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Investigation of the crosswind-influenced thermal performance of a natural draft counterflow cooling tower

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ABSTRACT

The present work deals with an experimental investigation of the thermal performance of a natural draft wet-type cooling tower with counter flow arrangement. The authors perform a thorough analysis of the simultaneous heat and mass transfer phenomenon between air and water. The investigation mainly concentrates on the effect of crosswind on the thermal performance of the tower. Performance index parameters such as the temperature drop (T_{drop}), effectiveness (e), and the tower characteristic ratio (KaV/L) are presented in the paper. Variation of the performance parameters in terms of inlet water temperature, water flow rate, and wind velocity is studied in a crosswind-influenced environment. When comparing the crosswind-influenced experimental data with that of the windless condition, it is observed that T_{drop} and e decrease by 4% and 4.5%, respectively, in a crosswind environment. However, this decreasing trend of T_{drop} and e is observed up to the critical Froude number, F_{cr}, followed by an increasing trend. Variation of the tower characteristic ratio in the crosswind environment for different values of inlet water temperature is also studied in detail. Two different regimes are found to exist as water and air flow within the tower. However, the capacity of cooling of higher water flow rates demonstrates that regime-II is more efficient than regime-I. Moreover, the correlative equations of different performance parameters are developed for both windless and crosswind conditions. Additionally, a correlation of tower characteristic ratio to different water–air mass flow rates is proposed.

1. Introduction

Cooling towers are an important part of many industrial applications. The primary task of a cooling tower is to cool water in thermal power plants, chemical processing plants and air-conditioning systems with atmospheric air. The heat load of the process plant is removed using cooling towers that facilitate heat and mass transfer between the two direct-contact fluids – hot water and ambient air [1–2]. Cooling towers, which are used most commonly, reduce the temperature of the circulating hot water by bringing it into direct contact with air. These are wet cooling towers. In a wet cooling tower, cooling is achieved partly by the evaporation of a fraction of the circulating water and partly by the transfer of sensible heat.

In general, cooling towers are separate from the main plant, so they are usually ignored until a crisis occurs. The performance of the cooling towers greatly affects the economy and safety of the plants, so much more attention is paid today to their design to ensure effective performance. The concept of zero discharge at power plants and other process plants has been implemented, so the cooling of circulating water is of great importance in those plants. In addition, the safety and reliable operation of the power plants largely depend on the performance of the cooling tower.

A natural draft tower makes use of the principle of density difference that exists between the heated moist air inside the tower and the ambient air outside of the tower. In the thermal design calculation of a natural draft wet cooling tower, the airflow characteristics play an important role, so the critical step in designing a tower is to make out the airflow resistance and ventilation quantity [3]. Crosswind has a large role to play on the performance of cooling towers. In windy weather, the interior flow pattern of a natural draft tower is nonuniformly distributed, and some coiled vortices are formed. Additionally, the atmospheric air flowing around the tower

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Nomenclature

a	Surface area of the tower per unit volume (m^{-1});	L	Water flow rate per unit area (kg/m^2hr);
C_{pw}	Specific heat of water at constant pressure of the moist air (J/kgK);	q	Water volume flow rate (m^3/hr);
D	Diameter of the tower bottom (m);	R_{lower}	Lower shell radius of the tower (m);
e	Effectiveness;	R_{throat}	Throat radius diameter (m);
F_{cr}	Critical Froude number;	R_{upper}	upper shell radius of the tower (m);
G	Air flow rate per unit area (kg/m^2hr);	T_1	Inlet water temperature (°C);
H_{total}	Total height of the tower (m);	T_2	Outlet water temperature (°C);
H_{throat}	Throat height of the tower (m);	V	Active volume per unit cross sectional area (m);
i'_s	Enthalpy of saturated air (kJ/kg);	w	Specific humidity of the moist air at entry of the tower (kg/kg dry air);
i_1	Enthalpy of moist air at the tower entry (kJ/kg);	α, λ	Constants.
K	Mass transfer coefficient (kg/m^2hr);		

weakens the interior flow pattern, so the tower performance deteriorates. The basic theory of cooling tower operation was first proposed by Walker et al. [4]. Merkel [5] was the first to present the heat and mass transfer model by practical usage of the basic differential equation. He showed that the total enthalpy difference is the driving force for both the sensible and latent heat transfer. Kloppers and Kroger [6], Smrekar et al. [7], and Fisenko et al. [8,9] carried out work on the heat transfer performance of cooling towers under windless conditions. Al-Waked and Behnia [10,11] performed numerical simulations and studied some of the factors influencing the efficiency of a wet-type cooling tower. They concluded that the heat transfer capacity is increased when the wind velocity is greater than 7.5 m/s. It is important to mention in this context here that a few number of experimental studies are available in the literature. However, the heat and mass transfer phenomena in different types of cooling towers was discussed in a comprehensive way [12–14]. To date, there is no study of wet-type cooling tower performance that offers exhaustive quantitative relations among the different performance index parameters of heat transfer.

The objective of this paper is to probe the thermal performance of a natural draft counterflow wet cooling tower. A thorough experiment is conducted to study the effect of crosswind on cooling tower performance.

Influential factors such as crosswind velocity and ratio of water to air mass flow rates are quantitatively studied. A quantitative relationship showing the variation of the tower characteristic ratio with the water–air mass flow rate ratio is proposed based on the experimental data. The obtained results, which correlate the combined heat-and-mass transfer with the ratio of mass flow rates of water and air, demonstrate an avenue to enhance heat transfer.

2. Experimental apparatus and procedure

The experimental apparatus used in this study is shown in Fig. 1, and the circuit comprising water and airflow is shown in Fig. 2. As illustrated in Fig. 1(a), the tower has two hyperbolic sections, meeting at the throat. Note that the components shown in Figs. 1(a) and (b) are conventional, where the dimensions H_{total}, H_{throat}, R_{lower}, R_{upper} and R_{throat} are the total height, throat height, the lower shell radius, upper shell radius and throat radius, respectively. The shell of the cooling tower is made of reinforced concrete. Attached to the end of the lower hyperbolic section of the tower, there is a water basin used for collecting the cooled water. The walls and the basin plate of the water basin are built of high performance concrete. It is important to mention in this context here that splash-type wooden decks used as the fill of the tower. The water–air interaction is taking place at the cooling circuit unit. Note that the cooling circuit as shown in Fig. 1(a) has been detailed in Fig. 1(b) as well.

The experimental circuit comprises of a cooling tower (the principal part of the circuit), a pump for feeding circulation water, a lower head tank (which contains an electrical heating coil), two valves to adjust the flow, and an overhead tank where hot water is stored for recirculation. Auxiliary items are also used in the circuit to measure the temperature of water and air during experimentation. The dry bulb temperature and the wet bulb temperature of the ambient dry air are measured by a psychrometer attached to the tower. A digital anemometer is used to measure the wind velocity. In addition, the relative humidity of the air at the cooling tower outlet is measured by a hygrometer. The cooling tower has a dimension of 35 cm × 60 cm × 150 cm (top diameter, bottom diameter, and height, respectively). The throat diameter and height of the tower are 33.6 cm and 113 cm, respectively. The two tanks used in the experimental circuit facilitate a steady circulation of water. Air temperatures at the entry and exit, as well as the incoming and outgoing water temperatures, are measured.

2.1. Experimental procedure in detail

The following steps are followed to carry out the experiment:

- Switch on the electric heater to heat the circulating water.
- Initiate the circulation of water flow by operating the pump and valves.
- The circulating water reaches the overhead tank.
- Inject airflow by switching on the fan as soon as the circulating water enters the tower top.
- Circulating water falls from top to bottom while air rises from bottom to top. The heat and mass transfer takes place during the course of flow.

This process continues for different values of circulation water flow rates (e.g., 0.12, 0.24, 0.36, 0.48, 0.60, 0.72, and 0.84 m^3/hr, respectively). To ensure that the experiment successfully simulates the actual working conditions of a cooling tower in process industries and power plants, circulating water of different and relatively higher temperatures is used during the experiment (40 °C, 45 °C, and 50 °C, respectively). To simulate the natural wind above ground, the wind velocity is produced by the fan. However, the windless condition corresponds to wind velocity of 0.0 m/s, and five other different wind velocities (0.2, 0.4, 0.6, 0.8, and 1.0 m/s) are considered to carry out the experiment, simulating crosswind conditions.

3. Cooling tower performance analysis

The present study uses three different performance parameters to investigate the thermal performance: the effectiveness, e; the drop in temperature, T_{drop}; and the most important parameter to