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ANEXPERIMENTAL STUDY ON HEAT AND MASS TRANSFER FOR CLOSED WETCOOLING TOWER USING DIFFERENT WATER DISTRIBUTION SYSTEMS

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Abstract: The aim of this research is to investigate experimentally heat and mass transfer characteristics of the modified Closed Wet Cooling Tower (CWCT) using different water distribution systems. A prototype of forced draft counter flow CWCT modified with added packing was designed, manufactured and tested for cooling capacity of 9 kW in Iraq. A series of experiments have been conducted for different operational parameters on thermal performance of CWCT with packing located under heat exchanger .To get a best performance of the nozzles, a comparative work had been applied for three types of spray water nozzles: jet, swirl and threaded. The results indicated that the suitable spray nozzle is the key aspect to enhance the thermal performance of the tower. Furthermore, it is found that swirl and jet types spray nozzle have more significant enhancement than threated type spray nozzle. So, the best performance for swirl type spray nozzle. For same operating conditions, it is found that over (7%) and (13%) enhancement of cooling capacity in swirl type than jet and threated types respectively.

Keywords: *Closed Wet Cooling Tower (CWCT), spray nozzle, packing, thermal performance*

دراسة تجريبية لانتقال الحرارة والكتلة في برج تبريد مغلق رطب باستعمال أنظمة توزيع ماء مختلفة

الخلاصة: الهدف من هذا البحث هو التحقيق العملي لخصائص انتقال الحرارة والكتلة لبرج تبريد رطب مغلق مطوّر باستخدام أنظمة توزيع ماء مختلفة. تم تصميم وتصنيع واختبار نموذج لبرج تبريد رطب مغلق ذو سحب قسري متعاكس الجريان مطوّر بإضافة الحشوات لسعة تبريد (9kW). أجريت سلسة من التجارب لبيان تأثيرات المعاملات التشغيلية على الأداء الحراري للبرج المغلق بإضافة الحشوة اسفل المبادل الحراري. للحصول على افضل أداء لمرشّاة الماء, تمت المقارنة بين ثلاثة أنواع من المرشّاة: المنفث ,اللولبي والمسطح. أوضحت النتائج أن استخدام المرشّاة المناسبة جانب مهم لتحسين الأداء الحراري للبرج .بالإضافة إلى ذلك لوحظ أن مرشّاة الماء من النوع المنفث واللولبي لهما تأثير فعّال على تحسين أداء البرج مقارنة مع النوع المسطّح .كذلك فان افضل أداء هو لنوع مرشّاة الماء اللولبي. لنفس ظروف التشغيل فان تحسين سعة التبريد بمقدار يفوق (7%) و (13%) لنوع المرشّاة اللولبي عن نوعي المنفث والمسطّح على التوالي.

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1. Introduction

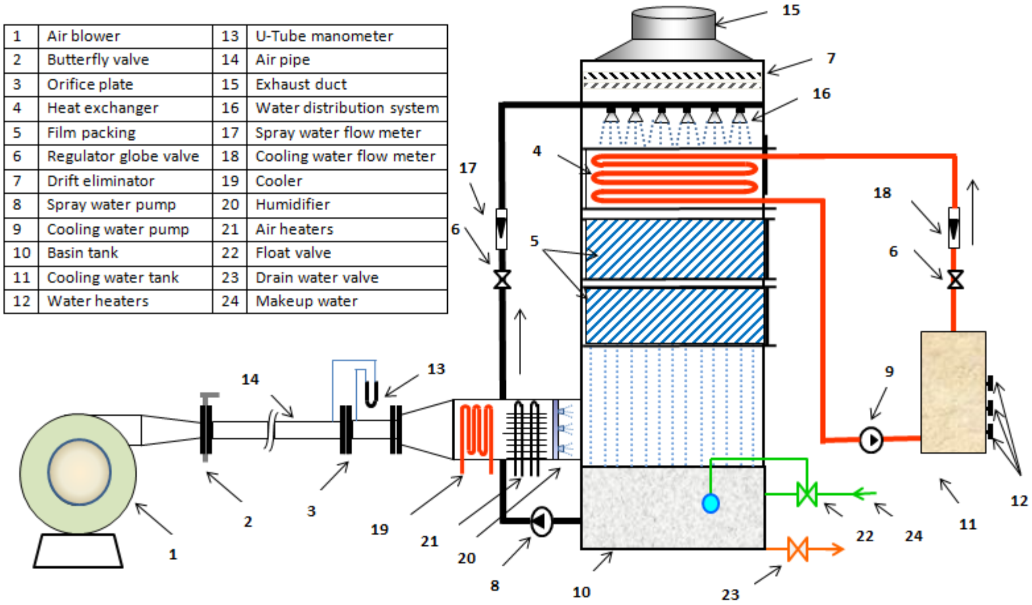
There are two types of wet cooling towers: open and closed cooling towers. In open cooling tower, the water is in direct contact with the air at surface of packing. In conventional CWCTs recirculated water is sprayed over a horizontal tube bundle, while air is drawn over the bundle and cooling water is circulated in tubes and never contacts the outside air .Because of these advantages of the close cooling tower that limited contamination risks with airborne and corrosion, it has a wide range of applications in the fields of electrical power, chemical industry and building air conditioning. With more and more closed cooling tower applications, the study also received increasing attention [1]. Much attention has been paid to issues on CWCTs relating to experimental studies and developed correlations of heat and mass transfer coefficients as a function of operating conditions. Oliveira & Facao [2], 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. Thermal performance of tow evaporative cooled heat exchangers, Investigated by Hasan & Sirén [3].They studies two heat exchangers; plane and plat-finned circular tube types occupy the exact volume and the ratio of total area (finned tubes /plate tubes) is four. Shim et al. [4 & 5] investigated experimentally the thermal performance of two heat exchangers in closed-wet cooling tower having a rated capacity of 2RT. 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 & Kroger [6] 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. Al-Tayyar [7] modified an available open circuit cooling tower (WL 320 Demo cooling tower, constructed by GUNT company in Germany) to make utilized likewise closed circuit cooling tower by designing furthermore manufacturing a heat exchanger located under packing. Zheng et al [8] investigated thermal performance of an oval tube induced draft counter flow CWCT based on heat and mass transfer under different operating conditions. The focus of this study is evaluating the thermal performance of modified forced draft counter flow CWCT with added packing for different water distribution systems in Iraq.

2. Experimental Setup and Procedure

2.1. Description of the Experimental Apparatus

A prototype of a modified counter flow CWCT was designed and constructed in which different operating parameters could be varied and tested in the laboratories of Environmental Engineering Department of Al-Mustansiriayah University College of Engineering. The general arrangement of the equipment is shown photographically in figure (1). In general, the apparatus consists essentially of cooling column and three major systems, Spray water, Cooling water and Air blowing. The tower fabricated from galvanized steel sheet to provide protection from rusting and corrosion, each sheet of 1.5 mm thickness, connected together by screws and nuts as a rectangular box of external dimensions (700 mm×400 mm×2300 mm), mounted rigidly on a frame which is welded construction with a channel section at the base welded together from the rectangle. As exists in every forced cooling, the test section consists of three zones: spray, fill (cooling zone) and rain zone. Spray zone is at a height of 180 mm suitable to ensure water distribution uniformly to all points in the fill section. 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. Six holes along the side of each (drawer) box were done to measure the water temperature, air dry bulb temperature and air relative humidity. The rain zone at a height of 450 mm in the case of three boxes and it will be variable when lifting one or two packing's and increases as decreases the packing height. Air from the atmosphere, enters the single stage centrifugal 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.



1	Air blower	13	U-Tube manometer
2	Butterfly valve	14	Air pipe
3	Orifice plate	15	Exhaust duct
4	Heat exchanger	16	Water distribution system
5	Film packing	17	Spray water flow meter
6	Regulator globe 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
11	Cooling water tank	23	Drain water valve
12	Water heaters	24	Makeup water

Figure 1. Schematic diagram for experimental apparatus

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. Plain tube heat exchanger was designed and manufactured for the present work. The tubes were fixed horizontally in test section inside supported frame of rectangular drawer. Cooling water moves through the tubes while the spray water and air moves over the tubes in perpendicular direction. The tubes are arrays in inline and staggered arrangement with (equilateral) tube pitch of $3D_o$ (pitch over diameter of 3) as shown in Figure (2). The specification of the heat exchanger shows in Table (1).

Table 1. Physical dimension of heat exchanger

Heat exchanger configuration	*Value*	*Unit*
Length	690	Mm
Height	166	Mm
Width	381	Mm
Tubes for coil	30	-
Vertical tube spacing	24	Mm
Horizontal tube spacing	80	Mm
Tube per row	5	-
Outside tube diameter	15.88	Mm
Tube thickness	0.81	Mm
Total heat transfer area	1032691.77	mm^2
Minimum free flow area	209148	mm^2

The water distribution system in the cooling tower should distribute the water uniformly over the tube bundle and packing inside the tower, to be the most coefficient method of uniformly water distribution in counter flow wet-cooling tower a pressurized spray system used with different types of spray nozzles. The spray water passes through the spray nozzles and constantly distributed at upper part of the test section, controlled by means of flow control valve globe type located downstream of the spray water pump. In the spray frame a header distributes or divides the deluge water into several conduits or lateral branches. Spray water nozzles were fitted the end of each lateral branch. A comparative and experimental work had been applied to get a best performance of the nozzles. Jet spray nozzle was used for applying the experiments and then other was used film (Threaded or flat) and swirl type nozzles. Three type nozzles are shown in Figure. (2). In Figure (3), the spray pattern for these nozzles is illustrated.

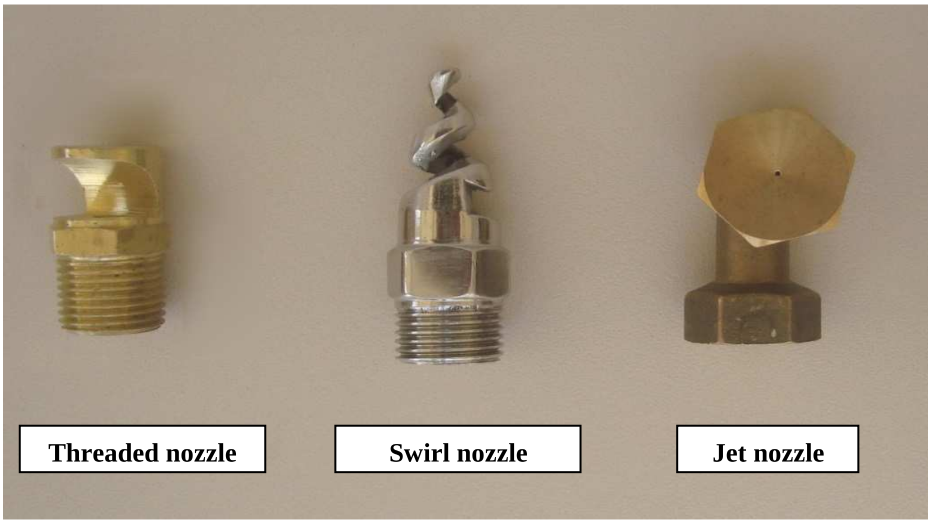


Figure 2.Types of spray water nozzles

Jet spray nozzle are used in square type cooling tower and round type cooling tower, water exits through an orifice, forming a conical pattern. The swirl nozzle impinges the fluid upon a protruding swirl. The hollow cone pattern is achievable by the swirl design of nozzle. This swirl shape breaks the fluid apart into several hollow cone patterns. By altering the topology of the swirl the hollow cone patterns can be made to converge to form a single hollow cone. The pattern of the threaded is formed by an elliptical or a round orifice on a deflective surface that is tangent to the exit orifice. Figure (3) shows the sprat patterns of these nozzles.

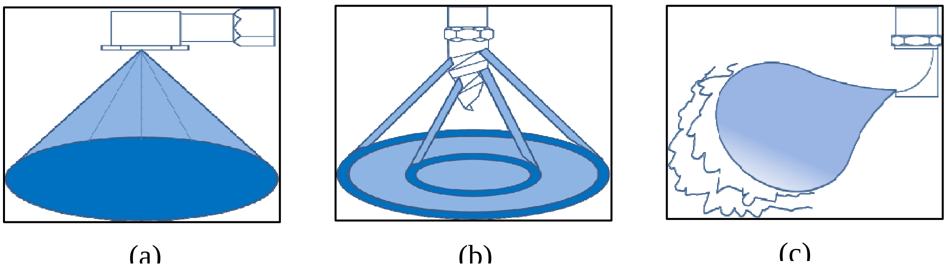
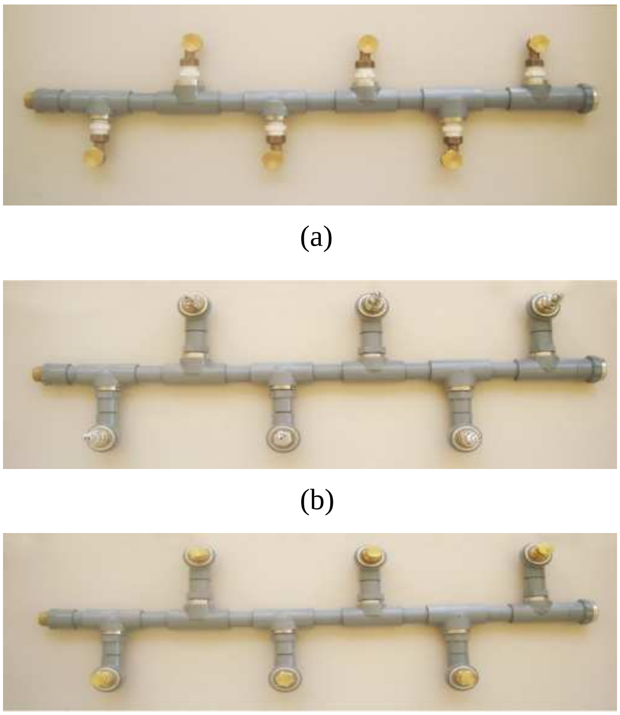


Figure 3. Spray pattern for: (a) jet nozzle, (b) Swirl nozzle and (c) Threaded nozzle

Figure (4) shows these spray nozzles arrangement. For threaded nozzles, the orifice directed inside holds meet each pair of nozzles to ensure uniform distribution covers all area of test section.

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 ^{0}C and 20 to 95% respectively.



(a)

(b)

(c)

Figure 4. Spray nozzles arrangement :(a) Jet nozzle, (b) Swirl nozzle and (c) Threaded nozzle

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 ^{0}C and 20 to 95% respectively.

2.2. Experimental Procedure

In order to evaluate the thermal performance of cooling tower, a series of experiments was carried out at different operational parameters. Operational parameters are listed in Table (2).To gain a better understanding of spray nozzle configuration on tower performance, the performance analysis has been illustrated for CWCT with packing (560 mm) height located under heat exchanger staggered tubes arrangement for different types of spray nozzles.

Table 2. Range of operational parameters

Parameter	Spray water flow rate	Cooling water flow rate	Air flow rate	Inlet water temperature	Air wet bulb temperature
Range	(10-70) l/min	(10-50) l/min	(0.12-0.35) kg/s	(35-55)° C	(5-24)° C

2.3. Performance Parameters

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

1-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:

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

2-Tower approach: is the difference in temperature between the cooler water temperature and the entering air wet-bulb temperature:

$$TA = T_{cw,out} - T_{awb,in} \tag{2}$$

3-Thermal efficiency: 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 [2 and 9]:

$$\eta = \frac{T_{cw,in} - T_{cw,out}}{T_{cw,in} - T_{awb,in}} \tag{3}$$

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

$$q = \dot{m}_{cw} C_{p,cw}\, CR \tag{4}$$

5-Mass transfer coefficient

The mass transfer coefficient obtained using enthalpy balance for an elementary transfer surface [2].

$$m_a dh_a = \alpha_m (h_i - h_a)\; dA \tag{5}$$

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

$$\frac{\alpha_m A}{\dot{m}_a} = ln\frac{h_i - h_{a,in}}{h_{mi} - h_{a,out}} \tag{6}$$

where, α_m 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_i 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 according to [8] 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 [10]

$$\dot{m}_a\left(h_{a,out} - h_{a,in}\right) = \dot{m}_{cw}C_{p,cw}\left(T_{cw,in} - T_{cw,out}\right) \tag{7}$$

Then the outlet air enthalpy calculates as:

$$h_{a,out} = h_{a,in} + \frac{\dot{m}_{cw}C_{p,cw}\left(T_{cw,in} - T_{cw,out}\right)}{\dot{m}_a} \tag{8}$$

6-Heat transfer coefficient

Heat transfer from cooling water inside tubes to spray water and air through a water film. The rate of heat transfer from cooling water dq_c is given by [11]:

$$dq_c = \dot{m}_{cw}C_{p,cw}dT_{cw} = -U_o(T_{cw} - T_{sw})dA \tag{9}$$

Integrated Eq.9 from the inlet to outlet of cooling water, with constant spray water T_{sw}, gives.

$$\frac{U_o A_c}{C_{p,cw} m_{cw}} = ln\frac{T_{cw,in} - T_{sw,m}}{T_{cw,out} - T_{sw,m}} \tag{10}$$

Where, U_o 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 [4]:

$$U_o = \left[\frac{R_o}{R_i}\frac{1}{\alpha_c} + \frac{R_o}{k_t}\ln\frac{R_o}{R_i} + \frac{1}{\alpha_s}\right]^{-1} \tag{11}$$

After the overall heat transfer coefficient was calculated from Eq.(10), it used to calculate, αs, tube to water film heat transfer coefficient (W/m^2 C).

$$\alpha_s = \left[\frac{1}{U_o} - \frac{R_o}{R_i}\frac{1}{\alpha_c} - \frac{R_o}{k_{tube}}\ln\frac{R_o}{R_i}\right]^{-1} \tag{12}$$

Where, α_c is the convection heat transfer coefficient of cooling water inside the tubes, it was calculated by the “Dittuse-Boelter” relation [12]:

$$\alpha_c = 0.023 \frac{k_{cw}}{D_i} Re^{0.8} Pr^{0.3} \tag{13}$$

Where, Reynolds number and Prandtl number were taken for the cooling water inside the tubes.

A MATLAB program was written to calculate the following parameters: water cooling range, tower approach, thermal efficiency, cooling capacity, heat transfer coefficient and mass transfer coefficient. The input data to this program is the measured parameters taken from the experimental runs.

3. Results and Discussion

3.1. Verification of the Experimental Apparatus

To verify the reliability of the experimental apparatus, energy balance of the air and cooling water was adopted using eq. (9).As shown in Figure (5), the unbalance of the heat gained by the ambient air and the heat lost by the cooling water are within ±10%. The heat balance of the apparatus could be claimed to be satisfactory.

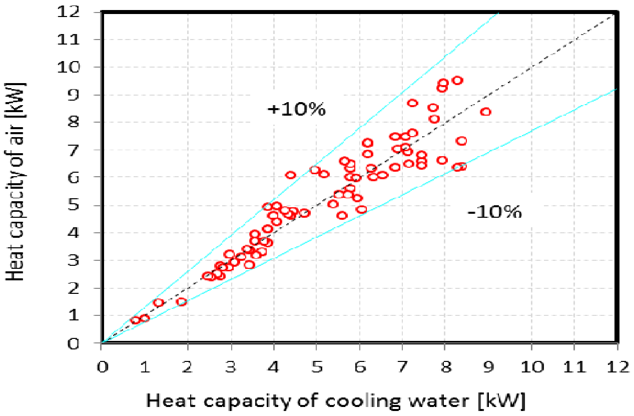


Figure 5. Energy balance of the experimental apparatus

3.2. Effect of Air and Spray Water Flow Rates

The effect of spray water flow rate on the cooling water rang for a different value of the air flow rate is illustrated in Figure (6). For each value of spray flow rate, as the air flow rate increases, the cooling water range is increases. This can be explained by as the air flow rate increases, rate of evaporated water increases too. On the other hand, cooling water range is increasing exponentially while the spray water flow rate is increasing. The most important reason for increasing cooling rang with spray water flow rate is increasing in the amount of water exposed to air during the unit time and providing a largest contact surface for the heat and mass transfer between water and air. The effect of spray water flow rate on the tower approach for different values of the air flow rate, is illustrated in Figure (7). It is clear that the tower approach inversely proportional to the air and spray water flow rates. As the air and spray water flow rate increases, the tower approach decreases since the outlet cooling water temperature decreases. The effect of air flow rate on the cooling capacity for different values of the spray water rate is illustrated in Figure (8). For each value of spray flow rate, as the air flow rate increases; the cooling water range is increases therefore, cooling capacity increased. This can be explained by as the air flow rate increases, rate of evaporated water increases too. On the other hand, cooling capacity is increasing exponentially while the spray water flow rate is increasing as a result of increasing in the amount of water exposed to air during the unit time and providing a largest contact surface for the heat and mass transfer between water and air. The effect of air flow rate on thermal efficiency for different spray water flow rates illustrated in Figure (9). The cooling tower thermal efficiency increases with the increase of air flow rate and spray water flow rate due to the increase in cooling range and the decrease in tower approach as its calculation from Eq. (4).This behavior was observed by Yoo et. al. (2010), [13]. Therefore, the best cooling tower thermal efficiency is achieved at the highest flow rates of air and flow rate of spray water as shown in Figure (9).

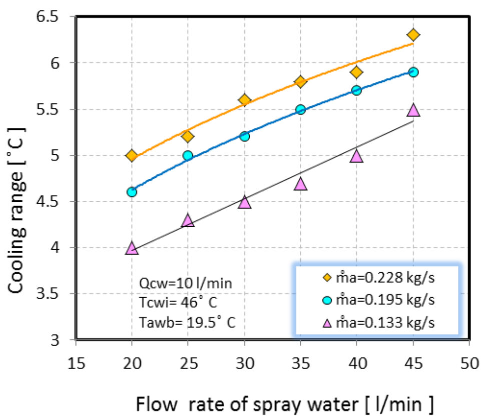


Figure 6. Variation of cooling range with spray water flow rate for different air flow rates

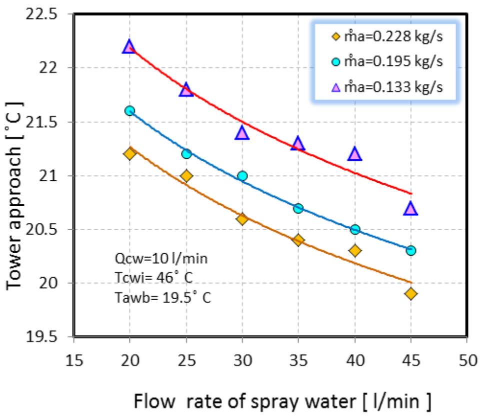


Figure 7. Variation of tower approach with spray water flow rate for different air flow rates

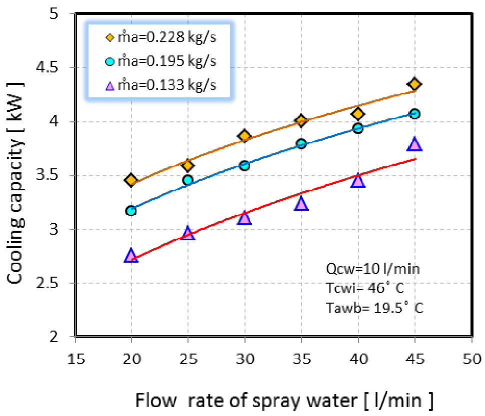


Figure 8. Variation of cooling capacity with spray water flow rate for different air flow rates

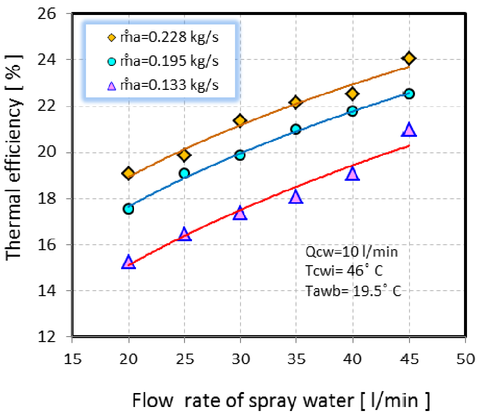


Figure 9. Variation of thermal efficiency with spray water flow rate for different air flow rates

3.3. Effect of Cooling Water Flow Rate

The relationship between the cooling water range and cooling water flow rate with different spray water flow rates are illustrated in Figure (10).It can be noted that the cooling water range is inversely proportional to the cooling water flow rate when both air and spray water flow rates are constant. For constant heat load, at low flow rate of circulation cooling water inside the heat exchanger tube, the opportunity to be the largest in completion of heat exchange with spray water and air through the tube surface within the tower test section for same air flow rate caused an increasing in temperature difference of cooling water. If maximum cooling range is desired, the low flow rate of cooling water should be used. For the same manner in Figure (6), cooling water range for 40 l/min spray water flow rate approximately 14% higher than that 30 l/min. The relationship between the tower approach and cooling water flow rate for different spray water flow rates are illustrated in Figure (11).It is clearly seen that the tower approach is proportional to the cooling water flow rate when both air and spray water flow rates are constant. This is mainly because when cooling water flow rate increases, outlet cooling water temperature decreases as a result of decreases in the temperature difference of the cooling water inside heat exchanger. The lowest of tower approach is achieved at the highest value of spray water flow rate and lower value of cooling water flow rate. For the same manner in Figure (6), tower approach for 40 l/min spray water flow rate approximately (18%) lower than that 30 l/min. The cooling capacity of tower versus cooling water flow rate with different spray water flow rates is shown in Figure (12). It can be noticed that the cooling capacity is proportional with cooling and spray water flow rates. When the spray water flow rate remains constant, cooling capacity increases significantly to increase in cooling water flow rate in spite of decreasing in cooling water range for this case according to Eq. (4). This confirms the experimental results of Shim et. al. (2008) [4]. The effect of cooling water flow rate on thermal efficiency for different spray water flow rates illustrated in Figure (13).As expected, the thermal efficiency depends on the cooling and spray water flow rates. Thermal efficiency inversely proportional with cooling water flow rate which is due to decrease in in cooling range .When the cooling water is low and spray water flow rate is high, the higher value of thermal efficiency is achieved.

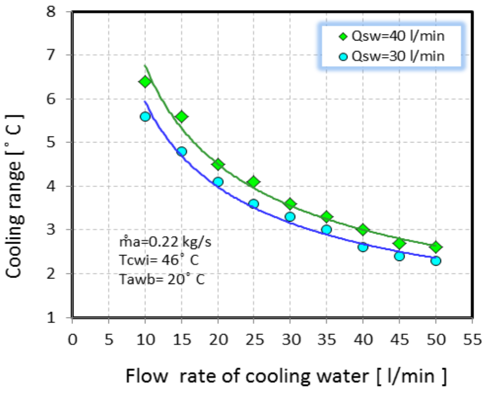


Figure 10. Variation of cooling range with cooling water flow rate for different spray water flow rates

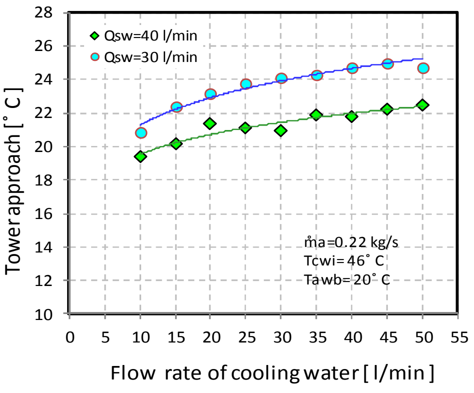


Figure 11. Variation of tower approach with cooling water flow rate for different spray water flow rates

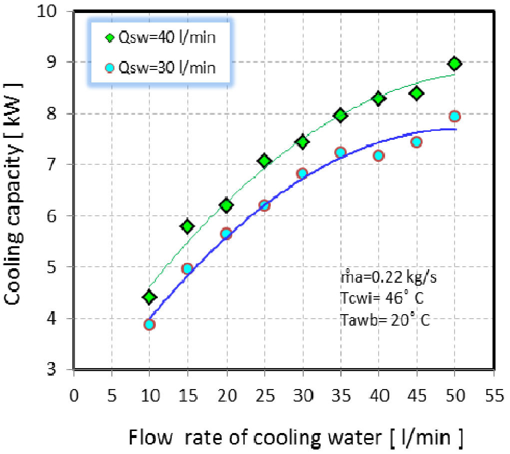


Figure 12. Variation of cooling capacity with cooling water flow rate for different spray water flow rates

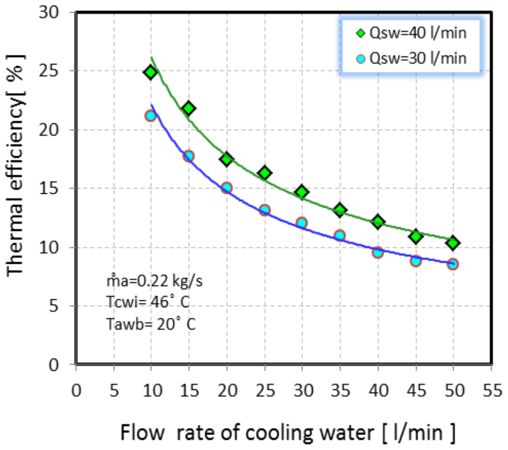


Figure 13. Variation of thermal efficiency with cooling water flow rate for different spray water flow rates

3.4. Effect of Inlet Cooling Water Temperature

The variation of cooling water range with inlet cooling water temperature for different values of spray water flow rate is illustrated in Figure (14). For each value of inlet cooling water temperature, as the spray water flow rate increased, the cooling water range is increased. It is apparent. that cooling water range increases .Which is due to the increasing in the air hold up as a result of a decreased viscosity of spray water that was caused by increased an inlet spray water temperature at the first stage of the tower. Therefore, at a higher inlet spray water temperature, the vapor pressure driving force is increased by operating cooling tower at a given inlet air condition, this conforms well to Shim et. al. (2008) [4]. What was observed from this figure is that the decrement of the cooling range at high inlet cooling water temperature is increased because of the increased in rate of heat and mass transfer. The variation of tower approach with inlet cooling water temperature for different values of spray water flow rate is illustrated in Figure (15). The tower approach inversely proportional with spray water flow rate and the rate of increase in tower approach is quite small at low inlet cooling water temperature for each values of spray water flow rate. On the other hand, for constant spray water flow rate, the tower approach increased linearly with the increasing of inlet cooling water temperature. Also, it is shown that if the inlet cooling water remains constant, tower approach increases when spray water flow rate decreases. Moreover, increasing spray water flow rate and decreasing inlet cooling water temperature simultaneously result in reducing the tower approach. Cooling capacity with respect to variable inlet cooling water temperature and spray water flow rate has been shown in Figure (16).It is shown that if the spray water flow rate remains constant, cooling capacity increases rapidly with the increase of inlet cooling water temperature due to increase in rate of heat and mass transfer. This behaviour is determined by different experiments of authors Shim et. al. (2008), [4] and Yoo et. al. (2010), [13].Figure (17) indicate the effect of variable inlet cooling water temperature upon the tower thermal efficiency for different values of spray water flow rates. The thermal efficiency increases almost exponentially as the inlet cooling water temperature increases for all values of spray water flow rates. The thermal efficiency is high at higher inlet cooling water temperature and spray water flow rate. Small increment at low water temperature will gradually increases with an increase in water temperature.

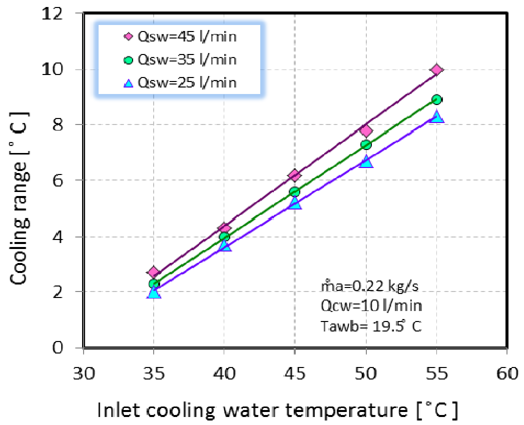


Figure 14.Variation of cooling range with inlet cooling water temperature for different spray water flow rates

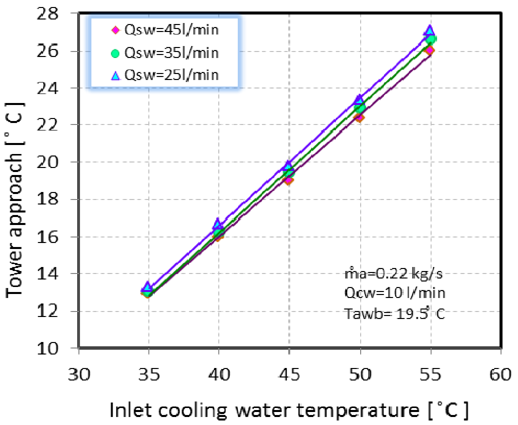


Figure 15. Variation of tower approach with inlet cooling water temperature for different spray water flow rates

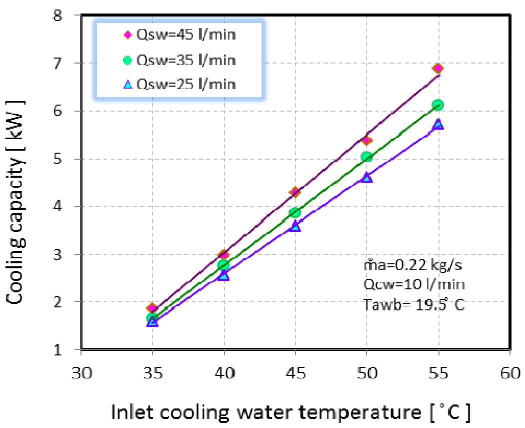


Figure 16. Variation of cooling capacity with inlet cooling water temperature for different spray water flow rates

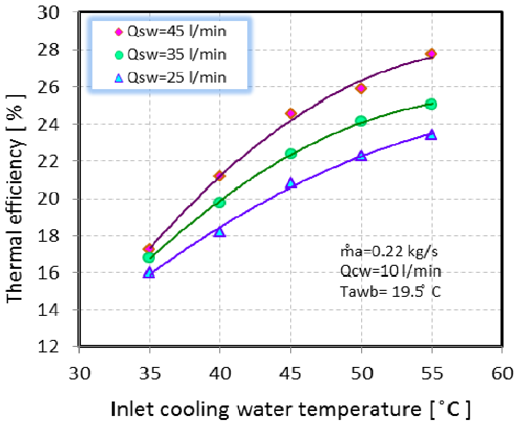


Figure 17. Variation of thermal efficiency with inlet cooling water temperature for different spray water flow rates

3.5. Effect of Inlet Air Wet Bulb Temperature (AWBT)

Cooling range with respect to variable inlet AWBT for different inlet cooling water temperature has been shown in Figure (18).For each inlet cooling water temperature, cooling range decreases almost linearly with the increase of inlet AWBT and vice versa. This is because when the inlet AWBT increases, the amount of heat exchange between air and water by convection and evaporation decreases due to a decrease in temperature difference between the inlet air and cooling water temperatures. Also, it can be known for the same reason that when inlet cooling water increases for the same inlet AWBT, the cooling range increases. Effect of inlet AWBT on tower approach for different inlet water temperatures illustrated in Figure (19).The tower approach decreases almost linearly with the increase of inlet AWBT for both inlet water temperatures because of the increase of outlet cooling water temperature which is illustrated in the effect of inlet AWBT on cooling range. Despite the increase in cooling range at low AWBT, the tower approach increase for this case as a result of increasing in temperature differences between the inlet AWBT and outlet cooling water. The change in cooling capacity versus inlet AWBT for different inlet cooling water temperature presented in figure (20). It is clear that the cooling capacity in inversely proportional with the inlet AWBT for both inlet cooling water temperatures. It is believed because any increase in inlet AWBT reflected to decreases the enthalpy potential between saturated vapor mixture (film surrounding the water droplet) and surrounding air. The effect of inlet AWBT on tower thermal efficiency for different inlet cooling water temperatures is investigated in Figure (21). It can be seen for both inlet cooling water temperatures that the thermal efficiency decreased as inlet AWBT increased which is brought about by the temperature fall at outlet of the heat exchanger. This behavior was observed by Sarker (2007), [14]. Also, it can be apparent that higher tower thermal efficiency achieved at higher inlet cooling water temperature.

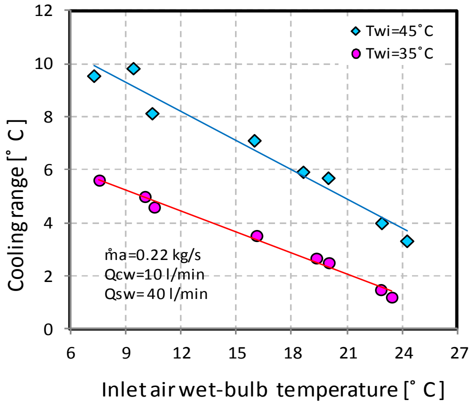


Figure 18. Variation of cooling range with inlet AWBT for different inlet water temperatures

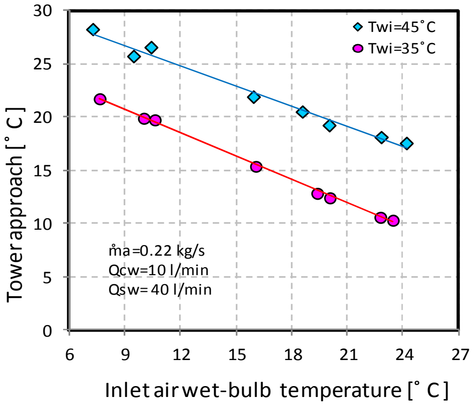


Figure 19. Variation of tower approach with inlet AWBT for different inlet water temperatures

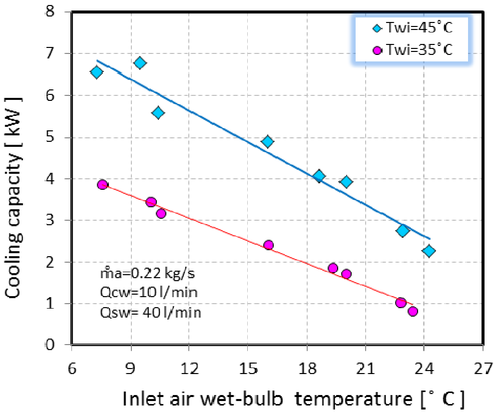


Figure 20.Variation of cooling capacity with inlet AWBT for different inlet water temperatures

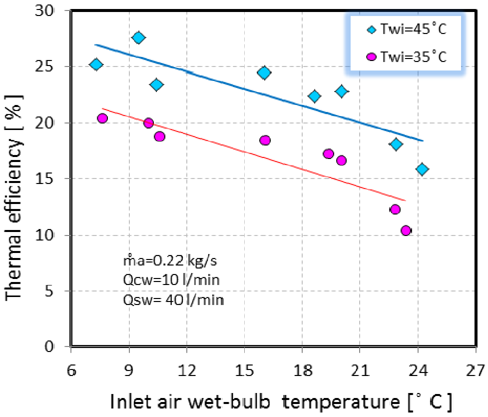


Figure 21.Variation of thermal efficiency with inlet AWBT for different inlet water temperatures

3.6. Effect of Spray Nozzles Type

Figures (22) to (25) represent the comparison between cooling range, tower approach, thermal efficiency and cooling capacity as a function of spray water flow rate for tested three spray nozzle types: jet, swirl and threated.

Figure (22) show the variation of cooling range with spray water flow rate for different nozzle types. As mentioned in previous figures, efficient spray water flow rate increases the efficiency of cooling tower. In other words, increases the number falling spray water drops and decrease its volume leads to increase contact area between spray water and air. The volume of drops must not be too small because they are easy to carry with the air outside the tower thus lost without the benefit. Swirl spray nozzle provides drops in the form of hollow cone, where the drops are concentrated on the area around cone-shaped ring as well as out quickly rotational tilted to hit the heat exchanger or packing considerably less vertical velocity on the heat exchanger or packing, which provide an opportunity delay water drops inside the test section. Jet spray nozzle produces full cone of drops in the form of jet which is the best in regular distribution of water on the surface of heat exchanger or packing. In swirl and jet spray nozzles the cone diameter proportional with spray water flow rate, increasing spray water flow rate allow better water distribution due to water overlap on the test section .This water overlap has an impact on the speed of air turbulence inside the test section and increase in drops evaporation process.

In threaded spray nozzle, the spray water comes out on the form of oval film of vertical velocity on test section. This film is not easily evaporated in spite of good water distribution on test section. Thus, it is indicated that for same spray water flow rate , the cooling range using the swirl nozzle type is higher than that in both jet and threated types about (7 %) & (13%) respectively. It is also observed that the spray water flow rate reaches higher value for swirl type. In Figure (23), the variation of tower approach with spray water flow rate for different nozzle types is illustrated. From this Figure, it can be concluded that swirl nozzle results in less tower approach of about (2%) and (3%), than both jet and threated types respectively.

Figure (24) gives an indication to the thermal efficiency enhancement of using different nozzle types. A bout (5%) and (15%) improvement rate were noticed for using swirl type compared to using both jet and threated types respectively. Figure (25) demonstrates comparison between cooling capacity and spray water flow rate using different spray water types. It can be concluded that for same spray water flow rate, over (7%) and (13%) enhancement of cooling capacity in swirl type than jet and threated types respectively.

3.7. Empirical Correlations

According to the results of the experiments of this work, for different operational parameters, correlations for heat and mass transfer coefficients were developed for cooling tower operates without packing. These correlations are:

a- Mass transfer coefficient

$$\alpha_m = 0.000001(G_{air})^{0.5038}(G_{sw})^{0.7456}(T_{cw})^{2.4478} \quad (14)$$

b- Heat transfer coefficient

$$\alpha_g = 0.1349(G_{sw})^{0.3758}(G_{cw})^{0.2051}(T_{cw})^{1.7749} \quad (15)$$

The average roots square mean error between correlations and experimental data for mass and heat transfer was (0.9666), (0.9424), respectively.

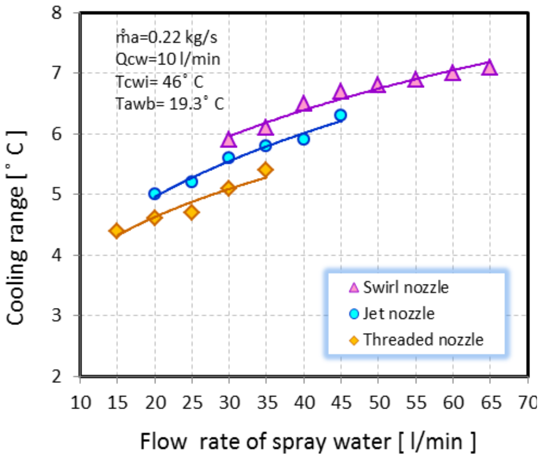


Figure 22. Variation of cooling range with spray water flow rate for different pray nozzle types

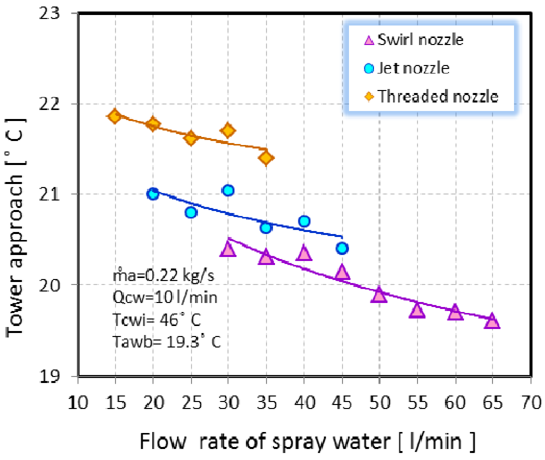


Figure 23. Variation of tower approach with spray water flow rate for different spray nozzle types

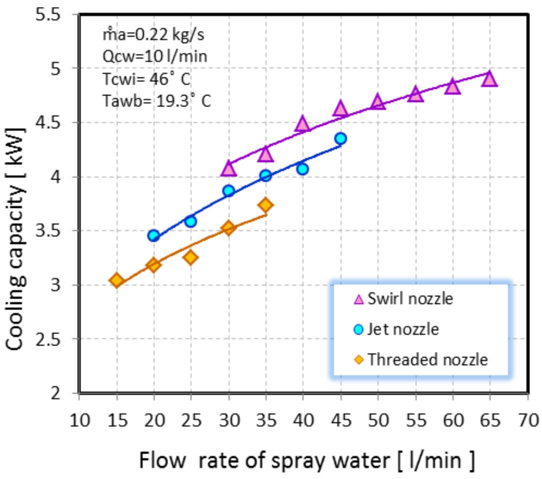


Figure 24. Variation of cooling capacity with spray water flow rate for different spray nozzle types

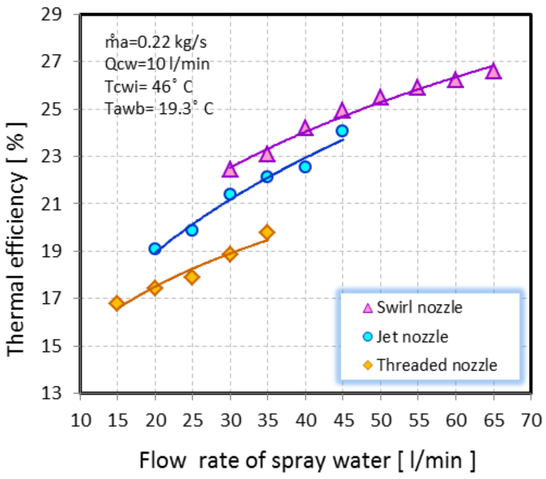


Figure 25. Variation of thermal efficiency with spray water flow rate for different spray nozzle types

4. Conclusions

This research has examined the thermal performance of prototype CWCT operate with added packing. Three types of spray water nozzle have been used: jet, swirl and

threaded. A comparative experiment of the modified CWCT with various operating conditions has also been conducted, through results can be summarized as follows:
The operational parameters have a direct effect on the cooling tower performance. So the best operational conditions achieved for higher cooling rang, thermal efficiency and cooling capacity and for lower tower approach.

The suitable spray nozzle is the key aspect to enhance the thermal performance of the tower. Furthermore, it is found that swirl and jet types spray nozzle have more significant enhancement than threated type spray nozzle. So, the best performance for swirl type spray nozzle.

For same spray water flow rate, over (7%) and (13%) enhancement of cooling capacity in swirl type than jet and threated types respectively.

Nomenclature

A=total heat transfer area, m^2
Cp=specific heat at constant pressure,(kJ/kg ^oC)
CR=cooling range,(^oC)
D=tube diameter,(m)
G=mass flux,(kg/m^2.s)
h=specific enthalpy, (kJ/kg)
k=thermal conductivity,(W/m ^oC)
$\dot{m}$=mass flow rate, (kg/s)
Q=volume flow rate,(l/min)
q=cooling capacity,(kW)
Pr=Prandtl number
R=tube radius,(m)
Re=Reynolds number
T=temperature(^oC)
TA= tower approach,(^oC)
Uo= verall heat transfer coefficient,(W/$m^{2o}C$)

Greek Symbols

α_m= mass transfer coefficient for water vapour, between spray water film and air,(kg/m^2 s)
α_s =heat transfer coefficient between tube external surface and spray water film,(W/$m^{2o}C$)
α_c =heat transfer coefficient for water inside the tubes,(W/$m^{2o}C$)
η = thermal efficiency,(%)

Subscripts

a=air
cw=cooling water
in=inlet
m=mean

out=outlet
sw=spray water
t=tube

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