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Performance analysis of a cooling tower system used for cooling hot thermal distillate from a desalination system under severe climatic conditions

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ABSTRACT

The water storage and distribution terminal in a city on the East coast of Saudi Arabia receives very hot potable water from thermal desalination process. The flowrate of water is 800–900 t/h during all seasons with the temperature of water ranging between 44°C–46°C. To lower the temperature of the hot water, cooling towers were installed to cool the water to 38°C and make it suitable for domestic consumption without affecting the water quality. The summer ambient temperatures can reach 47°C during the day with relative humidity up to 45%, while the night time ambient temperatures can exceed 30°C with relative humidity reaching as high as 70%–80%. The cooling towers sometimes fail to achieve the targeted temperature of 38°C during the summer months. This study and evaluation present the findings from one such time period which lasted for several days, when the water could only be cooled to temperatures ranging between 38°C and 40°C. Furthermore, it was found that higher relative humidity results in lower efficiency of the cooling towers.

Keywords: Cooling tower; Hot thermal distillate; Relative humidity; Wet bulb temperature; Range; Approach; Performance; Efficiency

1. Introduction

Some water standards stipulate the maximum temperature of water at the point of supply to the distribution network and use be 30°C [1]. However, the temperature of the water produced depends directly on the source of water, technology used for water production and the mode of transportation of water from the point of generation to the point of use. In the case of ground water which might be brackish (total dissolved solids (TDS) < 10 g/L), the temperature of the product water is less than the ambient temperature in most of the cases. In some cases, such as the ground water which is pumped from depths of up to 1,500 m in the province of Riyadh in the Kingdom of Saudi Arabia (KSA), the water temperature reaches 60°C–70°C [2]. Processing water through reverse osmosis (RO) system needs feed temperatures between (30°C–35°C) and this is achieved by using cooling towers. In case of RO systems, the temperature of the product water is 1°C–2°C higher than the feed water due to the usage of high-pressure pumps.

If thermal desalination technologies are used, the distillate (product water) temperature is dependent on the reject stream temperature of the process relative to the ambient feed (water) stream. This difference is considered on the order of 5°C–10°C in various locations, depending on the approach temperature of distillate cooling heat exchanger. For example, the multi effect distillation (MED) plants at Shoaiba, Marafiq, Sohar and Yanbu have distillate temperatures 40°C, 44°C, 38°C and 45°C designed for 35°C, 35°C, 34°C and 33°C seawater temperatures in summer conditions,

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respectively, and are purely based on the design adopted and the seawater temperature. Economic considerations and site constraints influence the approach temperature adopted and thus impact the distillate temperature.

Mahmoud et al. [3] discussed the options that could be adopted for cooling hot distillate at the seawater and ambient conditions seen on the east coast of KSA. After giving due consideration to the potential technologies that could be adopted and their specific limitations, they found that cooling towers provided the best solution. Boland [4] discussed the steam condensing pressure range for direct water cooling of condenser, water cooling with wet cooling tower, air cooled condenser and water cooling with dry cooling tower.

Cooling towers have found application in sectors ranging from water, wastewater, power to petrochemical industries. Kim et al. [5] used a cooling tower in their studies on adsorption desalination for providing cooled water to the evaporator. If there is contact between the inlet air and water, the towers are called open cooling towers (OCT) and closed-wet cooling towers (CWCT) if there is no contact between air and water. In OCTs a large amount of circulating water is required [6]. If the water stream is to be protected from contamination, CWCTs would be the better choice. This is achieved through a closed loop for the fresh water which requires extra plate type heat exchanger to keep it from getting contaminated.

Asvapoositkul and Kuansathan [7] considered variable working conditions of a hybrid (wet/dry) cooling tower and predicted the performance by developing a computational model. Ataei et al. [8] evaluated the performance of counter-flow wet cooling towers using exergetic analysis. Afshari and Dehghanpour [9] performed a review on cooling towers and simulated them in ANSYS Fluent. Qureshi and Zubair [10] developed a complete model of wet cooling towers with fouling in fills. Asfand et al. [11] simulated a 50 MW concentrated solar power (CSP) plant by considering both wet and dry cooling options, and studied the amount of water consumed. They considered an approach temperature of 5°C for the wet cooling tower and 6.75°C for the dry cooling tower. Javadpour et al. [12] discussed the effect of multi-walled carbon nanotubes (MWCNTs) on the performance of a forced draft cross-flow cooling tower.

Schulze et al. [13] discussed the environmental impacts of cooling tower operations in terms of energy and water demands. Ayoub et al. [14] presented a model for a natural draft wet cooling tower, assessed its performance as a function of the climatic parameters and estimated the effects of extreme weather conditions, with a focus on electricity generation from thermal power plants. Srisang et al. [15] designed a hybrid heat rejection system in Thermoflex for cooling hot water at 44.5°C from a CO_2 capture and storage plant in a coal fired power plant to be cooled to 25°C, and optimized the heat load on the dry cooling and wet cooling system.

Heat rejection from a cooling tower is low when the ambient temperature and humidity are high [16]. In a hybrid system with dry and wet towers, when the outlet water temperature is within the limits, dry cooling towers were used and when it exceeded certain threshold, the water was directed to wet cooling section. This strategy helped in reducing power consumption and water consumption [16]. Wei et al. [17] presented a simplified method for analysing the thermal performance of closed wet cooling towers (CWCT).

Wet cooling towers cost less than the dry cooling towers and the hybrid towers are the costliest. The aforementioned technologies were evaluated using Thermoflex [18]. Tower CWCT is an OCT in which the packing is replaced by a bank of coil tubes and the spray water contacts the inlet air to form falling films outside the coil tubes [12].

Abboud [19] discussed various parameters, namely the range, approach, effectiveness, cycles of concentration, cooling capacity, evaporation rate of water and liquid to gas ratio, which are capable of affecting the performance of cooling towers. Among the parameters discussed, efficiency is inversely proportional to the approach, and cooling towers in hotter climates usually have lower efficiencies due to the higher wet bulb temperatures [20]. Deorukhkar [21] presented several cases showing the influence of range and approach on effectiveness of cooling towers and additionally suggested considering the liquid to gas ratio (L/G ratio) in cooling tower performance evaluation.

Ruiz et al. [22] developed a new design of an inverted cooling tower capable of reducing the emission of airborne particles significantly. Navarro et al. [23] conducted a critical evaluation of the performance characteristics of the inverted cooling tower. Mishra et al. [24] found improvements in the range and approach of a cooling tower by conducting experimental investigations using a silica gel mesh column at the inlet of the cooling tower. It was also found that the aforementioned modification reduced water consumption even at an inlet water temperature of 50°C. Mishra and Alam [25] experimentally analysed the influence of using rotary silica gel mesh on the effectiveness, water saved and the outlet air temperature of an induced draft counterflow cooling tower. They also found that the height of the cooling tower could be reduced using silica gel mesh using a thermodynamic model. Rahman et al. [26] investigated the effects of using a nanofluid as a coolant in an induced draft counter flow cooling tower and found that the range increased by 4°C and the efficiency improved by 8%.

Despite the fact that the Eastern Province of KSA is humid and hot, the daily evolution of relative humidity is opposite to that of air temperature, which was also observed by Giannopoulou et al. [27] and Duan et al. [28]. This relation in evolution of ambient temperature and relative humidity was confirmed at the site considered for study during the operation. CWCT has been implemented at the site being discussed in this manuscript. The performance characteristics are discussed in terms of the ability of the considered solution to lower the hot distillate (water) temperature despite the challenging climatology during summer.

To the best knowledge of the authors, cooling towers have been used to provide cooled water for various processes in industries (e.g., power, wastewater, adsorption desalination), where the hot water is recycled in the process after cooling. However, the case presented in this study does not deal with recycling of the water, rather it deals with cooling of water to meet the requirements of the customers/end-users who were receiving hot potable water exceeding 44°C during summers.

2. Context of the problem

2.1. Cooling system set-up and monitoring system

A closed wet cooling tower (CWCT) was installed at a water distribution unit in a city on the east coast of KSA. It receives almost 800–900 t/h hot distillate at a temperature of 44°C–46°C during the year. Since August is the peak summer time in the Eastern Province of KSA, this time period was chosen to test and evaluate the performance of the cooling tower.

The evaluation was based on the following criteria [29,30]:

- outlet temperature from the cooling tower and the inlet temperature of the hot distillate which indicates the ability of the cooling tower to achieve the desired temperature.
- cooling tower efficiency that shows the effect of weather conditions on efficiency.

Cooling tower efficiency is given by the following formula:

$$\text{Cooling Tower Efficiency} = \frac{\text{Range}}{(\text{Range} + \text{Approach})} \times 100 \quad (1)$$

Range is the difference between the inlet water and outlet water temperatures. The difference between the outlet water temperature and the ambient wet bulb temperature is termed as approach.

The cooling capacity of a cooling tower can be calculated as [19]:

$$Q = \dot{m}C_p\left(T_{w,\text{in}} - T_{w,\text{out}}\right) \quad (2)$$

where Q = cooling capacity (kW), $\dot{m}$ = mass flow rate of water (kg/s), C_p = specific heat of water (kJ/kg·K), $T_{w,\text{in}}$ = hot water temperature (°C), and $T_{w,\text{out}}$ = cooled water temperature (°C).

Fig. 1 shows the six installed cooling tower units used to cool 800–900 t/h hot distillate from 44°C–46°C to 38°C. The cooling towers receive the hot water from a bypass line that allows supply of water to the city even during maintenance time. The cooling towers use a part of the product water as make up for cooling, where the quantity of makeup is very small. Each cooling tower contains a fan, a circulation pump and water basin. All units receive product water parallely in same quantity and can be controlled independently (Fig. 2). VFDs are integrated with the system to control the speed of the fans and reduce energy usage.

The process has 3 main streams as shown in Fig. 2: (i) the distillate water to be cooled is isolated inside heat transfer tubes which acts like the heat source in the system, (ii) the sprayed water over the tubes acts as the intermediate media, and (iii) dry air flows through forced fans absorbing evaporated water, with the extraction of heat occuring through the process of evaporation. The cooling tower unit is equipped with controls and a monitoring SCADA system as shown in Fig. 2. Each one of the 6 cooling tower units can be set to the activated or deactivated mode individually, depending on the heat load.

2.2. Cooling system set-up and monitoring system

The typical variation of ambient temperature and relative humidity at Jubail in the Eastern Province of KSA is shown in Table 1. The row containing "Sum" shows the temperature range and the percentage occurrence of relative humidity between 0%–100% in a year. Similarly, the column containing "Sum" shows the percentage occurrence of a particular range of relative humidity across the temperature range 5°C–50°C in a year. Air temperature crosses 45°C during summers and can reach values up to 47°C. The months of June, July and August experience high day time temperatures (>40°C) with moderate humidity and moderate (>30°C) night temperatures with high humidity. The temperatures can reach 47°C and more during the day with humidity reaching as high as 80% in the night.

Fig. 1. Installed cooling tower units at the site.

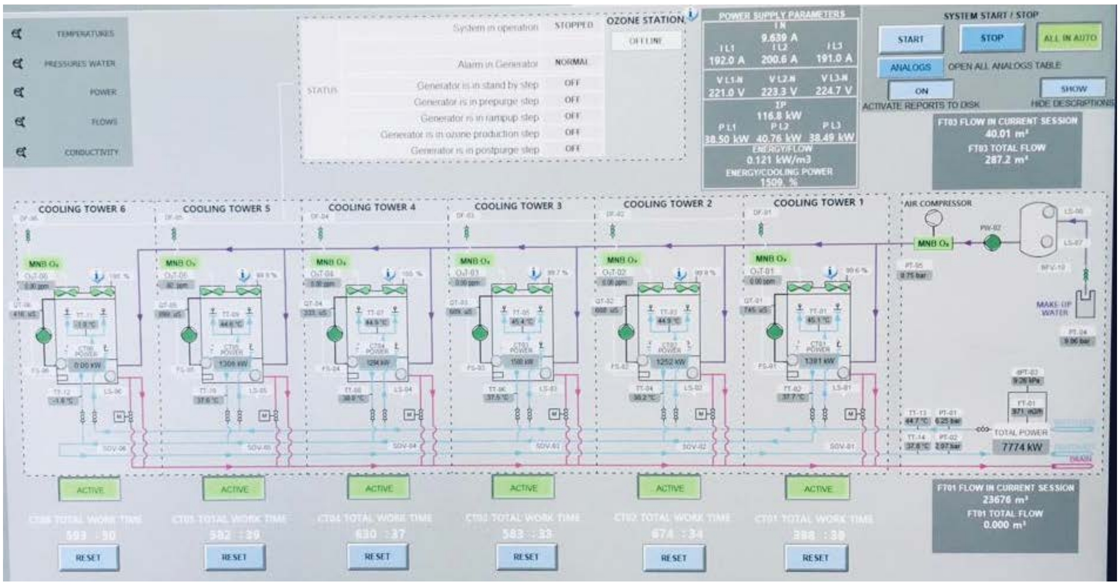

Fig. 2. SCADA system interface of the cooling tower system installation.

The variation of ambient temperature and relative humidity at the site during the month of August is shown in Fig. 3. During the day, the ambient temperatures are higher and the relative humidity is low. The ambient temperatures are lower during the night and the relative humidity is high. However, the temperatures are mostly above 30°C. Higher relative humidity results in higher wet bulb temperatures, thus reducing the amount of heat that can be rejected as less evaporation of water takes place.

3. Results and discussion

The cooling tower units were operated and the performance along with the weather conditions was monitored. The parameters monitored were:

- inlet hot water temperature and cooled outlet water temperature,
- flow rate,
- make-up, and
- relative humidity.

Fig. 4 shows a schematic where the air streams and water streams are shown. The incoming air stream exits the cooling tower after an increase in its relative humidity and wet bulb temperature, due to the evaporation of water in the tower. The amount of evaporated water is compensated by the make up water. m_1 is the mass flow rate of distillate (kg/s); m_2 is the mass flow rate of water being recirculated (kg/s); m_3 is the mass flow rate of make up (kg/s); m_4 is the mass flow rate of water being sprayed (kg/s); T_{1i} is the temperature of the hot distillate (°C); T_{1o} is the temperature of the cooled distillate (°C); T_2 is the temperature of the water in the tank (°C); T_4 is the temperature of the water being sprayed (°C); T_{a1} is the ambient air temperature (°C); T_{a2} is the air temperature of air leaving the cooling tower (°C); RH_{a1} is the relative humidity of ambient air (%); RH_{a2} is the relative humidity of the air exiting the tower (%); ω_{a1} is the humidity ratio of air at inlet (kg·H_2O/kg·dry·air); ω_{a2} is the humidity ratio of air at the exhaust (kg·H_2O/kg·dry·air).

Vengateson [31], the mass balance is:

$$m_3 = m_4 - m_2 \tag{3}$$

$$m_3 = m_{a1}\left(\omega_{a1} - \omega_{a2}\right) \tag{4}$$

$$m_{a1} = m_{a2} \tag{5}$$

Similarly, the energy balance on the control volume will be:

$$m_{a1}h_{a1} + m_4h_4 + m_1h_{1i} = m_{a2}h_{a2} + m_2h_2 + m_1h_{10} \tag{6}$$

The required cooled water temperature is reached most of the time. The inlet temperature and the outlet temperature of water is shown in Fig. 5 for the month of August. When the temperature and the relative humidity are the highest (Fig. 3) in August (temperature 47°C and relative humidity 67%), the inlet water temperature to the cooling tower system increased by 1°C from the source. Even when the fans of the tower, whose speed is controlled to maintain the outlet temperature were working at 100% load, the outlet water temperature failed to attain the targeted temperature of 38°C for nearly 250 h in continuous operation as the cooling temperature range dropped from 8°C to 6°C.

Fig. 6 shows the approach and range observed in the cooling tower system along with the water inlet, water outlet and wet bulb temperatures used for calculating the range and approach. The minimum and maximum range values are 4.8°C and 8°C, with the average value at 6.11°C. Similarly, the minimum, maximum and average values of the approach temperature are 6.96°C, 20.55°C and 11.75°C. The variations in the approach are due to the fact that the

Table 1
Relative humidity observed at various ambient temperature values at Jubail in the Eastern Province of KSA

Relative humidity	Ambient temperature									
	5°C–10°C	10°C–15°C	15°C–20°C	20°C–25°C	25°C–30°C	30°C–35°C	35°C–40°C	40°C–45°C	45°C–50°C	Sum
0%–10%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
10%–20%	0.000%	0.000%	0.000%	0.000%	0.114%	0.388%	0.479%	0.240%	0.011%	1.233%
20%–30%	0.034%	0.034%	0.000%	0.251%	0.674%	1.667%	1.655%	0.411%	0.023%	4.749%
30%–40%	0.171%	0.171%	0.263%	0.753%	1.815%	2.306%	2.477%	0.411%	0.000%	8.368%
40%–50%	0.148%	0.400%	0.811%	1.986%	2.306%	4.384%	3.208%	0.205%	0.000%	13.447%
50%–60%	0.228%	0.651%	2.146%	3.447%	2.900%	5.183%	3.094%	0.046%	0.000%	17.694%
60%–70%	0.126%	1.142%	4.669%	4.658%	2.865%	4.167%	2.055%	0.000%	0.000%	19.680%
70%–80%	0.137%	1.495%	4.304%	5.080%	2.717%	2.489%	1.495%	0.000%	0.000%	17.717%
80%–90%	0.023%	1.176%	2.911%	3.151%	1.575%	2.237%	0.228%	0.000%	0.000%	11.301%
90%–100%	0.160%	0.685%	1.918%	1.301%	0.571%	1.176%	0.000%	0.000%	0.000%	5.811%
Sum	1.027%	5.753%	17.021%	20.628%	15.537%	23.995%	14.692%	1.313%	0.034%	

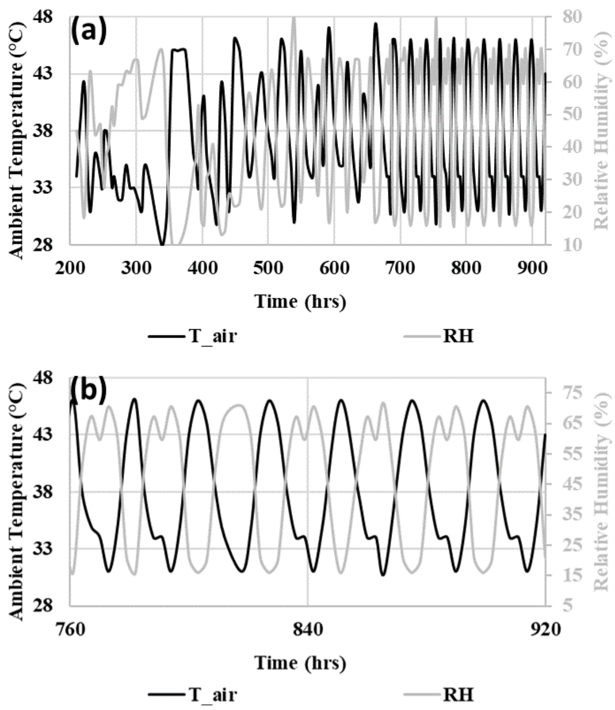

Fig. 3. (a) Ambient temperature and relative humidity observed at the site during August. High temperatures occur during the day with low humidity, and moderate temperatures occur during the night with high humidity. (b) Enlarged section of the plot showing the relationship between the ambient temperature and relative humidity.

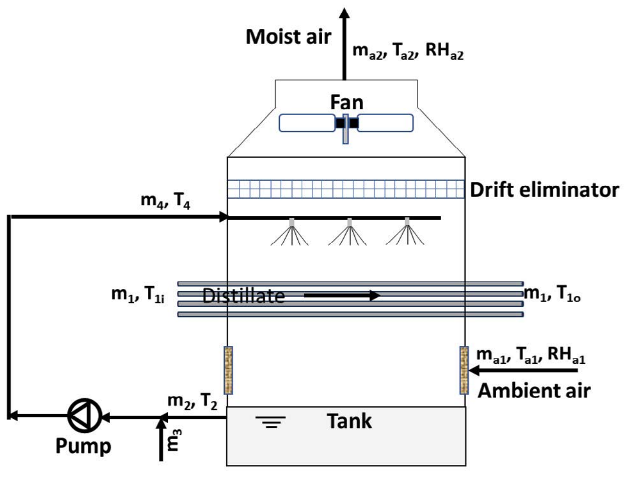

Fig. 4. Schematic showing the water and air streams entering and exiting the cooling tower system.

water outlet temperature values fluctuate within a narrow band of 3°C, whereas the wet bulb temperature varies between 16°C and 30°C.

Four cases with different ambient temperatures and relative humidities are presented in Table 2 with the values of air and water stream parameters. m_1, T_{1i}, T_{1o}, m_2, T_{a1} and RH_{a1} are measured values which are recorded, and T_2, T_4

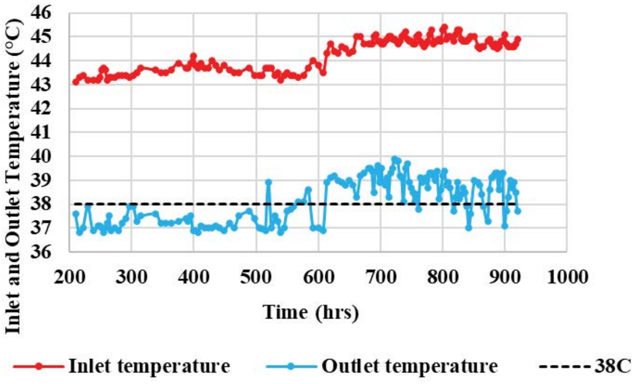

Fig. 5. Water inlet and outlet temperatures from the cooling towers with the desired 38°C shown.

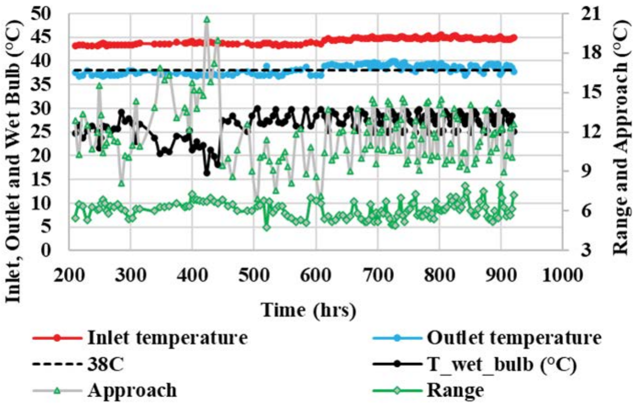

Fig. 6. Cooling tower inlet water temperature, outlet water temperature, ambient wet bulb temperature, range and approach. Also shown is a line indicating the desired cooled water temperature (38°C).

and RH_{a2} are assumed values. The wet bulb temperature of the air at the outlet is assumed to be 10°C higher than the wet bulb temperature at the inlet (following [19]). The ambient temperatures and the corresponding relative humidities are 31°C, 34°C, 44°C, 46°C and 70.48%, 70%, 20%, and 15.8%, respectively. The highest amount of air mass flow is seen in the 46°C ambient temperature and 15.8% relative humidity case.

Table 3 shows the efficiencies of the above-mentioned four cases of air temperature and relative humidity. The cooling tower system shows highest efficiency in the 46°C ambient temperature and 15.8% relative humidity case (case 4), with the lowest efficiency in the 44°C and 20% relative humidity case (case 3). Furthermore, the influence of the approach on the system efficiency is clearly visible when we compare cases 1, 2 and 3, where the range is almost same with some variation in the approach. When cases 2 and 4 are compared, though the approach in case 2 is lower than that in case 4, the slightly higher value of range in case 4 results in higher efficiency of the system.

The performance of the system is calculated in terms of efficiency using the approach and range values, and is shown in Fig. 7. The calculations show efficiency varying between 24.6% and 48.1%, with an average value of 34.6% and a standard deviation of 4.55%. An efficiency of 100% would mean the approach is zero. However, that is impossible to achieve. In hotter climates with high humidities, such as those seen in the Eastern Province of KSA, the approach values are usually high indicating lower cooling tower efficiencies when compared with other types of cooling towers which have efficiency in the range of 70%–75% [32,33]. The low efficiency of the system is caused by high relative humidity, which increases the wet bulb temperature, thus preventing more heat exchange by limiting evaporation. Whenever the value of the approach temperature is high, the cooling tower efficiency is low and vice versa.

Table 2
Various stream parameters of the cooling towers for different cases of ambient temperature and relative humidity

Case	m_1	T_{1i}	T_{1o}	m_2	T_2	m_3	m_4	T_4	m_{a1}	T_{a1}	RH_{a1}	m_{a2}	T_{a2}	RH_{a2}
	t/h	°C	°C	t/h	°C	t/h	t/h	°C	t/h	°C	%	t/h	°C	%
1. Low temperature, high humidity	850	44.6	38.9	98.71	44.6	6.83	105.54	44.6	357	31	70.5	357	37.3	95
2. Moderate temperature, high humidity	850	44.5	38.8	96.58	44.5	6.97	103.55	44.5	324	34	67	324	39.4	95
3. High temperature, low humidity	850	44.7	39.1	102.2	44.7	7.26	109.46	44.7	386	44	20	386	48.5	40
4. High temperature, low humidity	850	45.1	37.1	96.04	45.1	10.42	106.46	45.1	561	46	15.8	561	48.1	40

Table 3
Wet bulb temperature, range, approach and efficiency values for the four extreme cases considered

Case	T_{a1}	RH_{a1}	Wet bulb	T_{1i}	T_{1o}	Range	Approach	Efficiency
	°C	%	°C	°C	°C	°C	°C	%
1. Low temperature, high humidity	31	70.5	26.60	44.6	38.9	5.70	12.30	31.67
2. Moderate temperature, high humidity	34	67	28.81	44.5	38.8	5.70	09.99	36.32
3. High temperature, low humidity	44	20	25.40	44.7	39.1	5.60	13.70	29.00
4. High temperature, low humidity	46	15.8	24.95	45.1	37.1	8.00	12.15	39.70

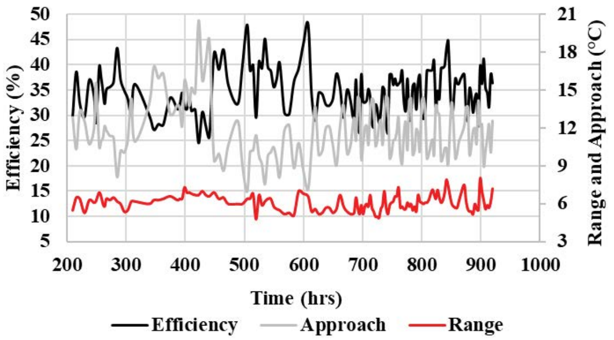

Fig. 7. Cooling tower system efficiency, range and approach.

As the approach increases, the cooling tower size decreases asymptomatically [19,34]. As the approach ranges between 7°C and 20.5°C, the cooling tower size factor varies between 0.75 and 1.5.

4. Conclusions

The water supplied from a thermal desalination plant to a storage and distribution terminal in a city on the east coast of KSA has a temperature between 44°C–46°C. Six adiabatic closed wet cooling towers (CWCT) were installed at the site to cool the water to 38°C without contaminating the water.

During peak summer, the ambient air temperature and relative humidity have an inverse relation qualitatively with the temperatures being high during the day (exceeding 40°C and reaching up to 47°C) and the relative humidity having high values during the night (reaching 70%–80%, with temperatures exceeding 35°C). The wet bulb temperature is a key factor in determining cooling achieved. Higher relative humidity leads to higher wet bulb temperature further leading to lower cooling range and approach temperatures. The wet bulb temperature exceeds 32.5°C about 8% of the time in a year, which leaves very small difference between the targeted temperature of 38°C for the cooled water and the wet bulb temperature.

From the performance, it can be concluded that wet bulb temperature is a key factor in the design which affects the heat transfer area used along with the approach temperature. Since the ambient air temperature and relative humidity are high during summer, a cooling range of 6° is acceptable, which is 75% of the target, that is, 8°C. As this application was just for the satisfaction of customers and meant as a complementary service, the cooling range selected is fairly sufficient. However, if the water is meant for use in industrial processes or if the water temperature is a critical process parameter as in the anaerobic bioreactors of wastewater treatment plants, then the design point shall be selected carefully to meet the requirement.

A more detailed analysis of the cooling tower system needs to be carried out for a period spanning a longer time for accurate determination of electric power consumption and operational costs. Air temperature, relative humidity and the mass flow rate of air at the system outlet need to be measured and the Liquid to Gas ratio needs to be determined, as it could have an impact on the operational costs. Additionally, nano fluids could be considered as heat transfer fluids to improve the range and efficiency.

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