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Parametric study on the outlet water temperature in a shower cooling tower and its application in different Iranian provincial capitals

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A B S T R A C T

This study investigates the performance of shower cooling towers under various geometric, physical, and environmental conditions. For this purpose, a shower cooling tower was thermodynamically modeled, and the governing equations were numerically solved using finite difference scheme. Contrary to the previous studies, the equation for droplet diameter variations during the evaporation process was also included among the governing equations, and the maximum error in the estimation of the outlet water temperature reduced to 1.2%. The results also showed that the decrease in the initial diameter of the sprayed water droplets lead to decrease of the process water temperature. While the process water temperature significantly drops because of the increase of air velocity, the changes in droplet spray speed have an insignificant effect on the outlet water temperature. The analysis of the effects of environmental conditions on the system's performance shows that as the air temperature decreases, the dependence of the outlet water temperature on the relative humidity of ambient air decreases. The comparison of countercurrent and countercurrent-concurrent towers indicates that using countercurrent-concurrent cooling tower cannot lead to significantly greater decreases in the outlet water temperature compared to countercurrent tower. The results obtained through the study of the performance of shower cooling tower utilized in Iranian provincial capitals also indicate that, the maximum and minimum temperature decrease occurs in cities located in cold and dry climates, and hot and humid climates, respectively.

1. Introduction

Cooling systems are used in most industrial production processes for the purpose of proper utilization and increased efficiency. Cooling towers are cooling systems that reduce the temperature of the water flow and transfer the heat to the ambient air [1–3]. In conventional cooling towers, the packing acts as a media for heat and mass transfer. The thermal energy is taken away from the hot water and then transferred to the cold and dry ambient air through direct contact. Although the packing facilitate the distribution of water and create a wide contact surface between the air and water, they are prone to fouling, and as a result, could reduce the efficiency of the cooling tower over time. The existence of the packing also leads to intensified pressure loss in the system. In order to overcome this problem, greater amounts of electric energy must be consumed. In addition, packing existing at the top sections of the shower cooling towers are more exposed to sunlight, thus providing the optimal conditions for the growth of algae and even pathogenic microorganisms [4]. The algae formed in this manner, through photosynthetic action, cause equipment corrosion and clog the packing. Since it is not possible to frequently clean or replace the packing, the water temperature drop decreases over time [5]. The difficulties connected with the conventional cooling towers have prompted the researchers to seek alternative similar systems that lead to fewer flaws in evaporative cooling towers and increase their efficiency. As a result, a different type of cooling tower, in which the packing grids are replaced with water distributers, was devised (Fig. 1). In this type of cooling tower, hot water enters the tower from the top and is turned into small droplets by means of the water spraying nozzles. Air stream is mechanically provided using some fans, and enters the tower from the bottom, travels upwards in a direction opposite to the water droplets, and reduces the water temperature through direct contact. The rate at which water in the tower is cooled by evaporation depends upon the total surface area of the water drops. A specified surface area may be achieved by supplying a given volume of very fine droplets, or by a larger volume of coarser drops. Because the creation of very fine drops requires water to be forced through a narrow aperture at high pressure, there is a trade-off between drop size and volume [6].

Shower cooling towers were first developed and experimentally evaluated by Givoni and Alhemiddii [7] in 1995. The system proposed, which was intended for air-cooling in hot areas, consisted of an open

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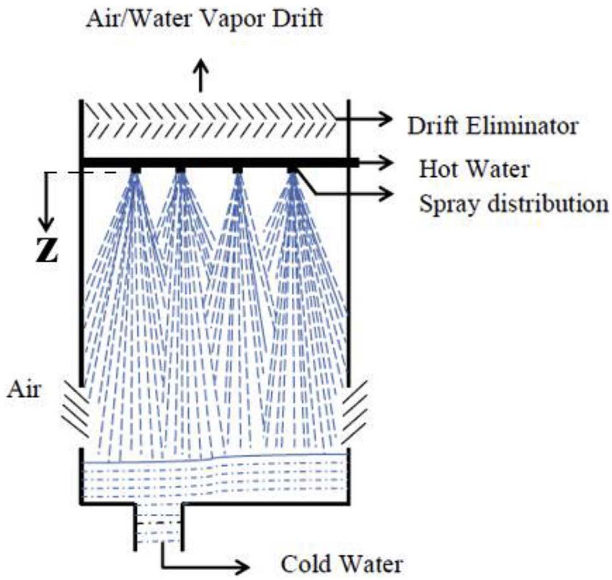

Fig. 1. Schematic diagram of a countercurrent shower cooling tower.

shaft with water spraying nozzles and a basin located respectively at the top and bottom of the tower. The system's performance was evaluated in Saudi Arabia, and the obtained results showed that the temperature of the inlet air dropped from 45 °C to 29 °C after it passed through the cooling tower. Yajima and Givoni [8] experimentally evaluated the decrease in the outlet air temperature in Japan. They recorded the variations of air temperature and relative humidity at the inlet and outlet of the shower cooling tower with the variation of water mass flow rate during a 24-h period for two cooling towers with different heights. The obtained results showed that the outlet air temperature depends on factors such as the tower's height, ambient air conditions, water mass flow rate and droplets' diameter. Givoni [9], in another experimental study, evaluated the performance of shower cooling towers in three regions with different climates (Los Angeles in USA, Riyadh in Saudi Arabia, and Yokohama in Japan). Comparison of the performance of the cooling towers in these three cities showed that these systems could significantly reduce the ambient air temperature especially when utilized in very hot and desert regions. He also studied the effect of the towers' height on the outlet air temperature. The results showed that an increase in the towers' height from 0.5 m to 1.0 m leads to a significant decrease in the air temperature. Meanwhile, for an increase in the towers' height from 2.0 m to 3.0 m the decrease in air temperature is insignificant. Despite the experimental evaluations presented in the aforementioned literatures, none of these studies implemented a theoretical method based on mathematical equations in order to study the system and predict its behavior. Qi et al. [10], in 2006, using a kinematic model and the governing equations for the heat and mass transfer processes, presented a one-dimensional model for the prediction of water droplets' velocity along the tower during the evaporative cooling process. The model mentioned was termed “HMT” (Heat and Mass Transfer) model. The governing equations were numerically solved using the finite difference scheme. It was shown that the difference between the values of outlet water temperature obtained through numerical calculations and the experimental data was only 0.4 °C. Qi et al. [11], a year later, using the artificial neural network “ANN” method, developed a computer program that enabled the designers to numerically estimate the outlet water temperature based on a series of experimental data. The results presented in this study showed that ANN method had an average error of 1.31% whereas the HMT method had an average error of 9.42%. Qi and Liu [12] in another study attempted to increase the accuracy of HMT method through omitting some of the simplifying assumptions such as considering the air in contact with water to be saturated, assuming the Lewis factor to be equal to one, and ignoring the decrease of the water mas flow rate due to evaporation. The results obtained in this study proved that the new model could predict the experimental data with excellent accuracy. Qi et al. [13] also attempted to discover the logical relations between the inlet variables and the outlet variable (outlet water temperature) using statistical relationships so that the outlet water temperature could be estimated based on experimental data. They proved that although the PPR (Projection Pursuit Regression) statistical method has a higher accuracy compared to the heat and mass transfer (HMT) model, it cannot be substituted by the HMT model because of the fact that the accuracy of the outlet results in the PPR method depends on the inlet data. Qi et al. [14] in an another work proposed a new mathematical model for the prediction of the performance of shower cooling towers and utilized it to predict the variations in temperature and exergy along the tower. The results of this study showed that the increase in towers' height leads to the decrease of the exergy. It was also found that the distribution of the exergy loss is high at the bottom of the tower, and that it decreases as we move towards the top of the tower. Muangnoi et al. [15] investigated the performance of water-jet cooling towers both numerically and experimentally. They also investigated the effect of the parameters such as the spray towers' height, water to air mass flow rate ratio, initial diameter of the water droplets, their initial spray speed, and the air velocity on the performance of the system. Using the numerical model presented in this study, the velocity of the outlet water droplets, process water temperature, outlet air temperature and relative humidity could be calculated. Chiesa and Grosso [16] compared different simplified simulation models of a Passive Downdraught Evaporative Cooling tower (PDEC) using experimental data. The collected inlet airflow data were used for calculating predicted outlet airflow values by using four equations and a software from literature. The comparison of those outlet airflow data allowed for assessing the effectiveness and the accuracy of the analyzed simplified methods, which were also used for simulating the PDEC in several dynamic simulation software such as Design Builder coupled with Energy Plus.

Reviewing the previous studies shows that although the water droplets' diameter decreases during the evaporation process along the cooling tower, this change in diameter has so far been ignored in all of the mathematical models proposed. Furthermore, the effects of different geometrical, physical, and environmental parameters on the outlet water temperature in different climate conditions has not so far been studied or compared. Moreover, while shower cooling towers are divided into two different categories based on their current patterns, namely the countercurrent and countercurrent-concurrent types, no comparison has ever been drawn between their performances. In this study, at first the accuracy of the previous mathematical model proposed for the prediction of the performance of shower cooling towers was improved by considering the evaporation of water droplets along the tower via adding the equation of droplets' diameter change to the governing equations. Next, the effect of geometrical, physical, and environmental parameters as well as the flow patterns on the performance of shower cooling towers was studied. Lastly, the performance of shower cooling towers in reducing the temperature of process water in different Iranian provincial capitals during summer was evaluated and compared.

2. Mathematical modeling of shower cooling tower

In order to model the shower cooling tower and determine its capability to cool the process water stream, some assumptions are needed. For modeling of the motion of water droplets from nozzles to the reservoir, it was assumed that: