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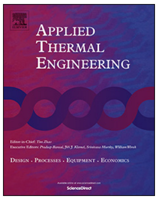

Research Paper

Numerical analysis of solar enhanced natural draft dry cooling tower configuration

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HIGHLIGHTS

- A 3-D model for solar enhanced natural draft dry cooling tower is developed.
- Different design options are comparatively analysed.
- The design option with partial blockage at collector entrance is more preferable.
- The design option with flat sunroof and parabolic tower is more preferable.

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ABSTRACT

Solar enhanced natural draft dry cooling tower (SENDDCT) is a new heat rejection device using solar energy to enhance its cooling performance. In an attempt to find out the optimal structural arrangement of SENDDCT, this paper conducts three-dimensional CFD simulations to compare cooling performances of various design options. The simulations commence by investigating whether the design option with lower-height heat exchangers at collector entrance has better cooling performance than that with partial blockage at the same location. Then the simulations compare the thermal performances of SENDDCTs with different sunroof and tower shape design, namely horizontal sunroof plus parabolic tower or titled sunroof plus cylindrical tower. Finally, analyses of the simulation results show that the design option with the partial blockage at the collector entrance, horizontal sunroof and parabolic tower would be the optimal selection in terms of thermal performance and structural robustness.

1. Introduction

Cooling towers, as heat rejection devices that dissipate waste heat through the cooling of working fluid to a lower temperature, are widely used in thermal power plants such as coal-fired power generators and nuclear power plants [1–4]. Cooling towers can be categorised into dry cooling and wet cooling in terms of the method employed to generate heat transfer between air (cooling medium) and working fluid to be cooled. A wet cooling tower operates on the principle of evaporative cooling. The working fluid (mostly water) is distributed into the tower by spray nozzles, splash bars or films to create a large direct contact area between the water to be cooled and the ambient air [5,6]. The airflow is either generated by the induction effect of water sprays (i.e. natural draft) or by the mechanical fan (or fans) (i.e. mechanical draft) and water is cooled to a lower temperature due to the energy consumption in the evaporation process. However, in the evaporative process, air not only carries away the waste heat of water but saturated water vapour as well. It inevitably leads to a considerable loss of water, which is unacceptable in arid areas. Hence, the dry cooling technology attracts more and more attentions nowadays, especially in water-limited regions. Unlike wet cooling towers, dry cooling towers rely on air to cool the working fluid to near the dry-bulb air temperature [7–12]. There is no direct contact between air and working fluid and consequently not any loss of working fluid to the atmosphere.

Traditional natural draft dry cooling tower (NDDCT) utilises the air pressure differential between inside and outside of tower to generate continuous air current flowing through heat exchangers. Consequently, the waste heat of working fluid inside heat exchangers transfers to the airflow. Compared to its counterpart, i.e., Mechanical Draft Dry Cooling Tower (MDDCT), NDDCT needs no fan (or fans) to blow or to induce the airflow through heat exchangers and thus no parasitic losses due to fan power consumption [13].

Since the driving force of NDDCT, i.e., the air pressure differential between the inside and outside of tower, highly depends on the ambient air temperature, NDDCTs suffer low cooling efficiencies in

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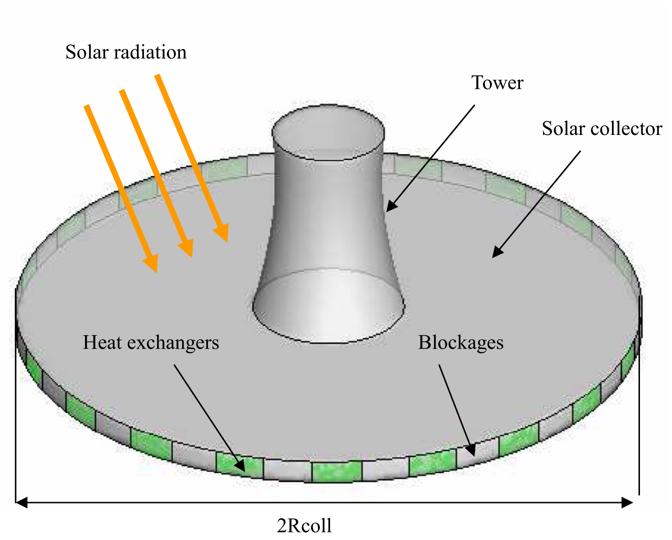

Fig. 1. Configuration of solar enhanced natural draft dry cooling tower.

hot periods especially at noon in summer when the ambient temperature is high which is usually the peak electricity demand period as well. To enhance the cooling performance of NDDCT under high ambient temperature, a new cooling system, named Solar Enhanced Natural Draft Dry Cooling Tower (SENDDCT), was developed under the inspiration of the fact that high ambient temperature always accompanies with high solar intensity [14–17]. The main difference between SENDDCT and solar chimney power plant (SCPP) is that the SENDDCT utilises the solar enhancement to accelerate the airflow through heat exchangers and accordingly to dissipate more waste heat, whereas the solar chimney power plant uses solar energy to generate the updraft for driving turbine to generate electricity [18–23].

Three major components of a solar enhanced natural draft dry cooling tower are the heat exchangers, solar collector (sunroof and ground), and tower. In the original structure design of SENDDCT, heat exchangers are placed vertically along the outer edge of solar collector and therefore collector entrance, exit (i.e. tower inlet) and heat exchangers are of the same height, as shown in Fig. 1. In order to reduce the pressure loss at collector-to-tower transition zone, the towers are designed with a parabolic shape that is the same as most of conventional natural draft wet/dry cooling towers [9–11]. Theoretically, the larger the solar collector size, the more solar enhancement would be obtained. For a SENDDCT with a fixed heat exchanger area, as the solar collector size is increased, the frontal area of heat exchangers may not offer full coverage to the perimeter of increased solar collector. In that case, the partial blockage at collector entrance has to be introduced to ensure air only flows through heat exchangers and the height of heat exchangers remains unchanged. However, there is a concern that partial blockage at solar collector entrance may generate vortices at the back of heat exchangers which may influence the cooling capacity of heat exchangers adversely. Hence, another structure design option at collector entrance is proposed: as solar collector diameter is increased, instead of introducing more blockages at collector entrance, the heat exchanger height is reduced to such a level that the corresponding frontal area of heat exchangers always covers most of the collector entrance area. Compared to the original design option, the latter can have the same collector size but rule out the possibility of vortex generation at the back of heat exchangers and thus there would not be any damages caused by vortices to the cooling capacity of the entire system. To find out the optimal structure design of SENDDCT, it is necessary to investigate whether the design option with low-height heat exchangers at collector entrance is more beneficial than the original one introducing partial blockage at the outer edge of collector.

On the other hand, in large-scale solar chimney power plant proposals in the literature, the height of sunroof increases adjacent to the tower base, so that the air is diverted to vertical movement with minimum friction loss at the collector-to-chimney section [22]. By contrast, the sunroof was designed with horizontal shape in original structure design of SENDDCT. Hence, there is a doubt that whether the structure design option with tilted sunroof and cylindrical tower is more suitable for SENDDCT in terms of cooling performance.

In an attempt to address these unsolved questions mentioned above and provide a guideline for the design and construction of SENDDCT, this paper conducts three-dimensional (3D) CFD simulations to investigate the optimal structural arrangement of SENDDCT. The simulations commence by investigating whether the design option with lower-height heat exchangers at collector entrance has better cooling performance than that with partial blockage at the same location. Then the simulations compare the thermal performances of SENDDCTs with different sunroof and tower shape design, namely horizontal sunroof and parabolic tower or titled sunroof plus cylindrical tower. Finally, a conclusion is dropped based on these comparative analysis results.

2. Development of 3-D model for SENDDCT

For a good basis of comparison, a case study example is needed here as the reference case in following comparison analyses. According to Zou et al. [14,15] and Kröger [24], major geometric and operating parameters of this test case (named as test case A) were elaborately chosen to meet industrial reality, their values are shown in Table 1. Note that the finned tube heat exchangers were selected and used in the present study, reflecting the industrial practice in power plants with dry cooling, and the frontal area of heat exchangers in test case A only covers half of the total collector entrance area (i.e., coverage ratio of 50%).

The development of 3-D numerical model for SENDDCT involves the determination of computation domain, setting of boundary conditions, and selection of governing equation. They are detailed in the following sections.

Table 1
SENDDCT configuration in the reference case (test case A).

Description	Symbols	Values
Row number	n_r	3/4 rows
Tower height (m)	H_c	150
Tower base radius (m)	R_{base}	52.5
Tower throat radius (m)	R_{throat}	33.35
Tower outlet radius (m)	$R_{toweroutlet}$	40
Sunroof radius (m)	R_{coll}	195
Height of collector entrance (i.e., height of heat exchangers) (m)	H_{coll}	15
Number of tubes per row	n_r	39
Transversal pitch (mm)	p_t	66
Fin pitch (mm)	p_f	2.5
Fin thickness (mm)	t_f	0.3
Fin root diameter (mm)	d_r	40
Fin diameter (mm)	d_f	65
Water inlet temperature (K)	T_{wi}	333.15 K
Air ambient temperature (K)	T_{ai}	303.15/298.15
Water velocity in the tubes (m/s)	V_w	1
Coverage ratio (the ratio of heat exchanger frontal area to collector entrance area) [−]	[−]	50%