Energy Conversion and Management 126 (2016) 971–981

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Experimental investigation on performance enhancement of forced draft wet cooling towers with special emphasis on the role of stage numbers

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ARTICLE INFO

Article history:
Received 1 June 2016
Received in revised form 26 July 2016
Accepted 20 August 2016

Keywords:
Wet cooling tower
Packing stages
Heat and mass transfer
Thermal image
Regression analysis
Optimum performance

ABSTRACT

Wet cooling towers play a prominent role in the transfer of waste heat from industrial thermodynamic cycles. However it is a complicated task to dictate and optimize their operational conditions on account of different mass and heat transfer mechanisms between water and air flows. In this research, air mass flow rate, hot water temperature, water flow rate and stage numbers of packing are changed experimentally in order to investigate their influences on the cooling tower performance. As a matter of fact, this research attempts to focus on packing density effects with an emphasis on the role of stage numbers of packing. Consequently, the obtained results indicate that coefficient of efficiency is in direct relation with the hot water temperature, stage numbers of packing and air mass flow rate, while it diminishes by increasing the water flow rate. On the other hand, the captured thermal images and pertinent temperature histograms are investigated so as to visualize and calculate the temperature distribution within the studied cooling tower. Eventually, mathematical equations are derived from regression analysis of the measured data to recommend some practical procedures for the sake of reaching optimum operating conditions of forced draft wet cooling towers.

1. Introduction

Enhancing the dissipation process of unwanted thermal energy is one of the most prominent tasks in the power plants. For this sake, cooling towers (CTs) are utilized almost everywhere which operate based on mass and thermal energy transfer from hot water to coolant air. According to the heat transfer mechanism between the hot water and coolant air flow, industrial cooling towers are divided into two main types of dry and wet cooling towers (DCTs and WCTs). In particular, WCTs operate based on direct interface between the hot water and coolant air flow which is caused by the water flow over the packing. Thus, WCTs utilize evaporation as a latent heat transfer mechanism as well as the sensible heat transfer mechanism (the only heat transfer mechanism in DCTs). It is worth mentioning that WCTs are more efficient in hot weather regions while DCTs are employed in low water areas that suffer from lack of water. Operation of WCTs generally depends on many parameters such as hot water temperature, air mass flow rate, water flow rate, packing type, etc. Thus, engineers can enhance performance of WCTs through optimizing the mentioned factors.

In recent years, a large volume of studies have been carried out on thermal performance of WCTs theoretically and experimentally. Facao and Olliveira [1] determined thermal and mass energy transfer coefficients experimentally. They presented the thermal performance of WCTs for the purpose of chilling. Goshayshi and Missendn [2] studied the mass transfer coefficient of various packings experimentally, and found out the dependency of packing coefficient on distance and pitch of packings. Kloppers and Kroger [3] proposed a model to relate thermal and mass energy transfer processes to WCTs. In addition, influence of the Lewis factor on thermal energy transfer performance of natural and forced draft wet cooling towers was studied by Kloppers and Kroger [4]. Soon after, Elsarrag [5] investigated the effects of ceramic tile packing on the cooling tower performance through relevant experiments. He also proposed a model to predict the outlet water and air temperature conditions. Smrekar et al. [6] found out that efficiency of the natural draft cooling tower may be enhanced by optimization of thermal energy transfer across the cooling tower. In the sequel, they suggested correlative relations to reach an optimum ratio of water to air flow rates. Lemouari et al. [7] conducted some experiments on heat transfer performance of a cooling tower utilizing different parametric studies which yielded similar model to that of Gharagheizi et al. [8]. Al-Waked and Behnia [9] investigated the influence of windbreak walls on the thermal performance of

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http://dx.doi.org/10.1016/j.enconman.2016.08.059
0196-8904/

Nomenclature

$C_{p,a}$	specific heat capacity of air, kJ kg^{-1} K^{-1}
h_{a1}	enthalpy of inlet air, kJ kg^{-1}
h_{a2}	enthalpy of outlet air, kJ kg^{-1}
$\dot{m}_a$	air mass flow rate, kg s^{-1}
n	size of the actual output
$\dot{Q}$	air cooling capacity, kW
$\dot{Q}_K$	cooling capacity by convection, kW
$\dot{Q}_V$	cooling capacity by evaporation, kW
q_w	water flow rate, m^3 h^{-1}
ω_2	outlet humidity ratio, kg$_w$ kg$_a^{-1}$
r	latent heat of evaporation, kJ kg^{-1}
SN	stage numbers of packing
T_{w1}	hot water temperature, °C
T_{w2}	outlet water temperature, °C
t_{db1}	dry-bulb temperature of inlet air, °C
t_{db2}	dry-bulb temperature of outlet air, °C
t_{wb1}	wet-bulb temperature of inlet air, °C
t_{wb2}	wet-bulb temperature of outlet air, °C
ω_1	inlet humidity ratio, kg$_w$ kg$_a^{-1}$

natural draft wet cooling towers (NDWCTs) under crosswind through the three dimensional CFD modeling. They concluded that the NDWCT performance could be enhanced by installing solid walls at the NDWCT entry. Muangnoi et al. [10] investigated effects of the inlet temperature and humidity on performance of a counter flow WCT based on exergy analysis and the second law of thermodynamics. Lemouari et al. [11] experimentally studied the mass and heat transportation between air and water flow rates. They suggested modification of the generalized mass and heat transfer coefficients through involving the influence of water and air transportation. In addition, Marques et al. [12] compared open/closed loop efficiency of a counter flow WCT. Their results showed a remarkable improvement in the performance of closed loop WCT in comparison with open-loop operation. Heidarinejad et al. [13] simulated a counter-flow wet cooling tower, and a good agreement was reached between their results and experimental data in the literature. They concluded that it is important to consider the rain zones and spray in analyses for enhancing the accuracy. In addition, Sarker et al. [14] investigated other properties of cooling towers including cooling capacity, pressure loss and efficiency. They concluded that using the finned tube leads to higher thermal efficiencies due to pressure loss enhancement in comparison with the bare tube. Furthermore, the heat and fluid flow properties of evaporation coolers were studied by Heyns and kröger [15]. Dependency of the thermal energy coefficient for water layer on the spraying water temperature and mass flow rate of air and water was demonstrated by their measured results. Zhang et al. [16] provided a theoretical foundation for applied design by proposing an analytical model for the coupled heat and mass transfer procedures in reversibly used cooling towers, and a good agreement was reached between their proposed model and the reported experimental results. Moreover, effects of weather conditions on the thermal properties of WCTs were studied by Papaefthimiou et al. [17], and a thermodynamic model was proposed in order to simulate the processes in WCT. It is notable that a good agreement was obtained between their simulation results and the experimental results. Zheng et al. [18] found out utilization possibility of oval tubes in the WCTs and suggested some correlations for optimum operating conditions. Furthermore, a criterion of drift eliminators design was developed by Lucas et al. [19] in order to enhance the thermal performance of cooling towers. They utilized the chemical balance method and carried out an experiment to study the drift loss from a cooling tower without and with different drift eliminators. Jiang at al. [20] carried out experimental and numerical analyses of a cross-flow closed wet cooling tower based on finned tube assembly. They also attempted to enhance the thermal performance by comparing the bare-tube with the fin-tube patterns. In addition, influences of rotational splash type packing on the operating conditions of forced draft counter flow WCTs were studied by Lavasani et al. [21]. Their results demonstrated that higher velocities of rotational splash type packing lead to enhance the heat transfer process. Ning et al. [22] investigated the WCT performance through considering influences of the defects, including conditions of nozzles drop, nozzles blockage and packing blockage. In particular, their results revealed more than 60% decreasing in the tower characteristic ratio under nozzles drop conditions. Askari et al. [23] investigated effects of multi-walled carbon nanotubes and nanoporous graphene nanoparticles on the thermal performance of a WCT through an experimental procedure. They studied thermal conductivity of nanofluids and observed 20% and 16% improvement compared with the base fluid in thermal conductivity of nanofluids for multi-walled carbon nanotubes and nanoporous grapheme nanofluids, respectively. In addition, Singh and Das [24] analyzed performance of a forced draft WCT using trickle, film and splash fills. They developed relevant correlations based on experimental data for performance parameters by considering mass flow rates of water and air as design variables. Moreover, they employed Non-Dominated Sorting Genetic algorithm in order to optimize performance of forced draft WCT. Shahali et al. [25] experimentally investigated effects of different input parameters such as water flow rate and air mass flow rate on thermal performance of a WCT. They proposed a guideline to attain the optimum operating conditions of WCT by the use of regression analysis. Moreover, Zhao et al. [26] presented a three dimensional numerical model in order to study characteristics of a high level NDWCT. They obtained air mass flow rate, air pressure drop, air temperature and some other parameters for high level NDWCT and usual NDWCTs under the same operational conditions. Rahmati et al. [27] employed experimental data so as to study the heat transfer performance of natural draft counter flow WCTs under cross-wind and windless conditions. They investigated the effects of inlet water temperature, water flow rate and cross-wind velocity on the water temperature difference and cooling efficiency.

On the other hand, enhancing the overall performance of engineering systems has been a major purpose of designers. Accordingly, a large number of investigations have been conducted so as to enhance technical performance of engineering systems such as power systems, heat pumps, heat exchangers, and data storage systems through experiments or mathematical modeling [28]. In particular, a large number of studies have been carried out in order to enhance the technical performance of cooling towers by evaluating influences of different parameters and procedures like rib numbers, alternative shell geometry, and radiator-type windbreakers [29].

To the best of our knowledge, no investigation has been performed on the WCT performance under simultaneous effects of hot water temperature, water flow rate, air mass flow rate and stage numbers of packing, particularly by virtue of the captured thermal images. Thus, effects of these parameters on the WCT performance are experimentally investigated in this study. First of all, the present study attempts to portray the measuring setup and test conditions. Then, the measured results are illustrated in order to