Comparison analysis of four wind breaking designs for the hybrid cooling-tower-solar-chimney system under crosswind conditions

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Abstract: A hybrid cooling-tower-solar-chimney system (HCTSC for short) is a novel heat rejection device that dissipates waste heat for coupled thermal power plant and generates electricity simultaneously. Since the heat exchanger bundles are vertically placed at the periphery of the solar collector, this novel natural dry cooling system is relatively vulnerable to the crosswind. In order to enhance its performance under the crosswind conditions, four types of counter-wind designs were proposed and numerically compared. Comparison results showed that all four wind breaking designs were indeed helpful for the improvement of the power output under high intensity crosswind condition but it is at the cost of its heat dissipation performance.

1. Introduction

The cooling tower is a type of cooling device to dissipate waste heat for coupled thermal power plant, such as coal-fired power plant and concentrating solar power plant (CSP). Taking it by and large, the cooling towers can be categorized into wet cooling tower and dry cooling tower. The evaporation in a wet cooling tower makes it unfavorable for power plant located in an arid area with shortage of water resources. With the booming of CSP technology, more attentions have been shifted to the dry cooling tower, especially the natural draft dry cooling tower which is characterized by almost no extra water consumption and less parasite loss.

A typical natural draft dry cooling tower mainly consists of heat exchangers and tower shell. The heat exchangers are either horizontally placed at the tower bottom, or vertically installed at the periphery of tower. The heat exchangers by which the hot water rejects the waste heat to the atmosphere causes an air temperature difference between inside and outside of the tower, therefore ambient air is sucked into the tower through the heat exchangers and flows out from the tower exit due to the chimney effect. Under the inspiration of the mechanism of the solar chimney power plant [1-2] and that of the solar ventilation system for buildings [3-4], to further exploit the momentum of airflow inside the tower, the concept of hybrid solar-chimney-cooling-tower system was proposed [5-6], as showed in Figure 1.

Note that in the structure design of the hybrid solar-ventilation-cooling-tower system, heat exchanger bundles are vertically placed at the perimeter of the solar collector, hence it generally suffer more from the crosswind than those natural draft dry cooling towers (NDDCTs) with horizontally-placed heat exchangers. With the aim of finding optimal counter wind strategy for HCTSCs during windy condition and identifying the relationship among the cooling performance recovery, the types and locations of wind-break walls, a series of numerical simulations was conducted in this present paper.
2. Modeling, comparison and discussion

To achieve research goals mentioned above, a three-dimensional model of HCTSC system was proposed [7]. In present comparison study, four different wind breaking designs were investigated, i.e., inner union-jack-like wind break wall (test case 1), inner union-jack-like wind break wall plus outer wind deflector (test case 2), inner cross-like wind break wall (test case 3), and inner cross-like wind break wall plus outer wind deflector (test case 4). The test case representing the HCTSC without adopting any wind breaking designs was also included in this numerical study to provide a reference for counter-wind performance evaluation (test case 0). These four wind breaking designs were depicted in the Figure 2. The thermodynamic characteristics of the reference HCTSC coupled with different wind breaking designs were studied and compared in order to determine which designs is most favorable for the performance of HCTSC on the windy weather.

Figure 2. Sketches for different wind breaking designs for HCTSC (top view): (a) inner cross-like wind break wall; (b) inner cross-like wind break wall plus outer wind deflector; (c) inner union-jack-like break wall; (d) inner union-jack-like break wall plus outer wind deflector.

Under the no crosswind condition, the chimney effect is the only driving force of the air current inside of the HCTSC. Surrounding air was evenly being sucked into the solar collector and then converged at the chimney bottom. After driving the turbine to generate electricity, the air flew out from the chimney in a direction normal to the ground, as seen in Figure 3(a). When the crosswind was introduced, the path line of the air flowing out of the chimney slanted to the leeward side under the crosswind effect no matter whether or not the reference HCTSC equips with any wind break walls. The stronger the crosswind, the more inclined the airflow path line, as shown in Figure 3(b-c).

Figure 3. Calculated airflow path line inside of the HCTSC without adopting any wind breaking design under different crosswind conditions: (a) no crosswind; (b) 4 m/s; (c) 8 m/s.

However, more interesting phenomenon was found related to the variation of airflow path line inside
of the solar collector under the joint influence of different wind break design adopted and variant crosswind intensity. Figure 4 (a) revealed that when the HCTSC without adopting any wind breaking designs exposed to a low speed crosswind (2 m/s), the intake non-uniformity occurs. And this tendency was more obvious than those in test cases 1-4, as revealed in Figure 4(b-e): vortices appeared in the side chambers of the windward part of the solar collector. A reasonable explanation for this finding was that when the low speed crosswind was introduced, the air flow pattern inside of the HCTSC depended on two factors: the crosswind effect and the buoyancy effect. Under such a low speed crosswind condition, for test case 0, the accelerated air entering from the windward side can directly reach to the leeward side of the solar collector causing extra pressure drop to the airflow sucked in from the leeward side by buoyancy. Hence, more air was taken in from the windward side, whereas less air entered from the leeward side. Reversely, in test cases 1-4, due to the existence of the wind break walls, the air passage between the leeward side and windward side was cut off and whole solar collector was separated into a few individual chambers. At a low crosswind velocity of 2 m/s, the blown-in air from the windward side was too weak to significantly affect the air entering from the leeward side of the solar collector, and each section can function almost independently and therefore more uniform airflow path appeared in the test cases 1-3. Another interesting observation is the effect of the introduction of outer wind deflector on the flow pattern inside of the solar collector. By comparing the airflow path lines between test cases 1-2 (i.e., Figures. b-c) and that between test cases 3-4 (i.e., Figures. d-e), a conclusion can be made that under a low-speed wind condition, the introduction of outer wind deflector can successfully curb the development of air re-circulation zone in the leeward chamber.

Figure 4. Calculated airflow path lines in the test cases 0-4 under low-intensity crosswind conditions:
(a) test case 0; (b) test case 1; (c) test case 2; (d) test case 3; (e) test case 4.

When high speed crosswind appears, air movement both inside and outside of HCTSC changed dramatically. To give a better picture of what happened for the airflow pattern inside of the solar collector under the effect of high speed crosswind. The airflow field (8 m above the ground surface) in five test cases 0-4 at the crosswind velocity of 8 m/s was drawn, as seen in Figure 5 (a-e). Comparing Figure 5 with Figure 4, a conclusion can be found that the stronger crosswind, the stronger vortices generated. Comparing the streamlines shown in Figure 5 (d) and Figure 5(e), another finding is that the outer wind deflector enlarged the low static pressure zones and therefore the larger size of vortices in the side chambers.

Figure 5. Calculated airflow path lines in the test cases 0-4 under high-intensity crosswind conditions:
(a) test case 0; (b) test case 1; (c) test case 2; (d) test case 3; (e) test case 4.

As can be seen in Figure 6(a), all four proposed wind break designs were effective for the recovery of the power generation capacity under wind conditions. Note that no matter what kind of wind breaking designs was chosen, the power output of the HCTSC followed the same pattern: with the increasing crosswind intensity, the amount of power output kept increasing. That was because that due to the existence of the wind break wall, the crosswind was forced into the chimney to generate electricity.
larger the crosswind intensity, the greater power output would be. Figure 6(a) also revealed that compared with other wind breaking designs, the one with inner cross-like wind break wall and outer wind deflector had the best performance in improving the power output of the HCTSC under crosswind conditions. When the crosswind speed was 10 m/s, with such a wind breaking design, the power output of the HCTSC can reach to 173 kW. It was a 50% increase in the power generation capacity compared with that for the test case 0 (without any wind break designs).

Figure 6. The variation in both the power generation capacity and heat dissipation capacity of the HCTSC with adopting different wind breaking designs under the crosswind conditions: (a) power generation; (b) heat dissipation.

However, the benefits from the wind breaking designs in terms of the enhancement in the self-power-generation capacity was at the cost of the heat dissipation performance, as shown in Figure 6(b). Take the design with inner cross-like break wall as an example, although the wind break wall can lead the blown-in air to flow up into the chimney to generate electricity, it simultaneously blocked the airflow passage between the windward and leeward sides of the solar collector. when the low-speed crosswind was introduced (i.e., 2-4 m/s), it not only increased forced convection heat transfer occurred on the heat exchanger bundles located at windward side, but also weakened the intensity of the buoyancy effect and therefore less air can be sucked into the solar collector from the leeward side. It means less heat can be dumped by heat exchanger bundles at the leeward side. The decrease in the heat dissipation capacity of heat exchanger bundles at the leeward side was roughly equal to the increase in the heat dumping performance of the heat exchanger bundles at the windward side. Therefore, there was not an obvious change in the total heat dissipation rate when wind speed varied from 0 to 4 m/s.

With the increasing crosswind speed, the crosswind became the dominant driving force in the heat dumping duty. Under such circumstances, the heat dissipation capacity mainly depended on the effective heat transfer area. In test case 0, the absence of inner wind break wall made accelerated airflow directly blow onto the heat exchanger bundles at the leeward side. Therefore, the HCTSC without adopting any counter wind methods had the largest heat dissipation capacity under high-intensity crosswind conditions (6-10 m/s). Reversely, the inner wind break wall design would block the air passage to the heat exchanger bundles at the leeward side of the HCTSC and hence the degradation of the heat dissipation capacity. Note that when the crosswind speed reached to 10 m/s, the counter wind design with inner union-jack-like break wall has lowest heat dissipation rate, i.e., 61 MW. Compared to the calculated result from the test case 0, there was an approximately 44% decrease.

It should be noted that the effect of wind breaking design on the HCTSC system are quite different from that on the natural draft dry cooling tower although their structures are similar. According to Al-Waked and Behnia [8] and Lu [9], the wind breaking design at the tower bottom are favorable for the recovery in the heat dissipation capacity when crosswind appears. The difference in the effect of wind breaking design between the HCTSC and the NDDCT under wind condition is due to the different arrangement of heat exchanger bundles. In the studies from Al-Waked and Behnia [8] and Lu et al [9], the heat exchanger bundles were horizontally placed at the tower bottom. In that case, the crosswind can be guided by the wind breaking wall into the tower to enhance the convection heat transfer rate of heat
exchanger bundles. However, for an individual HCTSC, instead of being placed horizontally, the heat exchanger bundles were placed vertically at the solar collector inlet. Therefore, the wind breaking designs function differently in these two different systems.

3. Conclusions
In order to quantify the effects of four wind breaking designs for the hybrid solar chimney cooling tower system under crosswind conditions, a series of numerical simulations were conducted. Based on the simulation results, the following conclusion can be drawn:

- All four proposed wind breaking designs work for the HCTSC in terms of the recovery of self-power-generation capacity under crosswind conditions. Unlike in the case of the HCTSC without adopting any wind breaking designs, no matter what kind of wind breaking design was adopted, there would be a significant enhancement in the power output of the HCTSC under high intensity crosswind conditions.
- However, this increase in the self-power-generation capacity by using a wind break design was at the cost of the heat dissipation capacity. At the crosswind velocity of 10 m/s, compared with the original structure, there was more than 40% decrease in the heat dissipation capacity once any of four wind breaking design was adopted.

This numerical study identified both the advantages and disadvantages of four wind breaking designs. It was clear that whether introducing the wind breaking design to the HCTSC should be determined by the trade off between the heat dissipation capacity and the self-power-generation capacity of the HCTSC. If the heat dissipation duty is the priority for the system owner, considering the benefit brought by the crosswind, no wind breaking design should be introduced. On the other hand, once the more green electricity output is the ultimate goal, the design with both inner cross-like wind break wall and outer wind deflector should be adopted.

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