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Cooling performance of solid containing water for spray assisted dry cooling towers

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ABSTRACT

This article investigates the performance of saline water, compared to pure water in spray cooling and demonstrates the existence of several advantages. To simulate the crystallisation behaviour of saline water droplets, a set of modifications are made to the multicomponent discrete phase model (DPM) of ANSYS FLUENT. After validation against single droplet data, a practical spraying application with a single nozzle in a vertical flow path is studied. The results are compared with a similar case using pure water as the coolant. It is shown that using saline water for spray cooling improves cooling efficiency by 8% close to the nozzle. Furthermore, full evaporation takes place substantially earlier compared to the pure water case. The mechanism behind this phenomenon is explained. The consequence of this is a reduction of up to 30% in the distance between nozzle and the creation of a dry gas stream. This paper provides new fundamental understanding in the area of saline spray cooling, and shows that the use of saline water can lead to a number of benefits, such as reduced water costs (compared to pure fresh water), reduced infrastructure costs (more compact cooling towers), and improved cooling performance.

1. Introduction

The efficiency of a dry cooling tower reduces on hot days. For instance, in arid areas production capacity losses of about 50% are predicted [1]. To enhance the performance of dry cooling towers, hybrid cooling methods are suggested to decrease inlet air temperature. The two most common hybrid methods available for dry cooling systems are: evaporative spray cooling and water deluge cooling which both cool the inlet air. Spray assisted dry cooling towers are more efficient and cost effective in arid areas as they do not require a large volume of water. In liquid spray cooling systems, small droplets are used to maximise the contact area between liquid and air resulting in higher total heat and mass transfer [1]. For instance, water sprays in Kogan Creek power station, Australia consume 140 l/s water on hot days to improve the total power production from 720 to 740 MW. Khan et al. showed that heat transfer while using water spray in a cooling tower is dominated by evaporation (up to 90% close to the nozzles) which results in a high rate of transferred energy [2].

Comparing the two common hybrid cooling methods, the evaporative spray cooling is more effective as the pressure drop on the air stream due to spray of water is small and may be neglected [3]. However, the temperature and relative humidity changes are the main assets. Al-Amiri et al. [4] reported that 100% saturation efficiency on the inlet air can be achieved in specific conditions. In their method, the large contact area provided by atomization, increases the total heat transfer to the spray and decreases the air temperature while the moisture content is rising [4]. Nonetheless, the size of the droplets plays a key role in full evaporation. High pressure nozzles are used to generate small droplets. Wachtell [5] showed that the droplet with the size of 20 μm or less can provide full evaporation in his experimental study. Since working conditions are involved in the process, different researchers found different droplet sizes for complete evaporation [6,7]. Alkhedhair et al. [8] performed a CFD analysis on a single spray nozzle for different air conditions. They showed that 81% of the water content of the spray evaporates at 40 °C and 40% relative humidity. Also, 8.1 °C temperature drop can be achieved for 20 μm at 1 m/s air velocity. They showed that the air velocity is an important parameter for the droplets trajectory [8].

However, as hot areas are typically arid spray cooling faces the obvious challenge of fresh water scarcity. In these regions using saline water for cooling applications, would provide more efficiency and power generation, without adversely affecting the scarce fresh water resource.

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Nomenclature

A	surface area (m^2)
a_1, a_2, a_3	constants in drag coefficient calculation
c_p	specific heat (J/kg K)
C_D	drag coefficient
D	diameter (m)
E	internal energy (J/kg)
F_D	drag force per unit mass (m/s^2)
F_{x1}	additional acceleration (m/s^2)
F_{x2}	other interaction forces per unit mass (m/s^2)
g	gravitational acceleration (m/s^2)
h	sensible enthalpy (J/kg)
h_D	mass transfer coefficient (kg mol/m^2 s)
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)
J	diffusive flux (kg/m^2 s)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
M	momentum transfer per unit length (N)
$\dot{M}$	mass transfer rate (kg/s)
N	molar flux of vapour (kg mol/m^2 s)
P	pressure (pa)
Pr	Prandtl number
Re	Reynolds number $= \frac{D_d V_r}{v_g}$
RH	relative humidity
S	source term
Q	heat transfer (J)
$\dot{Q}$	heat transfer rate (W)
t	time (s)
T	temperature (K)
V	velocity (m/s)
w	mass fraction
X, Y, Z	Cartesian coordinate system (m)
y	molar concentration
δ_{ij}	mean stain tensor (1/s)
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m s)
Φ	viscous dissipation (W/m^3)
v	kinematic viscosity (m^2/s)

Subscripts

0	initial condition
d	droplet
e	energy
g	gas
i, j	Cartesian components
in	condition at entry of computational cell
$\acute{i}$	fluid species
m	mass
mean	area weighted mean
mid	midline
mo	momentum
out	condition at exit of computational cell
r	relative
ref	reference
s	surface
t	turbulent
∞	free stream

The use of saline water does not only lead to design improvements for the spray cooling system, as outlined through the analysis presented in this paper, but can also lead to economical and environmental benefits. For example, after considering the capital and operational costs, Fabricio et al. showed that the using seawater as the cooling fluids reduces cooling utility duties by 49.69% [9].

Another example for such water is coals seam gas (CSG) water which is the rejected waste water produced during coal seam gas production. For instance, in arid areas in Queensland, Australia a large volume of CSG water is produced during the production of natural gas from coal-bed methane. By using and consuming this water an additional environmental benefit is attained [10]. Methane desorbs from coal if pressure is decreased in the underground reservoir by water pumping [11]. Therefore, here CSG water is available as a valuable source for spray cooling systems. There are, nonetheless, some dissolved and insoluble materials in this water. Kinnon et al. showed that NaCl is the main salt in the CSG water from coal-bed methane production in Bowen Basin in Queensland which constitutes about 84% (mass based) of the total dissolved salt [10]. Due to the similarities between the physical properties of NaCl and the other dissolved salts, the CSG water may be considered equivalent to water containing NaCl (saline water).

A negative side effect of using saline or CSG water is that all metal surfaces, particularly the heat exchanger surfaces are exposed to corrosion and solid particle (salt) deposition. Chloride ions in the water increases the rate of corrosion on the surface of the heat exchanger [12]. While this is undesirable, there are a number of engineering solutions to overcome this problem.

First, the hybrid cooling tower can be designed to avoid contact between liquid droplets (vapour) and surfaces. By ensuring evaporation of the droplets is complete before they reach the heat exchanger surfaces, the reactiveness of the saline solution is reduced [13] and cooling is maximised.

Second, corrosion resistive materials can be used. For example, Condamine power station in Australia uses CSG water to cool the condenser (see Fig. 1). Here corrosion is avoided by the use of a titanium condenser and fibreglass transmitting pipelines.

Other approaches to inhibit corrosion include the use of various paints and surface treatments [14,15] and controlling cooling water temperature [15,16].

Sadafi et al. [17] simulated the evaporation process from a solid-containing droplet including the slow formation of the crust. In their model, the evaporation process is split to four stages: temperature adjustment, isothermal evaporation, transition to crust formation, and drying out. This results in a better agreement with the experimental results compared to existing models [17].This work and previous studies by Rezaei et al. [18] show that the evaporation process in a dry cooling tower takes place at temperatures substantially below the boiling point, meaning that the heat transfer and evaporation is dominated by diffusion across the vapour gradient (partial) pressure. As these models are developed for cases with ambient temperature below the boiling point, they are not applicable to high temperature evaporation. In a subsequent study, Sadafi et al. [19] monitored the saline water droplet size at different ambient conditions using microscope digital camera. They showed that for 500 μm radius droplets with 3% and 5% initial NaCl mass concentrations the net energy required to evaporate the droplet falls by 7.3% and 12.2%, respectively (compared to a pure water droplet). Also, compared to the time of evaporation of a pure water droplet, the period with wet surface is shorter as a result of crust formation around the saline water droplet. This allows a shorter distance between spray nozzles and heat exchangers [19].