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Theoretical analysis of a wet cooling tower coupled with a desalination plant for fresh water yield

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ABSTRACT

The scarcity of clean water resources and the need for supplementary water supplies is already significant in many arid regions of the world and will be increasingly vital in the future. Many arid areas simply do not have fresh water resources in the form of surface water such as lakes, ponds and rivers. They may have only limited underground water resources; some are becoming more briny as extraction of water from the aquifers continues. It is estimated that some 35% of the world's irrigated areas suffer from salinity problems and remediation is seen to be extremely costly. A desalination plant is coupled with wet-cooling tower to utilize the water vapour (plume) from the top of cooling tower for the fresh water yield by a designed water cooled condenser. From the cooling towers, lot of plume carries heat energy is wasted and an idea behind this research focuses on diverting the plume to a condenser through the ducts. The water vapour is condensed by the condenser,and then the fresh water is pumped out with help of a positive displacement pump. A theoretical analysis is made by mass, energy equations considering desalination system with the cooling tower to get fresh water yield. The important parameters which affect the performance of the plant such as condenser flow rate, condenser temperature, water vapour flow rate, water vapour temperature, cooling load, mass flowrate of water and air, range and effectiveness through the tower have been considered to find out the maximum fresh water yield (lps). The theoretical results have been validated with the experimental results available in literatures. In this paper, a detailed design of a condenser and a theoretical analysis of the desalination plant coupled with cooling tower to get fresh water is presented. With help of the results from analysis, the power plant having cooling towers with the capacity 330 MW and 840 MW coupled with desalination plant were analyzed.

Keywords: Cooling load; Cooling tower; Condenser; Desalination; Fresh water; Optimum condition; Power plant; Yield

1. Introduction

Water is used in many process cooling applications. The cooling water itself must be cooled and re-circulated, expect where estuarine water or river water or brackish water exists. A cooling tower is used to reduce the temperature of a water stream by extracting heat from water and emitting it to the atmosphere [1]. Cooling towers make use of evaporation whereby some of the water is evaporated into a moving air stream and subsequently discharged into the atmosphere. Heat is transferred in the wet cooling tower due to convection and evaporation. Using air-cooled heat exchangers (wet cooling towers) which can operate either in forced draft or in natural draft, heat can be extracted from the cooling water. The evaporation released to atmosphere

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from cooling tower of the thermal power plant, creates environmental problems like global warming and some scarcity of water in power plant. In order to find a solution for both the scarcity of water and environmental issues, these water vapours from cooling tower are being collected and condensed for fresh water by using a designed condenser. In thermal power plants, large quantity of water is required for various processes. So, a desalination system has been coupled with a thermal power plant to utilize waste vapours (plume) from the cooling tower. The water vapours from the cooling tower is fed through the duct to the condenser, where it condenses to the fresh water and is collected periodically with the help of positive displacement pump. A part of fresh water is utilized for power plant needs and the remaining water is filtered for the potable use by villagers. The paper discusses about the (i) design of condenser, (ii) design of duct from cooling tower top to the condenser inlet, (iii) theoretical analysis to get the yield by solving the governing equations by applying mass, momentum and energy equations across the various components of the system by the simulation, (iv) few trial experiments were conducted on fabricated laboratory scale model cooling tower to compare the theoretical results obtained from solving governing equations. Then with the conditions of a specific trial from the experiments, the mass flow rate of water in the cooling tower in the model set-up has been scaled up to match the mass flow rate of water with that of industrial cooling tower. This helps to estimate the mass flow rate of the air, water and mass of evaporated water vapour through the industrial cooling tower. The water collected at the bottom of the cooling tower and is used in condenser of the thermal power plant to condense the steam into water, and it is supplied through the condenser of the desalination system. Further, it is sent back to the boilers to be converted back into steam to generate power. The important parameters which affect the performance of the plant are cooling load (heat load = applied load + pump load) of the tower, desalination plant condenser flow rate, condenser temperature, water vapour flow rate, water vapour temperature, mass flowrate of water and through the tower. But, in this research work, cooling load, mass flowrate of water and air through the tower, range, effectiveness are considered to find out the maximum fresh water yield (lps). Some literatures are very useful to proceed the analysis.

The important literatures related this topic is analysed one by one. Hanna [2] discussed in his research article that the volume of water vapours released by a cooling tower is at the rate of about 4T/hr/MW. This helped us to get some theoretical information that, normally 840 MW capacity thermal power plant cooling tower releases around 933 kg/s of water vapour as waste, since 840 MW power plant cooling tower has been considered for this research work. Hlawiczka et al., [3] discussed in their paper the acidity of vapour plume from the cooling tower. Acidity of products caused from the reaction of flue gas mechanisms emitted from a thermal power plant with H_2O contained in a vapor plume from a wet cooling tower was analyzed by them in a close locality of a power plant. The result of that study was to prove a very high, potential of occurrence of incidents of extremely acid depositions in the immediate vicinity of a power plant.

Chahine et al., [4] studied the air mass flow and heat transfer are simulated inside and outside the cooling tower. They derived the equations for the mass, transport of momentum and liquid potential temperature were solved Code Saturne, a CFD software. Pilot study on fog harvesting from cooling tower plume in thermal power plant was given by Ghosh et al., [5]. The effects of mesh geometry, shade coefficient and mesh clogging on gathering rate were studied. It was found that the collection rate decreases with mesh inclination angle with the vertical and collection rate of water surpassed the data reported in atmospheric fog harvesting projects by more than 100%. A three-dimensional in-house program based on a non-staggered, non-orthogonal system was employed by Lee et al., [6]. The standard k–ε turbulence model was used as a model for the turbulent flow. To analyze flow and heat and mass transfers in the cooling tower, the continuity, momentum, enthalpy equations and moisture fraction have been considered for both water and air. The results showed that under the same conditions mean moisture fractions in the cases with air-guide were lower than the cases without air-guide.

Vallero [7] discerned about the air pollution disasters were caused by various pollutants, including aerosols, oxides of sulfur and nitrogen, hydrogen sulfide, and toxic compounds. Means of characterization of plumes were discussed in detail. Jing et al., [8] showed that the performance of a cross flow closed wet cooling tower is better than parallel or counter flow patterns. Pooriya et al., [9] showed the variation of efficiency with increase in packing density, inlet temperature of water, etc. The quantity of recirculation in a cooling tower (counter-flow) was evaluated by Ge et al. [10] with computational fluid dynamics software. Results showed, in cooling towers, the crosswind can enhance recirculation, under lower air flow rate conditions. The recirculation ratio reached up to 15%. Results also disclose that air recirculation in cooling towers could result in the increase of chilling plant energy in overall, consumption by over 1.5%.

Feng et al., [11] analyzed the plume rising height from cooling tower was calculated by using six factors and five levels of orthogonal test method. Sarkar et al., [12] analyzed experimentally the performance characteristics of the Hybrid Closed Circuit Cooling Tower (HCCCT). Performance characteristics were compared by them and found that for the finned tubes, cooling capacities were around 22%. The paper by Xu [13] gives the evaluation of the plume potential and its result on the sizing of the plume reduction system in a large commercial office building in Hong Kong for real-world application.

Senthil Kumar et al., [14] did experiments on vacuum desalination system to get fresh water yield by different vacuum creations with assistance of an ejector pump. Maximum vacuum created by ejector at maximum jet pump efficiency i.e. optimum condition with respect to time was determined. By applying the momentum, mass and energy balances across the numerous components of ejector assisted desalination system, the governing equations were obtained by the same authors [15] for the analysis and those equations were solved using simulation to get fresh water yield. Validation of the simulated performance is made with the experimental data available from literature.

Wang et al., [16] discussed in his paper about visibility of the plume at certain conditions. The visibility of plume from towers subjected to the weather conditions, specially, the relative humidity and temperature of the ambient air. A numerical study by Mokhtarzadeh-Dehghan et al. [17] of two interacting full-scale dry plumes issued into neutral boundary layer cross flow. The study simulated plumes from a drought cooling tower.

It is observed from the literature that several investigators have analyzed desalination systems and cooling towers separately theoretically and experimentally. They have proposed different desalination systems and cooling towers with various combination of fluid flow through them. Low grade energy like solar energy, geothermal energy are also utilized for desalination. But a cooling tower coupled with a desalination system to get fresh water is scanty.

2. Description of a cooling tower – desalination plant

2.1. Principle of working

The schematic of the cooling tower coupled with desalination plant is shown in Fig. 1. The system consists of wet cooling tower, drift eliminator, water pump, air blower, condenser of the desalination plant, filter, packing etc. The air enters the cooling tower through a blower (or several blowers) and passes through the packing onto which the water is sprayed. The hot/warm water from thermal power plant condenser flows through the packing in contact with the counter flow of air, and is collected at the bottom of the cooling tower. The water drips are collected by drift eliminator (chevron collector or wire mesh). The moist air which is warm leaves the top of the tower. Cooling of hot/warm water takes place in the cooling tower as molecules of water diffuse from the surface into the surrounding air. The stream of air in interaction with the water molecule is assumed to be completely saturated. So the moisture available (the evaporated water) in this saturated air diffuse into the stream fast of it whose vapor pressure is comparatively lower. These molecules of water (moisture of the saturated air) get replaced by the layer of molecules currently present at the surface of the water (liquid) and the energy needed for this is taken from the remainder of the liquid. By this way the water gets cooled continuously. It is very important to circulate unsaturated air through the tower for active cooling to take place. The moist air carries water vapour (plume) is fed into the condenser of desalination plant though a designed insulated duct. The water vapour from the moist air is condensed by the cold water circulated through the tubes which is taken from cooling tower bottom. The condensation is nothing but, the fresh water is pumped out to the thermal power plant for the needs. The non-condensable gases are removed from the condenser by purging out frequently. Purging operation means drawing a mixture of vapour and non-condensable gases from the condenser, separating the vapour, and discharging the non-condensables. Some portion of the fresh water from the desalination condenser system is directed to membrane to get potable water. A visit was made to Mettur Thermal Power Station (MTPS) of capacity 840 MW to obtain operational data for this research. The important parameters were obtained are shown in Table 1. The climatic conditions during July, August and September, 2016 are given in Table 2.

2.2. Design of a condenser for the desalination plant coupled with cooling tower

A finned water cooled condenser was designed to condense the water vapour from the cooling tower by giving its latent heat to the cold water flowing through it, to get fresh water. Water cooled condenser is preferred because

Table 1
Details of wet cooling towers in Mettur Thermal Power Station

Sl. No	Description	Details
1	Total no. of cooling towers per 840 MW power plant	30
2	Water vapour released per cooling tower	31 kg/s
3	Type of cooling tower	Forced/free (our proposed system is applicable for both)

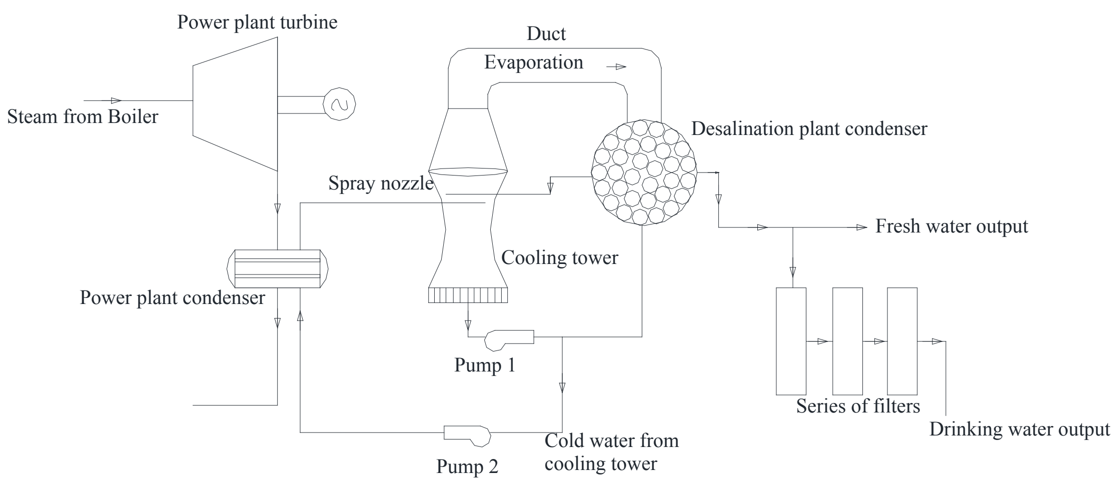

Fig. 1. Schematic diagram of the cooling tower coupled with desalination plant.

Table 2
Climatological table of air temperature taken in Mettur Thermal Power Station during July, August and September 2016

Month	Station level pressure	Air temperature										Mean wind speed
		Mean						Extremes		Humidity		
		Dry bulb	Wet bulb	Daily, Max	Daily, Min	Highest in the month	Lowest in the month	Highest	Lowest	RH	Vapour pressure	
	hPa	°C	°C	°C	°C	°C	°C	°C	°C	%	hPa	kmph
July	933.1	25.6	23.8	29.5	23	33.2	21.4	39.6	19.3	86	28.2	7.9
Aug	934.5	25.2	23.7	29.1	22.7	31.5	21.3	34.2	20	88	28.3	7.0
Sep	936.2	25.1	23.1	29	22.2	31.5	20.4	33.3	17.8	85	26.8	7.3

of adequate supply of inexpensive brackish water in MTPS and means of water disposal are available in the plant. Since the different materials have different abilities of heat transfer, therefore the size of the condenser of a given capacity were varied by selecting the right material. The SS316 L was selected for its anti-corrosion properties. Then annular fins (copper material) for the condenser tubes were selected for increasing the surface area and to augment the heat transfer rate. The condenser vertical tube array axis is oriented at a titled position of 120°, with respect to horizontal, so that the fresh water falling from the top tube will not interfere with the bottom ones. The two headers (vertical perforated plates) are in rectangular shapes are welded both the ends condenser to distribute the cold water from the cooling tower equally. This is done in such a manner that the leakage of water into the center condensing space is prevented. The inlet pipe carries cold water from the cooling tower is connected to the bottom of the header to ensure the supply of water through all the tubes for maximum water vapour condensation. The water vapour from the tower enters at the top and is forced to flow downwards over the tubes. A vent pipe is connected between the headers to take care of air lock. The fresh water is collected by an angle plate and is removed periodically. Two tapping are made at the bottom of the angle plate, one is directed to power plant fresh water needs and another one leads to the filter of the desalination plant for further purification for drinking purpose.

Condenser was designed by following the design procedure described here under.

a. By considering amount of water required and latent heat of vaporization, the heat rejected in the condenser was calculated.
b. From the heat rejection rate (the amount of heat rejected by vapour to the cold water), density and specific heat of the water, the mass of the cooling water required to be circulated through the condenser tube was estimated.
c. The water velocity through the tubes was found by considering mass of the water of the tube and diameter of the tube.
d. The condensing coefficient was calculated by considering density of water, latent heat of condensation of condensed water, and thermal conductivity and outer diameter of the tube using empirical correlation [18].

Table 3
Condenser details

Sl. No	Description	Details
1	Outer diameter of the tube	0.003175 m
2	Inner diameter of the tube	0.002875 m
3	Number of tubes	4,50,000 nos.
4	Length of each tube	10 m
5	Total length of condenser tube	45,00,000 m
6	Total length of condenser tube/cooling tower	1,50,000 m
7	No of tubes/cooling tower	15000 nos.
Annular copper fin details		
1	Thickness of the fin	0.0001 m
2	Height of the fin	0.001 m
3	Diameter of fin	0.052 m
4	Fins per inch	7

e. The waterside coefficient was estimated [18] from Reynolds number, Prandtl number, diameter of the tube and thermal conductivity of the tube material.
f. The circular fins were selected for this condition to improve the rate of heat transfer. The fin efficiency was estimated by following procedure described in the reference [19].
g. The overall heat transfer coefficient was computed by considering resistance of metal.
h. By knowing the inlet and outlet temperatures of the water and condensing temperature Logarithmic mean temperature difference (LMTD) was calculated.
i. Using LMTD and total effective heat transfer area, the length of the tube is calculated.

The design details of condenser are given in Table 3.

2.3. Design of the duct system

The water vapour from the cooling tower top is properly fed to the condenser of desalination plant by a designed duct in order to get fresh water. The galvanized sheet metal is selected as the duct material because the zinc coating of this metal avoids the cost of painting and rusting. 16 gauge (1.6 mm) thick galvanized iron was selected for this purpose. The fabric joints are used where the duct fasten to cooling tower at one end and condenser at other end. The circular duct is considered due to more water vapour carrying capacity. The dust size was determined by velocity reduction method.

2.4. Selection of pumps

The air along with water vapour flows from the cooling tower top into the condenser, reduces the rate of heat transmission. Moreover, the air leaks into condenser through various joints lead to less in condensation rate. Reciprocating Edward's dry air pump is selected to remove incondensable air from the condenser based on the calculation of mass of air per kg of uncondensed moist vapour. Horizontal axis double stage centrifugal pump is selected to remove fresh water.

4. Theoretical analysis

The mass and heat transfer characteristics of wet cooling tower can be determined by the conservation equations of mass and energy. The mathematical model is based on that of Marmouch et al. [20] with the following assumptions.

- The coefficients of mass and heat transfer are constant along the column.
- Specific heat of dry air and water are constant along the column.
- Lewis number is constant along the column.
- Heat and mass transfer between surroundings and the system is negligible.
- Constant temperature distribution at any cross section of the water stream.

These equations were used for simulation. Simulated performance was validated with the experimental data available.

Mass balance equations of water liquid, dry air, water vapour and are written without diffusion term, which is negligible [21].

The overall mass of dry air in the two phase mixture can be

$$m_a = \int_V [\alpha\rho_a + (1-\alpha)\rho_l w_{a,l}]dV = \int_V \Phi_a dV \quad (1)$$

where $w_{a,l}$ is mass fraction of dry air in the water and

$$\Phi_a = \alpha\rho_g\, w_{a,g} + (1-\alpha)\rho_l w_{a,l}$$

Dry air mass balance can be written as

$$\frac{\partial \Phi_a}{\partial \tau} + \frac{\partial \Phi_a v_i}{\partial x_i} = 0 \quad (2)$$

Overall mass balance of supersaturated moist air can by written as

$$\frac{\partial \rho}{\partial \tau} + \frac{\partial(\rho v_i)}{\partial x_i} = 0 \quad (3)$$

The sources of water liquid or water vapour are excluded in the above equation

Overall momentum balance can be written as

$$\frac{\partial(\rho v_i)}{\partial \tau} + \frac{\partial(\rho v_i v_k - \sigma_{ik})}{\partial x_k} = \rho g \delta_{i\delta} - \frac{1}{2}\zeta\rho\,|v|^2\delta_{i\delta} \quad (4)$$

where σ_{ik} is stress tensor

Overall energy equation is

$$\frac{\partial(\rho e)}{\partial \tau} + \frac{\partial(\rho v_k e - \sigma_{kj} v_j + q_k)}{\partial x_k} = g\rho v_\delta \quad (5)$$

In the condenser, the moist air, on contact with cold tube walls, there is film condensation included with latent heat restitution to the water circulating inside the tubes.

The following assumptions are made for the elaboration of the mathematical model.

- Heat transfer by radiation is not included.
- The gas-water interface is at thermodynamic equilibrium, and there is no gas dissolution in water.
- The moist air is a perfect gas.
- The condensation occurs on the water–water vapour interface.
- Pressure gradient and the surface tension effects are excluded.
- The temperature of the tube walls is uniform.
- The thickness of the film is small.
- The film flow is steady.
- There is wetting, the entire surface of the tubes outer is covered with liquid film.

The following equations give the mass and heat transfer in the condenser.

$$\partial M_c = -M_a \partial\omega \quad (6)$$

$$M_a \frac{\partial\omega}{\partial x} = K_{m,cond} P_{cond}(\omega_s - \omega) \quad (7)$$

$$C_{pw} M_a \frac{\partial T_W}{\partial x} = K_{w,Cond} P_{cond}(T_w - T_f) \quad (8)$$

$$\frac{dT_a}{dx} = \frac{K_{a,cond} P_{cond}(T_f - T_a)}{M_a(C_{pa} + \omega C_{pv}) + M_C C_{pw}} \quad (9)$$

These equations have been used for simulation. The above equations were solved using MATLAB program, by employing the Rung-Kutta method to solve a set of non-linear equations. Validation of the simulated performance is made with the experimental data available from literature. The theoretical analysis has done for the specific values. Then with the conditions of a specific trial from the theoretical analysis, the mass flow rate of water in the cooling tower was scaled up to match the mass flow rate of water in an cooling tower (power plant cooling tower) of capacity 840 MW. This helps in obtaining the mass flow rate of the air and mass flow rate of evaporated water through the cooling tower. A cooling tower (power plant's capacity of 330 MW) can have a water flow rate up to 24,000 m^3/h which turns out to be 6666.667 kg/s of evaporation. Taking the values of dry bulb temperature at inlet and outlet of air, relative humidity of air at inlet and outlet, temperature of water at inlet and outlet from Table 2, the values of evaporation were obtained.

5. Results and discussion

Fig. 2 gives the effect of mass of water through the tower on the fresh water yield where cooling was kept constant and air flow rates were varied. The theoretical analysis has been validated with experiments. It shows a good agreement between our model and the experimental results. When the mass flow rate of water increases, the yield increases. This is due to the high in heat transfer rate from air, flown in counter flow direction to water, leads to more evaporation. Hence the fresh water yield increases. Figs. 3 and 4 gives the effect for different cooling loads. From the figures, it is found when the cooling load increases, the fresh water yield increases. This is due to large amount of heat is transferred from warm water to cold air. A model cooling tower capacity of 1.6 kW was considered for this analysis. The range (difference within the limits) of the cooling tower was varied from 0.1 kW to 1.6 kW at four intervals and the results obtained from the analysis were used for 330 MW and 840 MW power plant cooling towers.

Fig. 5 discerns the effect of mass of air through the tower on the fresh water yield where cooling load was kept constant and water flow rates were varied. When the mass of air increases, the fresh water yield increases. This is due to heat and moisture carrying capacity increases in air as huge amount of air passes through the tower, leads to high evaporation rate to increase in fresh water yield. Figs. 6 and 7 give the data for the different cooling loads. From the figures, the fresh water yield decreases, when the cooling load decreases. The maximum yield 0.2 kg/s was found in the

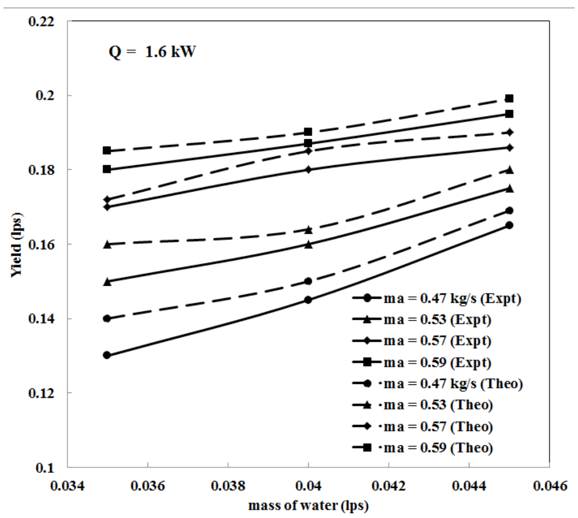

Fig. 2. Effect of mass of water flowrate through the cooling tower on fresh water yield for cooling load 1.6 kW, validation of our theoretical results with experimental available in literature.

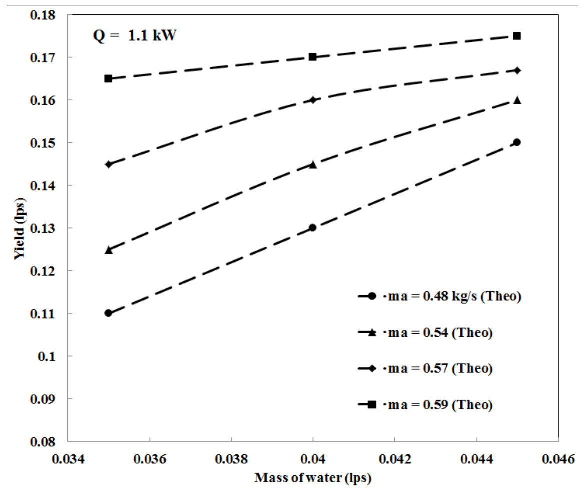

Fig. 3. Effect of mass of water flowrate through the cooling tower on fresh water yield for cooling load 1.1 kW.

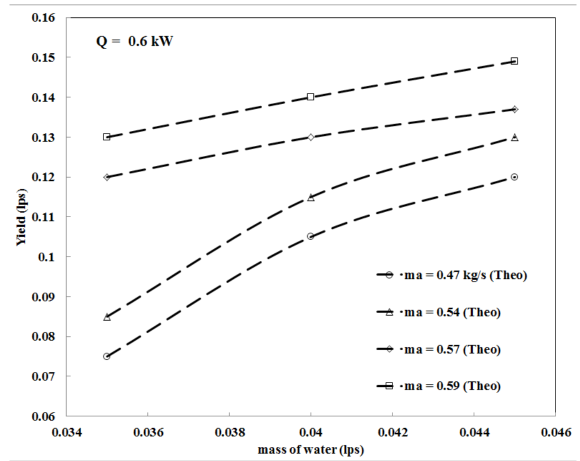

Fig. 4. Effect of mass of water flowrate through the cooling tower on fresh water yield for cooling load 0.6 kW.

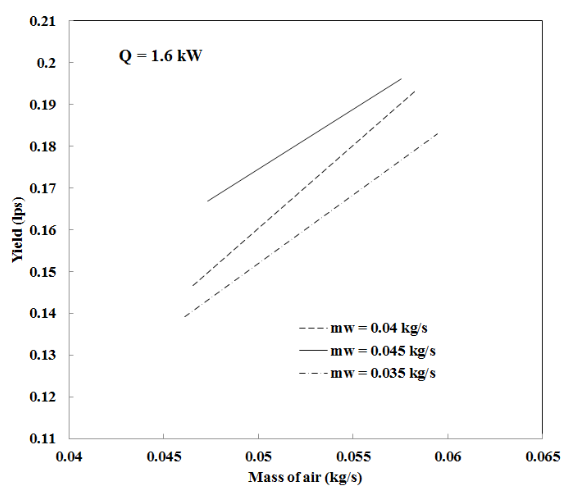

Fig. 5. Effect of mass of air flowrate through the cooling tower on fresh water yield for cooling load 1.6 kW.

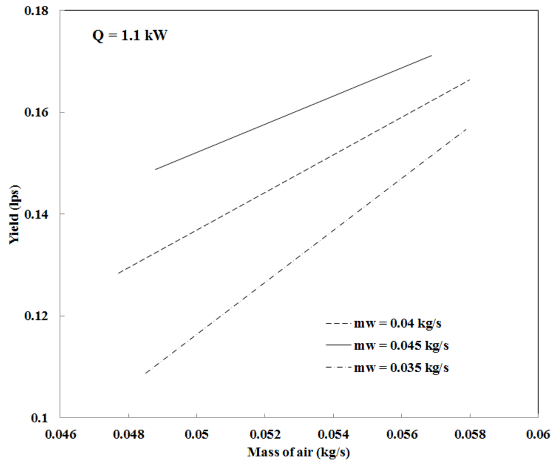

Fig. 6. Effect of mass of air flowrate through the cooling tower on fresh water yield for cooling load 1.1 kW.

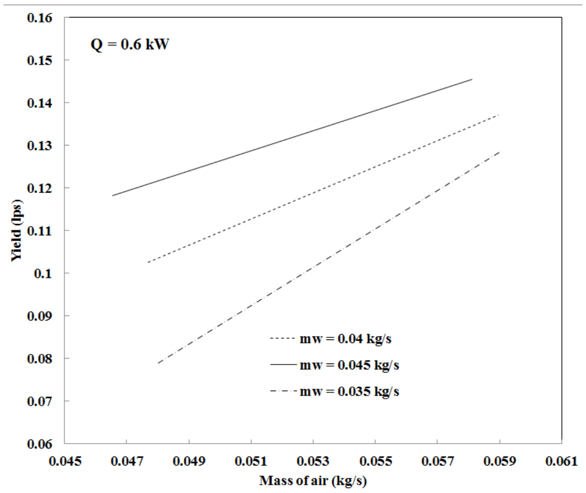

Fig. 7. Effect of mass of air flowrate through the cooling tower on fresh water yield for cooling load 0.6 kW.

theoretical analysis, at cooling load of 1.6 kW, mass of water of 0.04 kg/s, mass of air of 0.058 kg/s.

Fig. 8 gives the effect of cooling range on effectiveness (%) of cooling tower at different air flow rates. Experiments were conducted on model cooling tower to get these results. When cooling range increases the effectiveness increases because range is a function of temperature and the effectiveness becomes constant at high temperatures due to the evaporation loss and enthalpy difference between the hot water and air. And as the air flow rate increases the effectiveness also increases. For the range to increase for a fixed value of water inlet temperature the water outlet temperature must decrease. It means that the performance of the cooling tower is high when outlet temperature is decreased. The higher performance would account to the increased effectiveness of the cooling tower. As the air flow rate increases the water particles have more air to exchange the heat they possess and hence the water would cool down more effectively. This contributes to the increase in effectiveness as the air flow rate increases. The optimum condition of the cooling tower (effectiveness 55%,

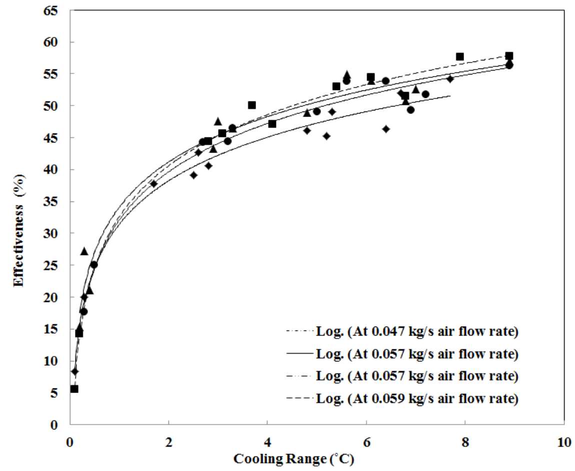

Fig. 8. Effect of cooling range on effectiveness to identify optimum operating condition of the tower.

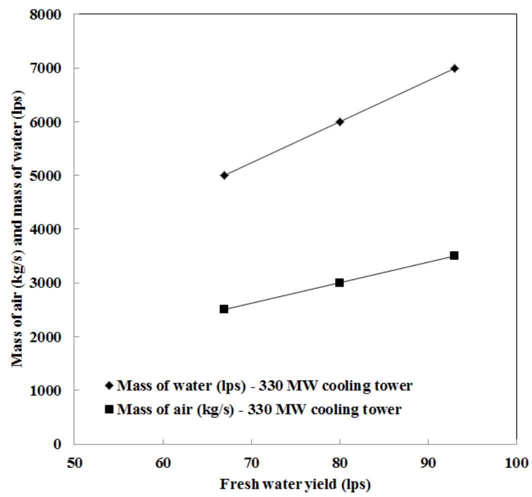

Fig. 9. Effect of fresh water yield on mass of air and water through cooling tower (330 MW capacity).

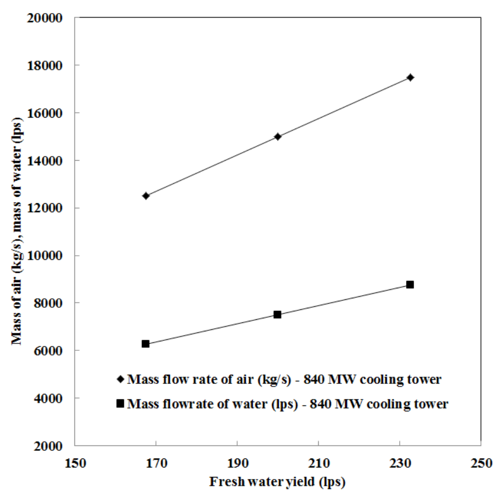

Fig. 10. Effect of fresh water yield on mass of air and water through cooling tower (840 MW capacity).

mass flow of air 0.059 kg/s) where there is maximum evaporation rate leads to maximum fresh water yield.

Figs. 9 and 10 show the effect of mass flow rate of water, mass of air on fresh water yield for 330 MW, 840 MW power plant capacity cooling towers. From the results of the theoretical calculations of a model cooling tower, the mass flow rate of water in the tower was scaled up to match the mass flow rate of water in an cooling tower of power plant capacity 330 MW and 840 MW. From the figures, it is inferred that the mass flow rate of water and air increase, the fresh water yield increases due to high in evaporation rate.

6. Conclusions

This paper presents a theoretical study of desalination plant coupled with cooling tower. A condenser of a desalination plant was designed which is coupled to a thermal power plant cooling tower to utilize the water vapour from the top of the tower to obtain fresh water. The theoretical analysis was made by considering all components of the system, the governing equations were formed solved by simulation to get fresh water. This study shows the effect of cooing range of model plant on the fresh water yield. With the conditions of a specific trial from the analysis, the mass flow rate of water in the tower was scaled up to match the mass flow rate of water in an industrial cooling tower of capacities 330 MW and 840 MW. This aids in finding the mass flow rate of the air and mass of evaporated water through the cooling tower of thermal power plant. Finally it is suggested that the cooling tower is operated at optimum condition, i.e., maximum effectiveness to get maximum fresh water yield.

Symbols

A — Area, m^2
C_p — Specific heat, kJ/kgK
D — Diameter, m
K — Mass transfer coefficient, W/m^2K
M — Mass flowrate, kg/s
P — Wetted perimeter, m
R — Ratio of water to air mass flow rates, %
RH — Relative humidity
T — Temperature, K
Q — Heat transfer rate, W
v — Velocity, m/s
q_k — Diffusion co-efficient
w — Mass fraction of dry air

Greek

ρ — Void fraction of gas phase, density
α — Volumetric void fraction
τ — Time
v — Velocity vector
η — Efficiency, %
ω — Absolute humidity (g/kg)
μ — Kinematic viscosity
Δt — Temperature difference in the condenser,°C

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