Experimental Study of the Impact of Added Packing on Performance Characteristics of Closed Wet Cooling Tower Based on Energy Analysis

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ABSTRACT

This paper presents thermal performance analysis of modified closed wet cooling tower (CWCT). The modification based on addition packing to the conventional CWCT. The experimental study based on heat and mass transfer principles includes: design, manufacture and testing prototype of a modified counter flow forced draft CWCT. A series of experiments was carried out at different operational parameters. Experiments are conducted to explore the effects of various operational and conformational parameters on the towers thermal performance. In the test section, spray water temperature, air wet bulb temperature, air dry bulb temperature, enthalpy, and relative humidity of air measured at intermediate points of the heat exchanger and packing. The results indicated the location and height of packing have significant effects on tower performance. It was noticed that the CWCT with packing has a better performance than without packing. Moreover, the maximum enhancement of performance observed for the CWCT with using the packing under the heat exchanger. Under the same operating conditions, the thermal efficiency for CWCT with packing under the heat exchanger and CWCT with packing above the heat exchanger approximately (40%) and (25%) higher than that CWCT without packing respectively.

Key words: ڌ losed wet cooling tower (CWCT); heat exchanger; counter-flow; packing.

1. INTRODUCTION

Researchers and designers keenly seek to improve the performance of cooling towers because of the extensive impact on the work and efficiency of the systems concerned to these towers. With more and more closed cooling tower applications, the study also received increasing attention (Pascal, and Dominique 2004). Much attention has been paid to issues on closed wet cooling towers (CWCTs) relating to experimental studies and developed correlations of heat and mass transfer coefficients as a function of operating conditions. (Armando., and Jorge 2000), designed a new CWCT in order to examined effects of the operating parameters on the saturation efficiency for a CWCT modified for use with chilled ceilings in buildings. (Gyuet al 2008;Gyuet al2010), investigated experimentally the thermal performance of two heat exchangers in closed-wet cooling tower having a rated capacity of 2 TR. Both heat exchangers have multi path that is consumed as the entrance of cooling water and are consisting of bare-type copper tubes of 15.88 mm and 19.05 mm. (Heyns and Kroger 2010), investigated the thermal performance characteristics of an evaporative cooler, which consist of 15 tube rows with 38.1 mm outer diameter galvanized steel tubes arranged in a triangular pattern of 76.2 mm. (Qasim and Hayder 2016;Qasim and Hayder2016; Qasim and Hayder2017;Qasim and Hayder2017), evaluated experimentally and computationally thermal performance of new design CWCT by added packing . In order to evaluation thermal performance of this CWCT for cooling capacity of 9 kW, a series of experiments was carried out at different operational and conformational parameters. Operational parameters demonstrate: air flow rate of, spray water flow rate, cooling water flow rate, inlet cooling water temperature and inlet Air Wet Bulb Temperature (AWBT). Conformational parameters indicate packing with different height, location of packing, heat exchanger's tubes arrangement, and types of spray nozzle. (Xiaocui et al 2017), investigated numerically the thermal-hydraulic performances of the CWCT installed with plain, oval, and longitudinal fin tubes in the heat exchanger. Operational parameters analyzed using CFD model. In this paper, the effects of various operational and conformational parameters on the thermal performance of modified CWCT based on heat and mass transfer principles.

2. EXPERIMENTAL SETUPAND PROCEDURE

2.1. Description of Test Rig

A modified CWCT was designed and constructed and tested in the laboratories of Al- Mustansiriyah University Faculty of Engineering. (Hyader 2015), describes arrangement of the CWCT that shown photographically in Figure (1), and the schematically representation in Figure (2).

Figure.1a.Photographic picture for experimental apparatus (lateral view).

Figure.1b.Photographic picture for experimental apparatus (front view).

1	Air blower	13	U-Tube manometer
2	Butterfly valve	14	Air pipe
3	Air flow orifice	15	Exhaust duct
4	Heat exchanger	16	Water distribution system
5	Film packing	17	Spray water flow meter
6	Regulator glob valve	18	Cooling water flow meter
7	Drift eliminator	19	Cooler
8	Spray water pump	20	Humidifier
9	Cooling water pump	21	Air heaters
10	Basin tank	22	Float valve

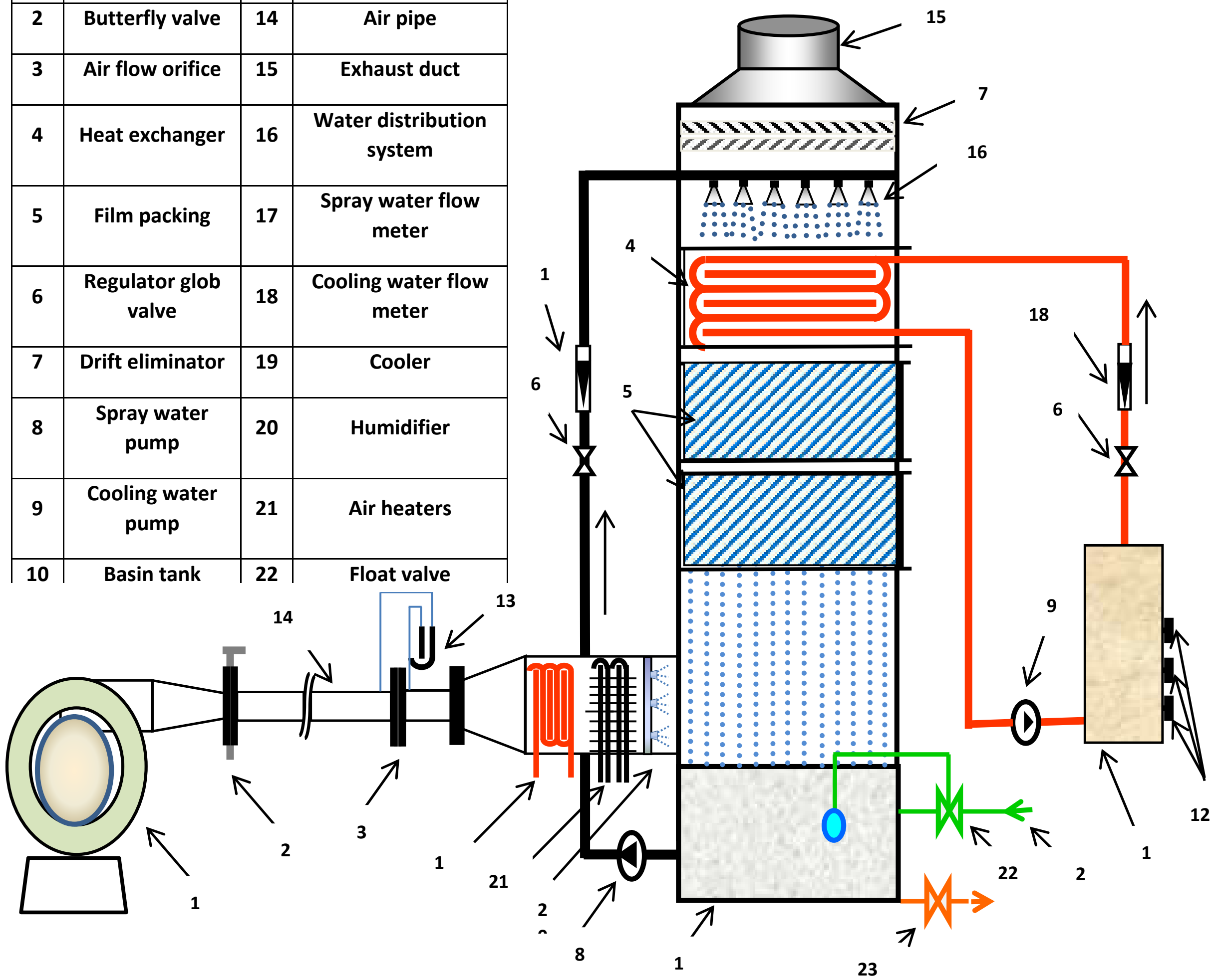

Figure 2. Schematic diagram for experimental apparatus

The tower fabricated from galvanized steel sheet connected together by screws and nuts as a rectangular box of external dimensions (700 mm 400 mm 2300 mm). As exists in every forced cooling tower, the test section consists of three zones: spray, fill and rain zone. Fill zone at 1000 mm height and characterized as consisting of three places for sliding removable drawer rectangular boxes at the same dimensions,manufacturing for packing and heat exchangers to ensure change the locations and types of heat exchangers and height of packing to study the influence of all these additions on the performance of the tower. The rectangular drawer made of galvanized steel with dimensions of 420 mm in width, 760 mm in depth and 280 mm in height. Air from the atmosphere, enters the blower at a rate which is controlled by the butterfly valve. The fan discharges into the PVC pipe and the entrance duct before entering the packed column. As the air flows through the packing and heat exchanger, its moisture content increases and the water in the heat exchanger are cooled. Pipe fitting in the tower illustrates in Figure (3).Hot water is pumped from the load tank through the control valve and a water flow meter to the heat exchanger placed inside the test section of tower. The plain tube heat exchanger was fixed horizontally in test section inside supported frame of rectangular drawer. Cooling water moves through the tubes while the spray water and air move over the tubes in perpendicular direction. The tubes are arrayed in staggered arrangement with tube pitch over diameter of 3. The specification of heat exchangers shows in Tab.1

Table 1. Physical dimensions of heat exchanger

Heat exchanger configuration	Value	Unit
Length (L1)	690	mm
Height (L2)	166	mm
Width (L3)	381	mm
Number of tubes for coil	30	-
Vertical tube spacing (XL)	24	mm
Horizontal tube spacing (XT)	80	mm
Tube per row	5	-
Outside tube diameter	15.88	mm

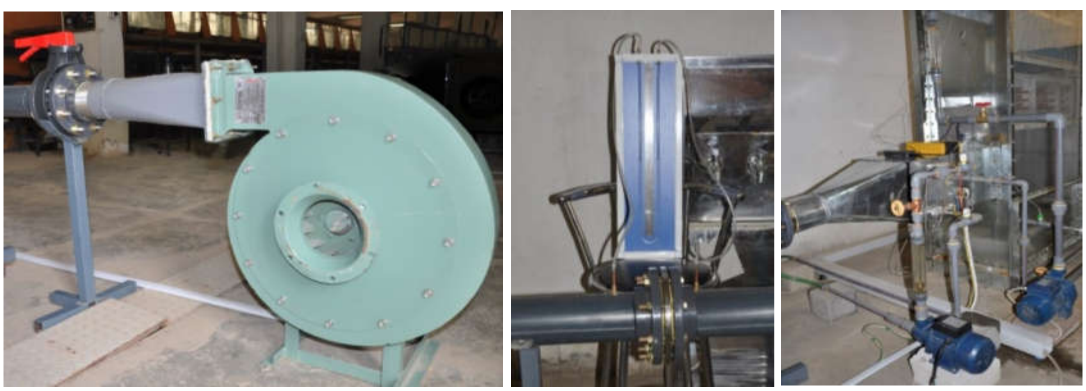

Figure 3. Pipe fitting in the tower

Thermocouples type K inserted before and after the cooler coil to measured cooling water temperature. To measure the spray water temperatures at intermediate locations inside test section, especially channels have been manufacturing to insert thermocouples through holes. These holes are closed by rubber stoppers through which thermocouples are inserted to measure the temperature profile. The variations of air dry bulb temperature and relative humidity along the test section as well as the inlet and outlet of the tower were measured by humidity meter, which combined temperature/humidity sensor. The humidity meter model TH-305 has a (main faction) temperature and relative humidity measurement range from 0 to 60 C and 20 to 95% respectively. The sensor probe handle is placed directly in the air stream and connected to display.

2.2Test Procedure

In order to evaluate the thermal performance of cooling tower, a series of experiments was carried out at different operational and conformational parameters. Operational parameters demonstrate: air flow rate of (0.12-0.3) kg/s, spray water flow rate of (20,25,30,35,40,45) l/min, cooling water flow rateof(10,15,20,25,30,35,40,45,50) l/min, inlet cooling water temperature of (35,40,45,50,55) C and inlet air wet bulb temperature of (7-24) C. Conformational parameters indicate: height of packing used (280 and 560) mm, location of packing (under heat exchanger and above heat exchanger). Thermocouples type K insert before and after the cooler coil to measured cooling water temperature. To measure the spray water temperatures at intermediate locations inside test section, specially channels have been manufacturing to insert thermocouples type K through holes .These holes are closed by rubber stoppers through which thermocouples are inserted to measure the temperature profile. The variations of air dry bulb temperature and relative humidity along the test section as well as the inlet and outlet of the tower were measured by humidity meter, which combined temperature/humidity sensor. The humidity meter model TH-305 has a temperature and relative humidity measurement range from 0 to 60 C and 20 to 95% respectively. The sensor probe handle is placed directly in the air stream and connected to display.

2.3. Performance Parameters

In viewpoint of energy analysis, the parameters used to determine the performance of cooling tower are:

Cooling range: is the temperature difference between the water inlet and exit states. Range can be measured by the temperature difference between the inlet and outlet from cooling tower:

$$CR = T_{cw,in} \quad T_{cw,out} \tag{1}$$

The most important parameter of cooling tower performance is the thermal efficiency, which can be defined as the ratio of actual released of heat to the maximum theoretical heat from cooling tower. The thermal efficiency for the closed circuit cooling towers was defined as (Armando., and Jorge 2000):

$$\eta = \frac{T_{cw,in} \quad T_{cw,out}}{T_{cw,in} \quad T_{awb,in}} \tag{2}$$

Cooling capacity is the heat rejected or heat dissipation, given product of mass flow rate of water, specific heat and temperature difference.

$$q m_{cw} C_{p,cw}\, CR \tag{3}$$

The mass transfer coefficient obtained using enthalpy balance for an elementary transfer surface (Armando., and Jorge 2000).

$$m_{air} d \quad _a = \alpha_m (\quad _i \quad _{air}) \, dA \tag{4}$$

Which is known as the Merkel equation and integrated for the whole heat exchanger in tower gives:

$$\frac{\alpha_m A}{m_a} = ln \frac{_{masw} \quad _{a,in}}{_{masw} \quad _{a,out}} \tag{5}$$

where, αm is the mass transfer coefficient for water vapor between spray water film an air , A is the surface area of the heat exchanger and h_{masw} is the specific enthalpy of the saturated air at the mean spray water temperature . The average of spray water temperatures was taken as the interface temperature while the inlet and outlet air enthalpies were calculated from Psychometric chart according to the measured data. Outlet air enthalpy could be also calculated considering that all the heat goes from water to air (Hayder 2015):

$$m_a \left(\quad _{a,out} \quad _{a,in} \right) = m_{cw} C_{p,cw} \, (T_{cw,in} \quad T_{cw,out} \;) \tag{6}$$

Then the outlet air enthalpy calculates as:

$$_{a,out} = \quad _{a,in} + \frac{m_{cw} C_{p,cw} \, (T_{cw,in} \quad T_{cw,out} \;)}{m_a} \tag{7}$$

Heat transfer from cooling water inside tubes to spray water and air through a water film .the rate of heat transfer from cooling water dqc is given as (Hayder 2015):

$$dq_c = m_{cw} C_{p,cw} dT_{cw} = \quad U_o (T_{cw} \quad T_{sw}) dA \tag{8}$$

Integrated Eq.8 from the inlet to outlet of cooling water, with constant spray water T_{sw}, gives.

$$\frac{U_o A_c}{C_{p,cw} m_{cw}} = ln \frac{T_{cw,in} \quad T_{sw,m}}{T_{cw,out} \quad T_{sw,m}} \tag{9}$$

where, Uo is the overall heat transfer coefficient between cooling water inside the tubes, tube wall and spray water on the outside .It is calculated by the following formula (Gyuet al 2008) :

$$\mathrm{U_o} = \left[\frac{R_o}{\mathrm{R}_i} \frac{1}{\alpha_c} + \frac{R_o}{\mathrm{k_t}} \ln \frac{R_o}{R_i} + \frac{1}{\alpha_s} \right]^{-1} \tag{10}$$

After the overall heat transfer coefficient was calculated from Eq.(9), it used to calculate, αs, tube to water film heat transfer coefficient (W/m^2 C).

$$\alpha_s = \left[\frac{1}{U_o} \quad \frac{R_o}{\mathrm{R}_i} \frac{1}{\alpha_c} \quad \frac{R_o}{\mathrm{k_{tube}}} \ln \frac{R_o}{R_i} \right]^{-1} \tag{11}$$

Where, αc is the convection heat transfer coefficient of cooling water inside the tubes, it was calculated by (Armando., and Jorge 2000):

$$\alpha_c = 0.023 \, \frac{k_{cw}}{D_i} Re^{0.8} Pr^{0.3} \tag{12}$$

3. RESULTS AND DISCUSSIONS

The impacts of operational parameters on heat and mass transfer coefficient for the packing under heat exchanger illustrates in fingers ((4) to (7). The variation of air-water mass transfer coefficient with air and spray water flow rates represented in figure (4). It can be seen that the mass transfer coefficient is in proportional relation with both air and spray water flow rates were increased. This is mainly because when spray water increases, the number of droplets increases so the air-water interfacial area increases with any increasing in air flow rate. Therefore, the mass transfer coefficient enhanced. The spray water heat transfer coefficient versus air flow rate with different spray water flow rates is shown in figure (5). It can be stated that the heat transfer coefficient is increasing with the increasing air and spray water flow rates. This can be explained by Eq. (9), when spray and air flow rate increase, the outlet cooling water temperature decreases, then the overall heat transfer coefficient increases. Also, spray heat transfer coefficient will be increases too.. The effect of cooling water flow rate on mass transfer coefficient for different spray water flow rates are illustrated in figure (6). This is indicated that the mass transfer coefficient depends on the cooling and spray water flow rates .As cooling water flow rate increases, mass transfer coefficient increases for all spray water flow rates. The effect of cooling water flow rate on spray water heat transfer coefficient for different spray water flow rates illustrated in figure (7). The results indicated that the heat transfer coefficient increases with increasing cooling and spray water flow rates. This is simply because of the increasing in the cooling capacity. As cooling water flow rate increases, it will be leads to an increase in the overall heat transfer coefficient and thus the heat transfer coefficient increasesThe air then gets hotter as it gains the sensible heat of the water and the water is cooled as its sensible heat is transfer to the air.Variation of spray water temperature, air dry bulb temperature, AWBT, humidity ratio, enthalpy and relative humidity of air along the height of the tower presented in figures (8) to (12) for two cases: CWCT with packing under the heat exchanger and CWCT with packing above the heat exchanger for 560 mm packing height. Spray water temperature distribution along the tower's height for CWCT shown in figure (8). For CWCT with packing under heat exchanger, it could be stated that the spray water temperature increments as spray water flows downwards the bottom of the heat exchanger then it will be decreasing continuously to reach its initial value as it approach the bottom of the tower along the packing height. This can be explained by the fact that higher heat exchange contrast spray water and cooling water across the tubes of heat exchanger whereas, the spray water temperature decreases along the packing height as a results of increase heat and mass transfer. On the other hand, for CWCT with packing above heat exchanger, it could be stated that the spray water temperature diminishes continuously as it flows downwards the bottom through the packing then it will be increasing to reach its initial value as it approach the bottom of the tower after flows downwards heat exchanger. This is expected in this case because the water losses heat both by convection and evaporation from both sections but in comparison with heat exchanger section, there is no source of heat to increase spray water temperature in packing section. Variation of air dray bulb temperature along the height of tower for CWCT shown in figure (9). It is interesting to see that for both packing locations, the air, which flows upwards initially reductions in temperature and after somewhat increments before leaving from the highest point of the tower. Also, it can be seen that the air dry bulb temperature of CWCT with packing under heat exchanger higher than that the temperature of CWCT with packing above heat exchanger in top region of the tower whereas, in the bottom region, the air dry bulb temperature of CWCT with packing under heat exchanger lower than the air dry bulb temperature for CWCT with packing above heat exchanger. This is because it increases when removed thermal energy from water to air in region where heat exchanger located. In other words, the potential of heat exchange between air and water increases in the heat exchanger section as a result of an increase in temperature difference. The examination of the influence of packing locations added with CWCT for AWBT, humidity ratio along the height of tower are displayed in figures from (10) to (11). From these figures, for both cases of packing locations, it can be stated that the value AWBT, humidity ratio and air enthalpy were increased gradually from the tower bottom to top. This increment is due to the transfer of thermal energy from warm spray water to the bulk air. The value of AWBT, humidity ratio and air enthalpy are higher at the final stage of the tower, because the air remains longer time period along the tower and more losses in the water heat energy at high stage achieved. Also, it can be seen from these figures that the AWBT, humidity ratio and air enthalpy of CWCT with packing under heat exchanger is higher than that the AWBT, humidity ratio and air enthalpy of CWCT with packing above heat exchanger in top region of the tower cooling zone whereas, in the bottom region, the AWBT, humidity ratio and air enthalpy of CWCT with packing under heat exchanger is lower than the AWBT, air enthalpy and humidity ratio for CWCT with packing above heat exchanger. The thermal energy, which is transferred to bulk air, increases at the location of heat exchanger leading to increase in the AWBT, humidity ratio and air enthalpy in this stage.. Influence of packing location on thermal efficiency and cooling capacity of CWCT shown in figure (12) and figure (13). Figure (12) shows the cooling capacity comparing for different positions of packing. The result indicated that the cooling capacity for CWCT with packing lower under heat exchanger and CWCT with packing above heat exchanger approximately (28%) & (16%) higher than that CWCT respectively. In figure (13), the thermal efficiency enhancement for different positions of packing is illustrated. It can be observed that the thermal efficiency for CWCT with packing lower under heat exchanger and CWCT with packing above heat exchanger approximately (52%) & (25%) higher than that CWCT respectively.

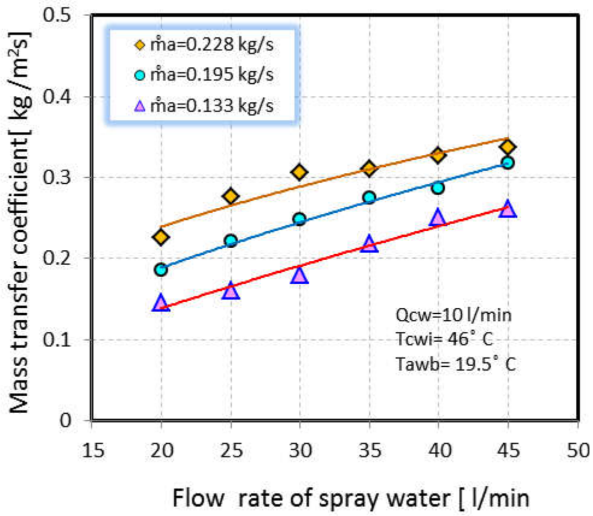

Figure 4. Variation of mass transfer coefficient with spray water flow rate for different air flow rates

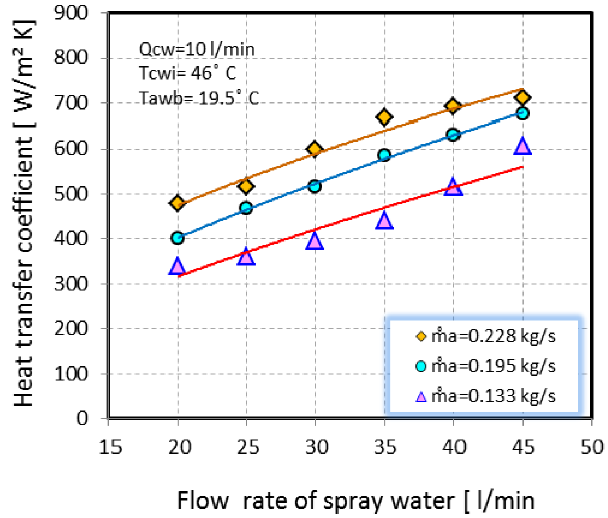

Figure 5. Variation of heat transfer coefficient with spray water flow rate for different air flow rates

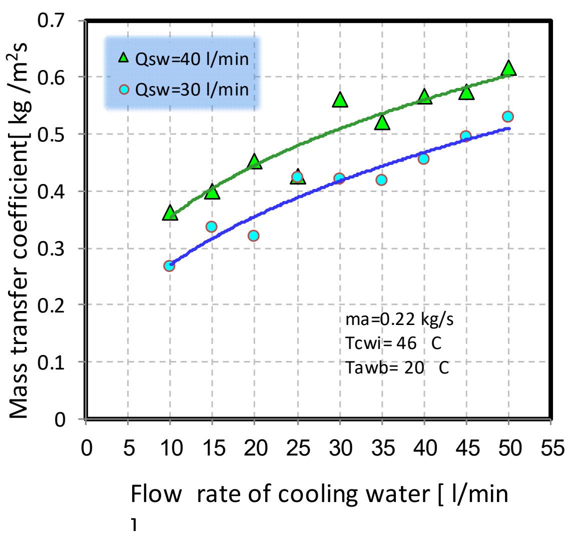

Figure 6. Variation of mass transfer coefficient with cooling water flow rate for different spray water flow rates

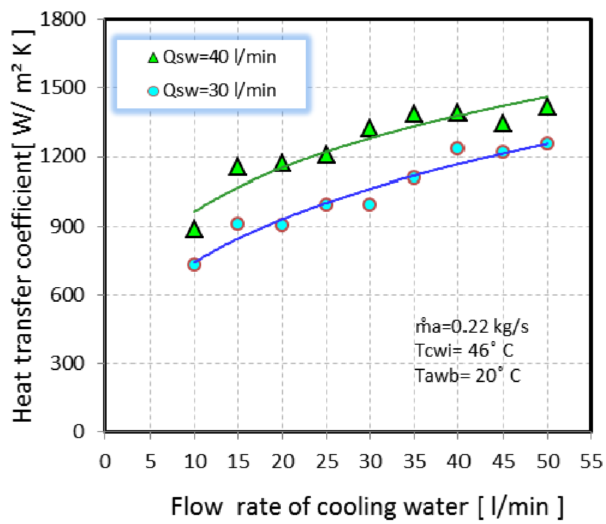

Figure 7. Variation of heat transfer coefficient with cooling water flow rate for different spray water flow rates

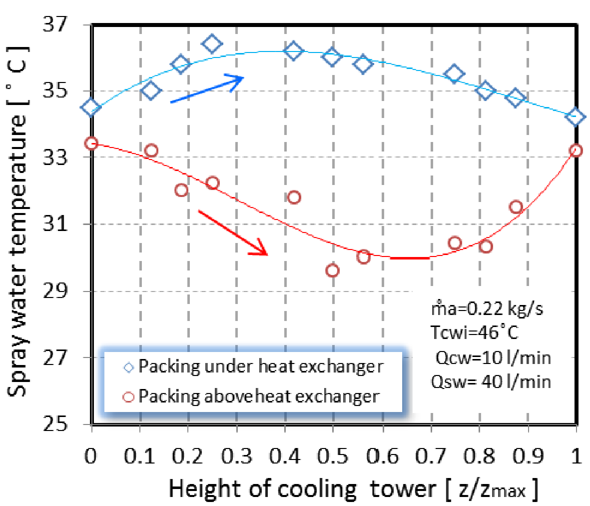

Figure 8. Variation of spray water temperature along the tower height for different locations of packing

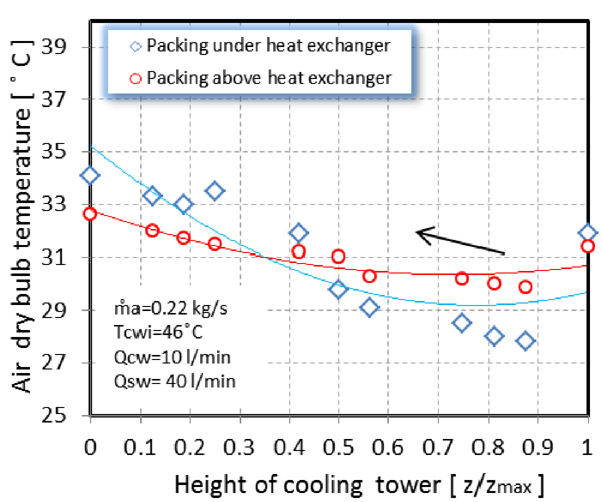

Figure 9. Variation of air dry bulb temperature along the tower height for different locations of packing

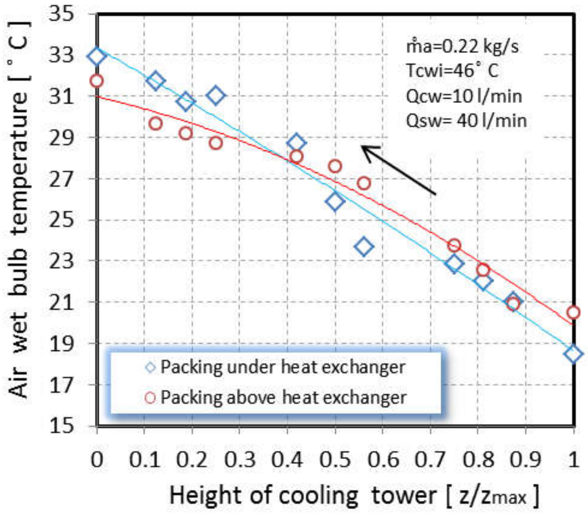

Figure 10. Variation of AWBT along the tower height for different locations of packing

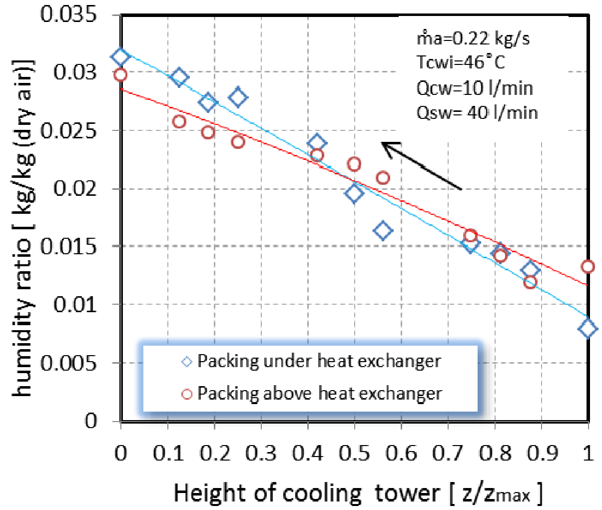

Figure 11. Variation of relative humidity along the tower height for different locations of packing

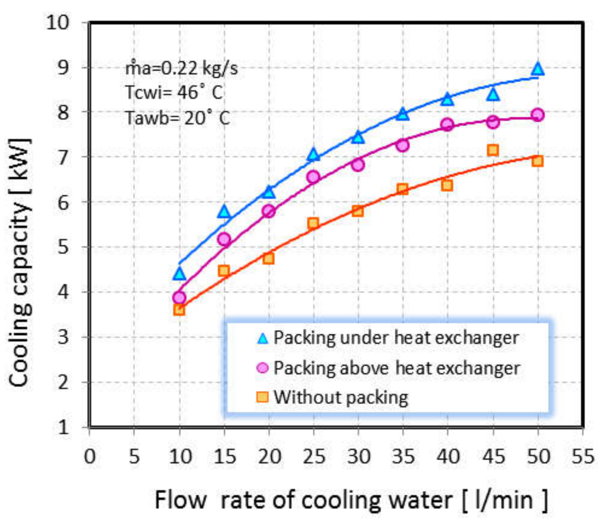

Figure 12. Variation of cooling capacity with cooling water flow rate for different locations of packing

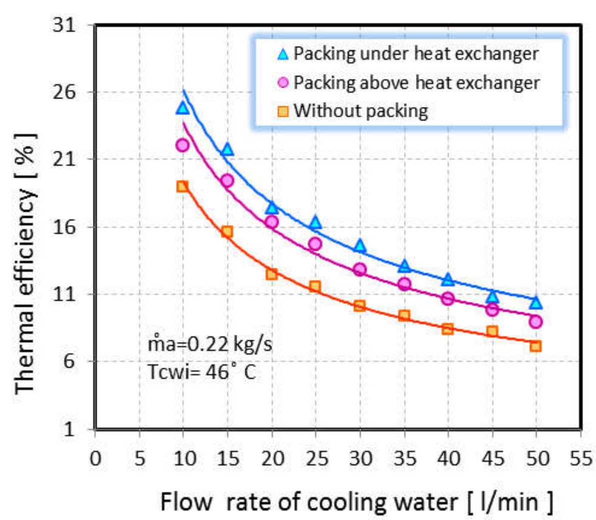

Figure 13. Variation of thermal efficiency with cooling water flow rate for different locations of packing

4. CONCLUSIONS

Based on energy analysis, the effect of packing location on the performance of CWCT was evaluated in the present paper. The CWCT with packing has a superior performance than without packing. Moreover, it is seen that the height of packing (560 mm) significantly affects tower performance in comparison with (280 mm) packing height. The result indicated that the thermal efficiency for added packing height of (560 mm) & (280 mm) approximately (40%) and (12%) higher than that conventional CWCT respectively. Comparing CWCT with packing for both locations under and above heat exchanger, it has been noticed that the best performance for the CWCT with packing under heat exchanger. The result showed that the thermal efficiency for CWCT with packing under heat exchanger and CWCT with packing above heat exchanger approximately (40%) and (25%) higher than that CWCT without packing respectively.

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Nomenclature	**Greek Symbols**
A total heat transfer area, m2	αm mass transfer coefficient for water vapour, between spray water film and air, kg/m2 s
Cp specific heat at constant pressure, kJ/kg oC	αs heat transfer coefficient between tube external surface and spray water film, W/m2 oC
CR cooling range, oC	αc heat transfer coefficient for water inside the tubes, W/m2 oC
D tube diameter, m	η thermal efficiency, %
h specific enthalpy, kJ/kg	ρ density, kg/m3
k thermal conductivity, W/m oC	Φ relative humidity, %
m mass flow rate, kg/s	ω humidity ratio, kg/kgdry air
q cooling capacity, kW	
Q volume flow rate, l/min	
Pr Prandtl number	
R tube radius, m	
Ra individual gas constant for air, J/kg.K	
Rv individual gas constant for water vapor, J/kg.K	
Re Reynolds number	
T temperature, oC	
Uo overall heat transfer coefficient, W/m2 oC	