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The transient start-up process of natural draft dry cooling towers in dispatchable thermal power plants

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ABSTRACT

A one-dimensional (1-D) transient cooling tower model is presented that can be used to simulate the start-up process of natural draft dry cooling towers (NDDCTs). The model simulates the behaviour of a NDDCT following a step increase in the heat exchanger temperature. The start-up process is analysed in two successive stages. In the first stage, the dominant mechanism is natural convection operating through generation and propagation of hot plumes rising from the heat exchanger surface. An understanding of different phases of plume development based on scaled analysis helps to predict the air flow development in this first stage. In the second stage, the air flow is driven by the draft caused by the difference in the inside and outside densities. The cooling tower system air flow development in the second stage is simulated through a quasi-steady state solution of the well-known draft equation. The simulation is repeated for three different input temperatures. The results show that the higher the input temperature, the higher is the inlet air velocity and shorter the start-up process. The results are validated against data from the commissioning tests of the University of Queensland natural draft cooling tower Gatton test rig. This study aims to help fill the knowledge gap in understanding the NDDCT start-up process. This understanding is important to the employment of NDDCTs in future thermal power plants operating in dispatchable mode.

1. Introduction

This paper is addressing a critical issue relating to the usability of natural draft dry cooling towers in renewable thermal power plants, e.g. concentrating solar thermal plants. Concerns on climate change and damage to the environment brought by traditional fossil fuels accelerate the utilization of clean energy sources such as wind and solar energy. Due to the abundant sunshine in most regions in Australia, both solar photovoltaic (PV) and concentrating solar thermal (CST) power generation are naturally feasible technologies for solar energy harvest [1–3]. The former system has the convenience of directly converting solar energy with no need for a heat engine. Its drawback is the high cost of electrical storage [4]. A CST power system could avoid this shortcoming by relying on thermal storage, which is much cheaper. A CST power system works by concentrating sunlight onto an absorber/receiver. The heat absorbed by heat transfer fluid (HTF) is transported to a thermal power plant [1]. Considering the relatively low cost of PV generation with the CST ability to produce electricity on demand using stored heat, a feasible solution is the close integration of the two in a single installation. While the sun is shining, the PV component would be generating electricity and the CST component would be storing solar heat. When there is no sun, the CST component would take over and start generating electricity using the stored heat. When the components are sized properly, such a combination would provide power through day and night [5,6].

While working together with PV system, the CST power generation system would have to work in a dispatchable mode, providing power on demand. Therefore it would be of significant value to understand what happens during the start-up process and how long it takes for the CST component to start up when the PV generation stops. Past research on the dynamics of CST generation has ignored the cooling tower dynamics [7–9]. This is a significant omission. As a significant part of CST power generation system, the transient thermal performance of cooling towers will undoubtedly affect its dispatchability, but unfortunately has not received enough attention although.

The motivation for using natural draft dry cooling towers with CST and other renewable power plants has been addressed earlier [10,11]. CST plants need high DNI levels and therefore are more likely to be built in dry areas. In such areas, water is scarce and dry cooling is the only option. There is a particularly high potential for CST in Australia remote sites. A relatively recent report

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Nomenclature

A	area (m^2)
B, C	constant
E	experimental
F	Buoyancy flux (kg m/s^3)
H	height, elevation (m)
K	flow resistance
N	number
P	pressure (Pa)
Q	heat transfer rate (W)
R	ideal gas constant
R_0	radius (m)
S	simulation
T	temperature (°C)
U	velocity (m/s)
W	vertical velocity (m/s)
Z	length scale
C_p	specific heat (J/(kg K))
Pr	Prandtl number
Ra	Rayleigh number
Re	Reynolds Number
b	horizontal radius (m)
g	gravitational acceleration (m/s^2)
k	thermal conductivity (W/(m K))
m	mass flow rate (kg/s)
$\dot{m}$	mass flow rate per layer (kg/s)
n	exponent
r	horizontal length (m)
t	time (s)
v	velocity scalar (m/s)
z	vertical direction

Greek letters

α	thermal diffusivity (m^2/s)
β	coefficient of thermal expansion (1/K)
η	entrainment rate
δ	thickness (m)
λ	spacing length (m)
ε	convergence value
τ	dimensionless radius ratio
υ	kinematic viscosity (m^2/s)
ξ	coefficient
Δ	difference
ρ	density (kg/m^3)

Super/Subscripts

I	first
II	second
a	airside
c	critical
i	iteration step
k	number of time step
s	self-similarity
w	near wall
0	characteristic
$'$	difference
$*$	initiation
am	ambient
he	heat exchangers
out	outlet
pl	plume
in	inlet
fr	front
lm	logarithmic mean
ts	tower support
to	tower outlet
ctc	heat exchanger compact
cte	heat exchanger expansion
$mean$	average
1, 2, 3, 4, 5	different locations of cooling tower

prepared by AECOM on behalf of the Australian Renewable Energy Agency stated that "currently there is over 1.2 GW of diesel generation capacity installed in off-grid Australia which supplies electricity to mines and communities at a cost of 240-450AUD/MWh in fuel only (excluding capital costs)" [12]. Replacement of diesel in these installations provides a natural commercialisation path for properly configured CST plants [13]. Natural draft dry cooling towers (NDDCT) offer a cost-effective choice for these kinds of power plants, since they have no water loss and no parasitic power consumption [10]. Plenty of former research has been made experimentally and numerically on the thermal performance of NDDCTs applied in both conventional thermal power plants and small size power plants [14–16]. Kröger et al. [17] concluded a 1-D steady-state model of NDDCTs via operation data logging from different power plants including Gagarin, Rugeley and Grootvlei power plants, making it simple to evaluate the thermal performance of NDDCTs in the absence of crosswind. Most of this past research has focussed on tall towers suitable for large conventional thermal power plants. For tall towers, the effect of cross wind is small. With a focus on relatively small renewable power generation (smaller than 30-MWe), our research group has focussed on shorter towers. Lu et al. [15] built the 3-D numerical model of Gatton tower with windbreak walls to reverse the negative effect brought by crosswind. He et al. [18,19] examined pre-cooling using wet media, which could significantly improve the efficiency especially in hot weather. Recently, Sun et al. [20,21] studied the influence of injection direction on the spray cooling performance and considered alternative nozzle types and placements to enhance the thermal performance by 3-D model.

Almost all past research was concerned with the steady-state thermal performance of NDDCTs. Few focused on the transient performance of NDDCTs, especially on the start-up stage. To fill this gap, this research mainly focuses on the start-up process of natural draft dry cooling tower and introduces a methodology to simulate start-up transients. While the method will apply to natural draft dry towers of any height, we will develop predictions for a short tower, with the aim of validating these predictions through experimental testing on our Gatton cooling tower.

Specifically, in a natural draft dry cooling tower, the flow of air over the heat exchanger bundles is caused not by fans but a draft force proportional to the density difference between the cold ambient air outside the tower and the hot air inside the tower. When the cooling tower is starting from cold, there is no such density difference and the draft equation that is used to predict the steady-state performance is not useful in such conditions.

Until the draft force becomes significant, the heat is transferred from the hot heat exchanger surface to the air through natural convection. Past studies of natural convection on horizontal plates suggest that the primary heat transfer mechanism in these instances is the generation of plumes that start from the hot surface and rise into the cold air above. A plume is a coherent structure that bursts and detaches from the thermal boundary layer