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Experimental study regarding the evolution of temperature profiles inside wet cooling tower under crosswind conditions

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A B S T R A C T

Based on similarity theory, this research details a thermal-state model experiment, concerning the evolution of the air/water temperature profiles inside a Natural Draft Wet Cooling Tower (NDWCT) under windless and crosswind conditions. Prior studies have shown that the air/water temperature distribution is fairly uniform and stable under windless (stagnant) conditions, but the uniformity is destroyed in the presence of windy conditions, and the air/water temperature of different points displays a large variation subject to the same crosswind velocity. Generally speaking, the highest air/water temperature values inside the whole tower lie on the windward and leeward direction, but the highest air temperature at the tower outlet appears near the leeward side zone, rather than exactly on the leeward side. Based on this research, the air/water temperature profiles regarding measurement of values can be obtained accurately under windless and crosswind conditions, a fact that can help confirm the specific location of vortex on the windward and leeward side. All of above findings can provide an important theoretical foundation concerning further research, specifically for energy-saving aspects NDWCTs.

1. Introduction

As a primary component of the cool-end system in thermal power plants including some nuclear power plants, the Natural Draft Wet Cooling Towers (NDWCTs) play an important role to cool the circulating water from the condenser, and its efficiency has a great impact on the total cycle efficiency of power plants. Therefore, it is extremely important and necessary to study the heat and mass transfer performance under crosswind conditions both from an academic as well as an industrial point of view.

Many studies in the past had concentrated on the thermal performance of NDWCTs from several aspects under windless conditions, including mathematical model development [1–4], exergy analysis [5,6], the thermal performance of the rain zone and filling [7,11], water distribution system [12], application of artificial neural network technology [13], and so on. Although some of the fundamental aspects of the thermofluid phenomena were derived from such studies, the heat and mass transfer performance of the cooling tower, including the natural draft dry-cooling towers (NDDCTs) and the natural draft wet cooling towers (NDWCTs), is actually influenced by environmental conditions, especially environmental crosswind [14–17], and such processes have not been studied extensively. Hence, the thermal performance of a generic cooling tower under crosswind conditions is worth researching, providing useful outcome both at an academic and applied level.

In the literature several studies can be found related to heat and mass transfer performance of NDDCTs under crosswind conditions. A. Jahangiri et al. [18] pointed out that environmental conditions strictly affect Heller air-cooling tower's performance; thus it was proposed to inject steam generator's flue gas into the tower for better air suction. Results showed that the flue gas injection would help improve the performance of the cooling tower to some extent. A. Hossein et al. [19] developed a 3-D model to investigate the effect of water spray and crosswind on the effectiveness of the NDDCTs. This computational fluid dynamics (CFD) study discovered that NDDCTs operated most effectively at the crosswind velocity of 3 m/s, and as the wind velocity continues to rise to more than 3 m/s up to 12 m/s, the tower efficiency would decrease by approximately 18%, based on windless condition. One CFD model had been carried out by Y. Lu et al. [20] to numerically analyze the heat transfer performance of a 15 m-high small NDDCT under different crosswind velocity. Simulations showed that, at certain crosswind velocity, the crosswind significantly degrades the cooling performance. However, the negative effect of the crosswind could

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be turned into advantage by introducing windbreak walls. Likewise, R. Al-Waked and M. Behnia [21–22] also established the CFD model to study the performance of NDDCTs, and put forward the proposal to use windbreak walls to improve the thermal performance of NDDCTs. In addition, the effect of crosswind on an indirect dry cooling tower with or without windbreaks had been studied by H. Reshadatjoo et al. [23], the phenomena responsible for the reduction of air intake flow rate (AIFR) under crosswind conditions were identified, and results obtained had been compared with the available experimental results.

Compared with the NDDCTs, the crosswind has less effect on NDWCTs, but it still cannot be neglected during the actual operation. What's more, in the conventional thermal design of NDWCTs, the impact of crosswind, which actually exists in most cases, has not been adequately analyzed and paid appropriate attention.

T.J. Bender et al. [24–26] studied the influence of crosswind on the heat transfer performance of wet cooling towers by means of wind tunnel experiment and numerical computation, but these studies did not agree with the basic approaches of geometric similarity and dynamic similarity between the model and prototype tower. Based on the comparison of the calculated results with experimental data [27,28], A.I. Petrichik et al. [29] concluded that the efficiency of evaporative heat transfer in a cooling tower was influenced by the wind that may rise near the cooling tower.

R. Al-Waked and M. Behnia [30–32] developed a CFD model for NDWCTs, and found that environmental crosswind affected seriously the cooling efficiency. The CFD studies revealed that the circulating water temperature differences were found to be less than 1 K for the whole span of crosswind velocities. M. Gao et al. [33,34] also studied the effect of crosswind on the thermal performance of NDWCTs by thermal-state model experiments and artificial neural networks technology, and arrived at some similar conclusions. Y. L. Chen et al. [35] conducted experimental studies on the cross walls effect on the thermal performance of NDWCTs under crosswind conditions. Experimental researches showed that, at all crosswind velocities, the cross wall at a setting angle of 0° resulted in higher performance than that at 45°, regardless of the cross wall shapes. Moreover, the cross wall at 45° degraded the thermal performance under high crosswind velocity conditions. K. Wang et al. [36] had reported experimental research on the guiding channel effects regarding the thermal performance of NDWCTs subject to crosswinds, and found that although the guiding channels with 70° setting angle led to better cooling performance, they may actually be caused by more circulating water consumption. M. Gao et al. [37] concluded that the unsymmetrical circumferential inflow air and vortex under crosswind conditions destroyed the air dynamic field inside cooling tower, affecting seriously the whole airflow rate, which in turn deteriorated the heat and mass transfer performance.

As can be seen from the above brief review, previous studies demonstrated that environmental crosswind leads to adverse effects on the thermal performance of NDWCTs, and in fact prior researches revealed the influence mechanism, circumferential inflow air profiles, vortex distribution and prevention measures, attributes that are more valuable to NDWCT research; however, previous studies did not analyze the vortex's specific location and influence range, and also failed to discuss the air/water temperature evolution patterns inside the whole wet cooling tower, aspects that are crucial to the further energy-saving research.

Therefore, in this paper studies are conducted regarding the development of the air/water temperature fields inside the wet cooling tower under crosswind conditions via basic thermal-state model experiments to reveal the relevant fundamental heat and mass transfer processes.

2. Experimental study design

2.1. Experimental objectives

The vortices inside NDWCTs under crosswind conditions deteriorate the heat and mass transfer performance of filling and raining zone [37], and hence give rise to substantial temperature variations at different points inside tower. But the specific temperature values at different points had not so far been considered and/or discussed in previous experimental studies. This is a stumbling block for the development of experimental research for NDWCTs.

For that reason, an appropriately designed thermal-state model experiment regarding the development of air/water temperature profiles is conducted in this paper to confirm the temperature values at different points inside a generic NDWCT. During this experiment, the air/water temperature at different points is monitored in real-time by a suitable data collection system and measured by copper-constantan thermocouples under different operating conditions. The confirmation of air/water temperature patterns can lay the foundation on researching for accurately accounting for the influence of the crosswind with a view to enhancing heat and mass transfer performance.

2.2. Experimental setup

The experimental setup is displayed via the schematic diagram depicted in Fig. 1. The model tower adopted in this experiment is designed to simulate a typical NDWCT in large-scale power plants in terms of the engineering similarity theory [15,33,34,37]. i.e., the relevant scale measure of model to prototype tower is 1:100. In addition, the details of the primary measurement setup and instruments are listed in Table 1.

The whole experimental activity hence simulates the actual working process of a typical NDWCT in current thermal power plants, and the crosswind velocity is controlled by frequency conversion fans, including the upper and lower fan shown in Fig. 1. Prior to the start up of the experiments, the circulating water is heated up to required temperature by several electric heaters, and then transported to the upper tank by the circulating water pump. During the experiments, the circulating water enters the model tower and goes through the fillings from top to bottom, while the dry air flows through the fillings from bottom to top. The heat and mass transfer are conducted in the presence of cross flow.

2.3. Similarity criterion

The dimensions of the model cooling tower is given as 37 cm × 68 cm × 85 cm (top outlet diameter × bottom diameter × height), and the height of the tower inlet is 50 mm. The test process also complies with the dynamic similarity, kinematic similarity and thermodynamic similarity besides the geometric (scale) similarity, including the Froude number and wind velocity scale.

Under actual operating conditions, it is difficult to implement *Re* and *Fr* number similarity simultaneously. The velocity in *Re* number varies inversely with the model scale in terms of Eq. (1) and (2), while the velocity in *Fr* number varies directly with the square root of model scale in terms of Eq. (3). Therefore, the *Re* and *Fr* number similarity cannot be satisfied simultaneously in one model experiment. In this thermal model experiment, the driving force of buoyancy and the inertial force of crosswind are the main factors to be considered, while the viscous force is less important. Therefore, the density *Fr* number similarity, which is defined by Eq. (3), should have the priority to be satisfied over the *Re* number [38].