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Full scale experimental study of a small natural draft dry cooling tower for concentrating solar thermal power plant

Xiaoxiao Li *, Sam Duniam, Hal Gurgenci, Zhiqiang Guan, Anand Veeraragavan

School of Mechanical and Mining Engineering, The University of Queensland, Brisbane, Australia

HIGHLIGHTS

- A 20 m high natural draft dry cooling tower is designed and tested.
- The cooling tower model is refined and validated with the experimental data.
- The performance of the cooling tower utilized in a CST power plant is investigated.
- Ambient temperature effect on Rankine cycle and Brayton cycle is discussed.

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ABSTRACT

Concentrating solar thermal power system can provide low carbon, renewable energy resources in countries or regions with strong solar irradiation. For this kind of power plant which is likely to be located in the arid area, natural draft dry cooling tower is a promising choice. To develop the experimental studies on small cooling tower, a 20 m high natural draft dry cooling tower with fully instrumented measurement system was established by the Queensland Geothermal Energy Centre of Excellence. The performance of this cooling tower was measured with the constant heat input of 600 kW and 840 kW and with ambient temperature ranging from 20 °C to 32 °C. The cooling tower numerical model was refined and validated with the experimental data. The model of 1 MW concentrating solar thermal supercritical CO_2 power cycle was developed and integrated with the cooling tower model. The influences of changing ambient temperature and the performance of the cooling tower on efficiency of the power system were simulated. The differences of the mechanism of the ambient temperature effect on Rankine cycle and supercritical CO_2 Brayton cycle were analysed and discussed.

1. Introduction

The concern over the depletion of fossil fuels as well as greenhouse emissions provide the motivation for seeking alternative energy sources. Solar energy is abundant and clean. Most regions of Australia are blessed with almost continuous sunshine. Moreover, due to the population distribution of Australia, there are vast remote areas with isolated communities and mining sites that are off-grid and currently rely on diesel power generation. Replacement of diesel with Concentrating Solar Thermal (CST) is commercially feasible but requires CST technology suitable for down scaling. Thus the Australian Solar Thermal Research Initiative (ASTRI) is developing scaleable and modular CST power generation systems, which can be utilized in the remote parts of Australia.

Like all other thermal power generation, a CST power plant is a heat engine. In a heat engine, the thermal efficiency increases with an increase in the average temperature at which heat is supplied to the system or with a decrease in the average temperature at which heat is rejected from the system. Therefore, the cooling tower is an integral part of the power plant and its performance significantly influences the plant performance [1]. Unlike conventional thermal power plants, the CST power plants proposed for Australian regional community will have smaller capacities and are likely to be located in areas with strong direct normal irradiance (DNI), but short of fresh water supplies. For such plants, short natural draft dry cooling tower (NDDCT) technology which feature no water losses and virtually no parasitic power consumption offers a cost effective option [2,3].

A great deal of experimental research has already been published on the cooling performance of tall NDDCTs for large conventional thermal power generation. Kröger et al. [4] summarized the previous full scale experimental studies of the industrial dry

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* Corresponding author.
E-mail address: x.li3@uq.edu.au (X. Li).

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Nomenclature

A	area (m^2)
C_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
d	diameter (m)
h	enthalpy ($kJ\ kg^{-1}$)
H	height, elevation (m)
K	flow resistance
L	length (m)
m	mass flow rate (kg/s)
n	number
p	pressure (Pa)
Q	heat transfer rate (kW)
q	heat flux ($kW\ m^{-2}$)
Re	Reynolds number
T	temperature (°C)
v	velocity scalar ($m\ s^{-1}$)

Greek letters

η	efficiency
ρ	density, mean density ($kg\ m^{-3}$)
Δ	property difference

Subscripts

a, w	air side, water side
com	compressor
e	effective
i, o	inside or inlet, outside or outlet
t	tube

cooling towers. The experimental data of the Gagarin power plant, Rugeley power plant, and Grootvlei power plant were recorded in their book. Wei et al. [5] studied the unfavorable effects of wind on the cooling efficiency of dry cooling towers. They tested a hyperbolic shape NDDCT with 125 m height and base diameter of 108 m. The mean air draft speed, the distribution of the mean temperature of the heat exchanger and the distribution of the mean temperature along the central axis of the tower were measured with and without wind. Amur [6] investigated the performance of a prototype natural draft wet cooling tower in the Mount Piper power station at Sydney. The air velocity inside the tower was measured by number of anemometers installed inside the tower along four different diameters. The authors recorded the crosswind speeds and the cooling tower air velocities with the plant working at full load. Chaibi et al. [7] reported the result of pilot tests on the cooling performance of a direct cross flow mechanical cooling tower in southern part of Tunisia. The authors recorded the experimental data of the vertical water temperature profile and the variation of the cooling efficiency during the year. Hu and Chen [8] collected the cooling tower data from two industrial cooling towers located in Zouxian and Xuzhou Huarui power plants in China. The authors compared the water outlet temperatures against their numerical models. The bulk of past literature on natural draft dry cooling towers is for tall towers (>100 m) serving large conventional thermal power plants. The emerging interest in NDDCTs for small to medium renewable thermal power plants motivates research on shorter towers. Lu et al. [9] tested a scaled version of a 15 m-tall NDDCT in a wind tunnel. The air-cooled heat exchangers were represented using an electrical heater. The authors compared the air temperature and velocity measurements against their CFD model predictions and found them matching quite well. Zhai et al. [10] discussed the wind-break wall method on NDDCT using both experimental investigation and computer simulation. The experimental scale is 1/640 of the prototype. The natural draft phenomenon is represented by mechanical fans in this test. The velocity of the crosswind and the air velocity profile inside the cooling tower were measured. Gao et al. [11] studied the influence of the vortices inside the wet cooling tower using a 36 cm × 68 cm × 85 cm (top diameter x bottom diameter x height) model. The temperature profile inside the tower was measured and the influence of the vortices inside of the cooling tower was discussed.

In the last few years, a number of researchers investigated the cooling systems of CST power plants using both Rankine and Brayton cycles. Martin [12,13] investigated the optimization of the operation of a CST power plant with dry cooling system over a year, considering the molten salts storage, the power block and the air cooling system. Barigozzi et al. [14] discussed the optimization of the cooling system for a waste to energy cogeneration plant. Palenzuela et al. [15] evaluated the different alternatives for the effective integration of desalination technologies in the cooling of CST power plants. Habl et al. [16] compared the wet and dry cooling technologies for the Rankine cycle of a CST power plant. Liqreina [17] investigated the dry cooling options for a 50 MW parabolic trough CST plant. Supercritical CO_2 (sCO_2) power cycles are considered for CST power plant because they offer high efficiencies with scaleable modular and compact turbomachinery designs [18–23]. Reyes-Belmonte et al. [24] discussed the optimization of a recompression sCO_2 cycle for a CST power plant. Small changes on cycle parameters such as working temperatures, recuperator efficiencies or mass flow distribution between low and high temperature recuperators were discussed in this paper. Osorio et al. [25,26] studied the dynamic behavior of a CST sCO_2 cycle under different seasonal conditions. Effects of mass flow rate, intermediate pressures, effective area of the recuperator and number of compression–expansion stages on the performance of the system were analysed. Turchi et al. [27] investigated the potential to dry cool various sCO_2 Brayton cycle configurations. Padilla et al. [28] conducted a detailed energy and exergy analysis of four different sCO2 Brayton cycle configurations with dry air cooling for each configuration considered. Moore et al. [29] investigated the performance of a modular air cooled condenser for a steam cycle based CST plant. Singh et al. [30] analysed the dynamic performance of a direct heated and dry cooled sCO_2 Brayton cycle, using a simplified cooling tower model. Conboy et al. [31] investigated forced draft dry cooling of sCO_2 for advanced nuclear reactors and compared it with dry cooling of steam. It was determined that at same operating points, steam is more difficult to dry cool since it experiences no temperature change thus requiring significantly higher air flow rates compared to airflow required for sCO_2.

The experimental study of the cooling tower is a very important preparation for the future application. However, the experimental studies, especially the full scale experimental study for small NDDCTs, are still not extensive. No full scale experimental study about the short-NDDCT (less than 30 m) has been reported in the literature. There have been numerous studies investigating forced draft air cooling of the sCO_2 Brayton cycle, and NDDCTs have been widely studied in isolation, no studies are found which address performance of NDDCT cooled sCO_2 Brayton cycle.

In order to fill the gap, the Queensland Geothermal Energy Centre of Excellence (QGECE) have built a 20 m NDDCT with an advanced measurement system at the Gatton campus of the University of Queensland. In this research, the performance of this cooling tower was tested with the constant heat load 600 kW and 840 kW and with the ambient temperature ranged from 20 °C to 32 °C. The one-dimensional cooling tower model was refined and