Energy Conversion and Management 108 (2016) 336–347

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

An investigation on spray cooling using saline water with experimental verification

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A R T I C L E I N F O

Article history:
Received 31 August 2015
Accepted 10 November 2015
Available online 23 November 2015

Keywords:
Saline water
Spray cooling
Phase Doppler Interferometry
Discrete phase model
Heat and mass transfer

A B S T R A C T

A natural draft dry cooling tower rejects heat in a power plant. Spray cooling of the inlet air to the cooling tower improves the total efficiency of the power plant. To overcome the scarcity of natural water sources, this research is studying the usage of saline water in spray assisted dry cooling towers. A nozzle is analysed experimentally. It is shown that the CFD model captures the spray well. A full cone spray is simulated in a vertical cylindrical domain representative of cooling tower flows. To investigate the influences of initial and ambient conditions on the spray performance, fourteen different cases are simulated and trends analysed. It is shown that the distances from the nozzle, after which the dry stream starts (wet lengths), are in the range of 4.3–5.25 m depending on the test conditions. A dimensionless study is performed on the wet length and cooling efficiency as the two main parameters. Finally, to predict the wet length and cooling efficiency, two dimensionless correlations are presented and their impact on cooling tower operation is discussed.

1. Introduction

Utilising saline water for spray cooling is an area that has received little attention, despite offering benefits both with respect to fresh water conservation and improvements in power generation efficiency. The aim of the current study is to improve the knowledge base associated with the use of saline water in spray cooling applications. An experimental study is performed to partially verify the presented CFD simulation of a single spray. After the reliability of the model was assured, the influence of initial and ambient condition on the spray performance was investigated and a practical analysis on the spray performance was made.

The outcome of this research is applicable in concentrated solar thermal (CST) power plants. In CST plants the hot temperature of the cycle reaches up to 600–700 °C [1]. Since the efficiency in a power plant is limited by Carnot efficiency ($1 - T_c/T_h$), to increase the total efficiency the cold temperature of the cycle should be decreased. To reduce the cold temperature (inlet air to the cooling tower), saline water spraying of the inlet air is suggested (Fig. 1) and studied in this work as a part of Australian Solar Thermal Research Initiative (ASTRI), a project supported by the Australian Government.

A CST plant is usually built in arid areas. Thus, a comprehensive study on evaporative spray cooling considers the scarcity of fresh water. To preserve the drinking water resources, and achieve an efficient performance, saline water is suggested for cooling purposes. In addition to performance improvement (8% higher cooling efficiency and 0.96 °C lower mean temperature [2]), using saline water instead of fresh water results in budget saving due to saving in natural water cost and generating excess electricity. In an economic study Ashwood and Bharathan showed that a 7.5 °C reduction in temperature due to spray cooling leads to 14% improvement in power generation rate in a 20 MW power plant [3]. Another study showed that, using sea water for cooling reduces the utility costs by 49.69% [4].

A drawback of using saline water is that heat exchanger surfaces are exposed to deposition and corrosion and solid particles (salt). To overcome these issues, in some cases such as in Condamine power station in Australia, corrosion is avoided using resistive materials (titanium condenser and fibreglass pipeline). Surface treatments [5–7] and controlling cooling water temperature [6,8] are the other methods. However, this work focuses on a design point of view to prevent the contact of wet droplets with the surfaces. This is done by ensuring that full evaporation is achieved before the sprayed stream reaches the metal surfaces. Here, the reactiveness of the saline solution is small [9].

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http://dx.doi.org/10.1016/j.enconman.2015.11.025
0196-8904/

Nomenclature

A	surface area (m^2)
a_1, a_2, a_3	constants in drag coefficient calculation
c	mass concentration
c_p	specific heat (J/kg K)
C_1, C_2	non-dimensional constants
C_D	drag coefficient
$\bar{d}$	size constant (m)
D	diameter (m)
D_{32}	Sauter Mean Diameter, SMD (m)
f	frequency (Hz)
f_1, f_2	non-dimensional variables
F, G	non-dimensional functions
F_D	drag force per unit mass (m/s^2)
F_s	safety factor
GCI	grid convergence index
h	sensible enthalpy (J/kg)
h_{fg}	specific enthalpy of evaporation (J/kg)
$H_{lat,ref}$	latent heat at the reference conditions (J/kg)
H_{pyr}	heat of pyrolysis per unit mass (J/kg)
k	thermal conductivity (W/m K)
$\vec{l}$	unit vector of direction
L	distance (m)
L_{wet}	wet length (m)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
n	size distribution parameter
N	number of droplet
Nu	Nusselt number
p	order of convergence
Pr	Prandtl number
r	grid refinement ratio
Re	Reynolds number = $\frac{D_d u_r}{v_g}$

RH	relative humidity
Q	heat transfer (J)
t	time (s)
T	temperature (K)
u	velocity (m/s)
Y	mass fraction of droplets in the spray
ε	relative error of solution
$\eta_{Cooling}$	cooling efficiency (%)
θ	scattering angle
λ	wavelength (m)
μ	dynamic viscosity (kg/m s)
v	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
Ψ, Ω	non-dimensional numbers

Subscripts

0	initial condition
c	cold
D	Doppler shift
d	droplet
g	gas
h	hot
i	integer component
in	condition at entry of computational cell
l	illuminating beam
out	condition at exit of computational cell
r	relative
ref	reference
s	light scattered wavefront
w	water
wb	wet bulb

To correctly capture the physics of saline droplet evaporation, the evaporation process should be split into four stages: temperature adjustment, isothermal evaporation, transition to crust formation, and drying out [10]. A detailed study of single droplet evaporation by Sadafi et al. showed that for 500 μm radius saline water droplets, absorbed energy for evaporation decreases by up to 12.2% compared to pure water [11]. Moreover, due to crust formation, a dry stream achieves in an earlier time for saline water.

For the simulation of saline droplet evaporation in CFD, Sadafi et al. [2] developed and verified an approach that modifies the multicomponent discrete phase model (DPM) in ANSYS FLUENT [12]. After comparing the results obtained for 3% NaCl concentration (by mass) with pure water, they showed that using saline water shortens the length from the nozzle, covered by the wet stream. This allows designers to reduce the distance between the nozzle and the heat exchangers, thereby shortening cooling towers without loss of spray cooling efficiency.

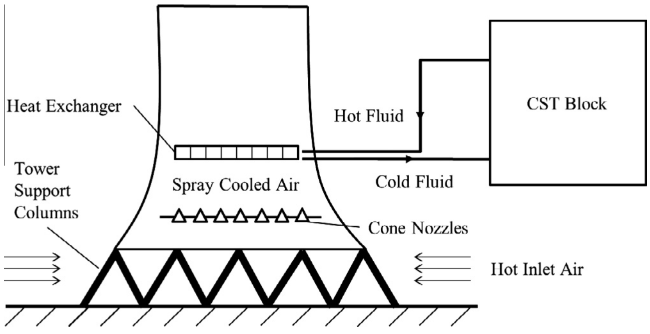

Fig. 1. Schematic cross-section of typical spray-assisted natural draft dry cooling tower.

To perform experimental studies on water spray systems, Phase Doppler Interferometry (PDI) is widely used by researchers. For example, Vetrano et al. used PDI to measure the size and velocity of the droplets in a full cone spray [13]. Using the Weber and Ohnesorge numbers, they presented a correlation to predict the Satur Mean Diameter (SMD) for a viscous liquid. Foissac et al. performed an experimental study on a single nozzle at high mass flow rate of 1 kg/s [14]. To obtain a local high resolution information about the spray, they used PDI and measured the size and velocity of the droplets passing through an optically defined probe volume. They reported no droplet at the core of the spray due to the hollow cone type of the nozzle. Therefore, the measurement were made in a ring and a Log-Normal distribution was observed for the droplet size distribution. Using PDI, Xie et al. investigated the thermal effects of a pressure swirl nozzle in spray cooling [15]. They reported that higher local droplet velocity occurs where there is a higher local droplet flux in the spatial distributions. Pawar et al. used PDI to validate their Euler-Lagrange model for a hollow cone pressure swirl nozzle spray [16]. They showed that, to obtain a reliable size and velocity for droplets, 5000 samples is adequate for each measurement.

In this study, the influences of initial and ambient conditions on the cooling performance of a single nozzle spray of NaCl–water solution are investigated. Firstly, using the experimental PDI results obtained in this study, a CFD model is partially validated. Then, after adjusting the geometry in the model, a wide range of initial conditions (for spray and ambient air) are simulated and non-dimensional analysis is applied to the data.