Energy Conversion and Management 122 (2016) 504–514

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Experimental investigation on thermal performance of natural draft wet cooling towers employing an innovative wind-creator setup

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ARTICLE INFO

Article history:
Received 8 April 2016
Received in revised form 18 May 2016
Accepted 6 June 2016

Keywords:
Natural draft wet cooling tower
Heat and mass transfer
Cross-wind conditions
Natural wind speed profile
Cooling efficiency
Multiple regression analysis

ABSTRACT

Natural draft wet cooling towers are one of the most widely-used types of wet cooling towers in the large-scale power plants. In the present research, the heat transfer performance of natural draft counter-flow wet cooling towers is investigated under cross-wind and windless conditions by virtue of an innovative wind-creator setup provided so as to implement intrinsic features of the natural wind speed profile precisely. As a matter of fact, this investigation will focus on the influences of cross-wind velocity, inlet water temperature and water flow rate on the water temperature difference and cooling efficiency of the studied cooling tower, with an emphasis on the role of wind speed features. Interestingly, a twofold trend is exhibited by the water temperature difference and cooling efficiency with respect to variation of the cross-wind velocity. Furthermore, to have a more applicable study, regression analysis of the experimental results is utilized for the sake of developing general mathematical equations and thus facilitating further analyses. Finally, these mathematical equations are employed in order to recommend a guideline for the purpose of reaching optimum operating conditions of natural draft wet cooling towers.

1. Introduction

Cooling towers (CTs) are devices responsible for dissipating waste thermal energy to the ambient environment. CTs operate based on mass and thermal energy transfer from high temperature water to coolant air. In wet cooling towers (WCTs), water flows over the packing and thus a direct interface between the warm water and coolant air flow occurs. As a matter of fact, the heat and mass transfer occurs easily during the performance of natural draft wet cooling tower (NDWCT) when the hot water flows through the fills from top to bottom and also the dry air flows in the reverse direction through the fills. Therefore, in WCTs, an insensible heat transfer is also considered in addition to the sensible heat transfer. There are different types of wet cooling towers, and among them, natural draft counter-flow wet cooling towers are widely-used in the large-scale power plants [1]. Many factors such as wind velocity, packing types, inlet water temperature and volume flow rate of water affect operational conditions of WCTs. Therefore, a large number of research efforts have been devoted to the thermal performance and operational conditions of WCTs through experimental and theoretical analyses of the mass and thermal energy transfer mechanisms. Fisenko et al. [2] presented correlations for natural and forced draft in order to obtain thermal performance of CTs. They also optimized the performance of CTs under different atmospheric conditions [3]. Stabat and Marchio [4] employed mass and thermal energy balance and heat transfer laws to present a model based on Lewis factor for the sake of predicting water and energy usage in various operations. Soon after, Kloppers and Kroger [5] investigated effects of the Lewis factor on thermal energy transfer performance of natural and forced draft WCTs. They explained the relation between the Lewis factor and the Lewis number (ratio of thermal diffusivity to diffusion coefficient). They concluded that in the cases of relatively warm and humid inlet ambient air, effects of the Lewis factor on the performance assessment of WCTs decrease. In addition, after enhancing the Lewis factor, the temperature of outlet water and water evaporation rate decrease, while the heat rejection rate increases. Smrekar et al. [6] showed that the efficiency of natural draft cooling tower could be increased through optimization of the thermal energy transfer across the CT. They analyzed the water transportation mechanisms across the CT and subsequently suggested correlations in order to find an optimum ratio of water to air flow rates. Furthermore, the experimental study of ceramic tile packing and its influence on the CT performance was first carried

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http://dx.doi.org/10.1016/j.enconman.2016.06.016
0196-8904/

out by Elsarrag [7]. In consequence, a model was developed according to correlations for the sake of predicting the outlet water and air temperatures conditions. Al-Waked and Behnia [8] investigated the influence of wind break walls on the thermal performance of natural draft wet cooling towers under cross-wind through the three dimensional CFD modeling. Eventually, it was concluded that the NDWCT performance could be enhanced by installing solid walls at the entry of the NDWCT. In addition, Lemouari et al. [9] carried out experiments on heat transfer performance of a cooling tower with different parametric studies and yielded a similar model to that of Gharagheizi [10]. Hosoz et al. [11] established an artificial neural network (ANN) to forecast the performance of a wet cooling tower based on experimental data. Their ANN model was presented on the basis of a standard back propagation algorithm and subsequently this model was utilized to predict performance parameters of the considered WCT such as the rate of evaporated water, rate of heat rejection, dry bulb temperature, humidity of the outlet air and outlet water temperature. Furthermore, Gao [12] employed a three-layer back propagation (BP) network model with one hidden layer to predict performance of WCT under cross-wind conditions. In another investigation [13], they employed artificial neural network as a model to study effects of cross-wind based on level Froude number. Muangnoi et al. [14] investigated effect of the ambient temperature and humidity on the performance of a counter flow WCT based on the second law and exergy analysis of thermodynamics. On the other hand, it is common to use drift eliminators in WCTs in order to minimize water loss from the system. For this purpose, Lucas et al. [15] investigated the thermal performance of a forced draft counter-flow WCT fitted with different drift eliminators. Moreover, Lemouari et al. [16] investigated the mass and heat transfer between water and air flow rates which have indirect contact with a packed cooling tower. Consequently, modification of the heat transfer and generalized mass coefficients was recommended by involving effects of water and air transportation. Al-Waked [17] investigated the thermal performance of two adjacent NDWCTs inside power plant structures numerically for eight crosswind directions by employing a CFD code. Finally, he concluded that the NDWCT performance under crosswind conditions is influenced by the NDWCT location behind other NDWCTs, structure of the approaching crosswinds and the NDWCT location in front of/behind the power plant structures. As well, Wang et al. [18] studied the thermal performance of a NDWCT model under crosswind conditions. Three patterns of air guiding channels were utilized under different crosswind velocities. Their results demonstrated that the air flow rate and efficiency of cooling increased when the inlet air was directed. Gao et al. [19] experimentally concerned the evaluation of the air/water temperature profiles inside a NDWCT under windless and cross-wind conditions. Their study can provide an important theoretical foundation especially for energy saving aspects of NDWCTs. In another investigation, Gao et al. [20] performed a thermal-state model experiment in order to study the change of circumferential inflow air on the bottom of wet cooling tower, and the distribution of vortex inside tower under environmental crosswind conditions. Furthermore, Mondal et al. [21] carried out a complete analysis of the simultaneous heat and mass transfer phenomenon between water and air to investigate the thermal performance of a NDWCT. Ultimately, their observation showed that the effectiveness and temperature drop decrease in crosswind conditions by 4.5% and 4%, respectively.

On the other hand, improving operational performance of engineering systems has been being a main purpose of designers. Hence, a large number of researches have been carried out in order to improve operational performance of engineering systems such as power systems, hybrid energy systems, diesel engines and data storage systems [22] through experiments or mathematical modeling. In particular, a large number of research efforts have been carried out in order to improve operational performance of the natural draft dry cooling towers under crosswind conditions by using different procedures such as radiator-type windbreakers [23], alternative shell geometry with elliptical cross section, and Savonius turbines adjacent to cooling towers [24].

Unfortunately, to the best of our knowledge, no experimental investigation has been performed to consider and implement intrinsic features of the crosswind precisely in the case of cooling towers. Therefore, in the present study, intrinsic features of the natural wind are investigated in more detail and subsequently utilized in the experimental apparatus by means of an innovative wind-creator setup. In addition, the heat transfer performance of NDWCTs under cross-wind and windless conditions is investigated by employing the experimental results. Furthermore, effects of cross-wind velocity, inlet water temperature and water flow rate on the water temperature difference and cooling efficiency are considered. Then, the regression analysis of the experimental results is carried out in order to develop general mathematical equations. In the sequel, accuracy examination of the data fitting is performed by virtue of the root mean square error (RMSE) and correlation coefficient. Ultimately, the obtained mathematical equations are utilized to propose a guideline for the sake of reaching optimum operating conditions of NDWCTs.

2. Wind speed profile

Industrial NDWCTs are often exposed to strong wind gradients due to their height. As a result of many studies, it is unquestionably obvious that the wind blow plays a prominent role in varying performance of NDWCTs. Nevertheless, the wind features have not been implemented precisely in the previous experimental literature [25]. Therefore, it is necessary to investigate intrinsic features of the wind blow in more detail and subsequently utilize them in the experimental apparatus. On the other hand, irrespective of investigations in the field of cooling towers, many measurements and theoretical studies have been carried out so as to investigate intrinsic features of the wind [26]. It is demonstrated that the air movement is retarded by natural and man-made obstructions and, in turn, the wind speed is reduced near the ground surface [27]. Consequently, the wind speed is variable up to a particular height termed the "gradient height" where the corresponding speed is defined as the "gradient wind speed". Over the gradient height, the wind speed has a constant speed equal to the gradient wind speed. Beneath the gradient height, it is noteworthy to mention that variation of the wind speed with height is remarkably affected by ground roughness.

In order to model the natural wind speed profile, the power law wind speed model [27] (Eq. (1)) could be a suitable choice because it presents an accurate and acceptable wind speed profile employed in most of the engineering studies. It should be noted that this model falls in good fit within the actual wind profiles in nature. According to the power law wind speed model, the wind speed could be obtained through the following profile [27]:

$$\begin{cases} V_z = V_g\left(\frac{z}{z_g}\right)^{1/\alpha}, & 0 \leqslant z \leqslant z_g \\ V_g, & z \geqslant z_g \end{cases} \tag{1}$$

where V_z and V_g refer to the wind speed at height z and gradient wind speed. In addition, z, z_g and α designate the height over the ground, gradient height and exponential coefficient, respectively. It should be noted that z_g and α are dependent on surface roughness of the ground which is identified by the size and spacing of buildings, towers, mountains, etc. For convenience, based on natural topography and constructed features, four exposure categories are