu	Nusselt number
P_r	Prandtl number
P	pressure (Pa)
Q	heat transfer rate for radiator (W)
R_{ed}	droplet Reynolds number
S_c	Schmidt number
S_{ct}	turbulent Schmidt number
S_e	source term of energy (W/m^3)
S_m	source term of mass (kg/m^3 s)
S_{mo}	source term of momentum (kg/m^2 s^2)
Sh	Sherwood number
T	temperature (°C)
V_a	air velocity (m/s)
V_d	droplet velocity (m/s)
V_{cell}	computational cell volume (m^3)
V_r	droplet relative velocity (m/s)
V_w	droplet volume (m^3)
w	humidity ratio (kg/kg of dry air)
X_d	droplet position (m)
Y_j	mass fraction of specie j
ΔP	pressure drop

Greek symbols

α	spread parameter
β	evaporated water fraction
ρ	density (kg/m^3)
ε	turbulent dissipation rate (m^2/s^3)
δ_{ij}	mean strain tensor (1/s)
τ_{ij}	mean stress tensor (kg/m^2 s)
μ	dynamic viscosity of air (kg/(m·s))
μ	turbulent dynamic viscosity (kg/(m·s))
Φ	viscous dissipation (W/m^3)
k	turbulence kinetic energy (J/kg)
τ_c	droplet relaxation time (s)
ν	velocity (m/s)
η_c	cooling efficiency

Subscripts

a	air
d	droplet
l	local value
w	water
v	vapor
sat	saturation
e	evaporation
t	time
int	droplet-air interface
i, j, k	cartesian coordinate directions
wb	wet-bulb
rd	radiator

Abbreviations

NDDCT	natural draft dry cooling tower
CFD	computational fluid dynamics
NDDCT	natural draft cooling tower
UQ	University of Queensland

study the crosswind effects on dry cooling tower. They found that the unfavorable pressure distribution around tower entrance, the affected tower hot plume and the leading edge separation induced cool air contributed to reduce the tower cooling performance. Su et al. [6] used finite volume method to simulate the thermal performance of dry cooling tower under crosswind conditions, and confirmed the declining thermo-dynamical effect of crosswind. Zhao et al. furthered the crosswind study by considering the delta layout form of column radiators. They used a three-dimensional (3D) numerical model to explore the cooling performance of a natural draft dry cooling tower with vertical two-pass column radiators (NDDCTV) under crosswind [7]. They concluded that the poor cooling performance of NDDCTV caused by crosswind would lead to an increased water exit temperature. Specifically, the worst scenario occurs at the 12 m/s crosswind condition, rising the water temperature by 6 °C when compared with the no-crosswind counterpart. More recently, Zhao et al. updated their research by coupling the ambient air temperature impacts with the crosswind influence on the performance of NDDCTV [8]. By setting a constant heat load and a uniform entry water temperature, they focused on analyzing the cooling performance of each sector under crosswinds. The deteriorating performance under crosswinds shows two patterns: for low cross wind velocity, the cooling performance of NDDCTV deteriorates sharply, while for high cross wind conditions, it experiences a slight variance.

In addition to the susceptibility to the crosswind, another reason for the low acceptance for NDDCT is the substantial loss of heat rejection rate in summer days [4]. As a result, power plants utilizing dry cooling technologies can experience a significant 20% net power reduction during high ambient temperature periods [9]. This is a catastrophe for plants based on low temperature resources (e.g. geothermal plants) where the power output reduction can be as high as 50% in hot summer days [10,11]. What is worse, this issue is compounded since the reduction goes along with the peak power demand which means a greater loss for power plant owners with flexible electricity pricing.

To overcome the low efficiency problem related to dry cooling during high ambient conditions, spray cooling has been developed to cool the inlet air by introducing a controlled, small quantity, and fine water droplets. This method, famed for its simplicity, low capital cost, and ease for operation and maintenance, has been reported to be a potential solution that deserves a further investi-