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Influence of ambient conditions and water flow on the performance of pre-cooled natural draft dry cooling towers

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HIGHLIGHTS

- We develop a model to simulate wetted media and natural draft dry cooling tower.
- We examine the influence of ambient conditions and water flow on tower performance.
- The effect of water flow on tower performance is negligible.
- Dry cooling tower can benefit from pre-cooling when the ambient air is hot and dry.
- The water evaporation rate of pre-cooling is less than wet cooling tower.

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ABSTRACT

A simplified heat and mass transfer model in cellulose medium was developed to predict the air outlet temperature and humidity after evaporative cooling. The model was used to simulate the operation of pre-cooled Natural Draft Dry Cooling Towers (NDDCTs) by a validated MATLAB code. The effects of supplied water flow rate to the media, ambient temperature and humidity on the performance of pre-cooled NDDCTs were investigated. It was found that the effect of the selected water flow rates on tower performance is negligible. Both ambient temperature and humidity affect the tower performance.

1. Introduction

A Natural Draft Dry Cooling Tower (NDDCT) creates the air flow through the heat exchanger bundles by means of buoyancy effects due to the difference in air density between the inside and outside of the tower [1]. NDDCTs have received widespread attention because they do not consume water, have low maintenance requirements and cause small parasitic losses. Since NDDCTs rely mainly on convective heat transfer to reject heat from the working fluid, they are not as effective as wet cooling towers which can achieve much higher rates of cooling by water evaporation [2]. The performance of dry cooling is particularly reduced when the ambient air temperature is high. Reduced cooling tower performance lowers the efficiency of the thermal power stations they are serving. Hybrid cooling may be a cost-effective solution by limiting water consumption only to the periods when the ambient temperatures are too high [3–5]. Hybrid cooling is the combination of dry and wet cooling. Kroger [3] reported that there are many ways of combining dry and wet cooling, including deluge enhancement, combinations of dry and wet cooling units, pre-cooling the entering air by humidification. Rising energy costs, together with water scarcity, urge the use of evaporative cooling systems that are economical and highly water and energy efficient [6,7].

Past research has focussed on hybrid cooling with mechanical draft cooling towers. An earlier paper [8] by the present authors is the first report of a study investigating the conditions under which wetted-medium evaporative cooling can be used in NDDCTs. The present paper expands that study by incorporating the effect of water flow rate through wetted media as well as the effect of ambient temperature and relative humidity on the cooling performance of NDDCTs.

The objectives of this paper are threefold: (1) to develop a model to predict air outlet temperature and humidity after evaporative

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Nomenclature

A	area, m^2
A_{e3}	effective reduced flow area, m^2
A_s	heat and mass transfer area, m^2
c_p	specific heat, J/(kg K)
d	diameter, m
F_T	temperature correction factor
f_D	friction factor inside the tube
g	gravitational acceleration, m/s^2
H	height, m
h	heat transfer coefficient, W/(m^2 K); enthalpy, J/kg
h_{ae}	effective heat transfer coefficient, W/(m^2 K)
h_{wb2}	enthalpy of saturated water vapour at wet-bulb temperature of the inlet air, J/kg
K	loss coefficient
l	medium thickness, m
le	characteristic length, $\mathrm{le} = V/A_s = \xi^{-1}$, m
m	mass flow rate, kg/s
Δp	pressure drop, Pa
Q	heat transfer rate, W
Q_1, Q_2	heat rejection rate, W
Q_w	water flow rate, m^3/h
RH	air relative humidity, %
T	temperature, K
ΔT	temperature difference, K
u	velocity, m/s
1/(UA)	overall thermal resistance, K/W
V	volume of medium, m^3
W	medium width, m
w	humidity ratio, kg$_w$/kg$_a$

Non-dimensional groups

Fr_D	densimetric Froude number defined in text
Nu	Nusselt number, $Nu = (h\ \mathrm{le})/k$
Nu_w	Nusselt number of water, $Nu_w = (h_w d_e)/k_w$
Ny	characteristic heat transfer parameter, m^{-1}
Pr	Prandtl number, $Pr = \upsilon/\alpha = (\mu\ c_p)/k$
Re	Reynolds number, $Re = (u_a\ \mathrm{le})/\upsilon$
Re_w	Reynolds number of water, $Re_w = (\rho_w u_w d_e)/\mu_w$
Ry	characteristic flow parameter, m^{-1}

Greek symbols

α	thermal diffusivity, m^2/s
η	cooling efficiency, %
η_{tb}	correction factor
θ_m	the mean flow incidence angle, °
k	thermal conductivity, W/(m K)
μ	dynamic viscosity, kg/(m s)
υ	kinetic viscosity, m^2/s
ξ	specific surface area of medium, m^2/m^3
ρ	density, kg/m^3
σ	ratio of minimum to free stream flow area
σ_c	contraction ratio
φ_{cf}	dimensionless mean temperature difference
φ_h, φ_c	dimensionless temperature changes of water and air

Subscripts

1	the conditions at ground level
2	the conditions at the average height of tower inlet; inlet or before pre-cooling
3	the conditions at the entrance of heat exchanger; outlet or after pre-cooling
4	the conditions at the exit of heat exchanger
5	the conditions at the outlet of the tower
a	air or based on air side; air dry bulb
ci	inlet contraction
ct	separation and redirection of flow at the lower edge of tower shell
ctc	contraction at heat exchanger
cte	expansion at heat exchanger
d	downstream
e	evaporation; tube
f	fin
fr	total effective front of heat exchanger
he	form and friction at heat exchanger
hes	heat exchanger supports
hx	heat exchanger
lm1, lm2	logarithmic mean
LV0	latent heat of vaporization evaluated at 0 °C
medium	cellulose medium
mfr	medium front
s	sensible
to	kinetic energy at the outlet of tower
ts	tower supports
v	saturated water vapour
w	water or based on water side
wb	wet bulb
wi, wo	hot water inlet and outlet

cooling and the water evaporation rate; (2) to determine the effects of water flow rate through the medium and ambient conditions on the pre-cooled NDDCT performance; (3) to investigate the water evaporation of the wetted-medium evaporative pre-cooling systems. A simplified heat and mass transfer model in wetted media was developed to predict the air outlet temperature and humidity after evaporative cooling. The model was used to simulate the effects of pre-cooling systems on the NDDCT performance. The trade-off between cooling performance and pressure drop was included. The MATLAB code of NDDCT without pre-cooling system was compared with the case study reported by Kroger [1] and found good agreement. This validated MATLAB code was then adapted to simulate the operation of the proposed tower with and without pre-cooling.

2. Configurations of pre-cooled NDDCT

2.1. Pre-cooled NDDCT

A hyperbolic, natural-draft, dry-cooling tower pre-cooled with wetted medium packing is shown in Fig. 1, including the cross section, top view of the cooling tower and partial magnification of pre-cooling system. The wetted media considered in this study is made of cellulose paper as can be found in commercial brand, CELdek evaporative cooling pad. The media will be referred to as cellulose media in the rest of the paper. The heat exchangers used extruded bimetallic finned tubes. The heat exchanger bundles were laid out horizontally at the lower end of the tower and were arranged in the form of A-frames placed in a radial pattern. The