Design and Optimization of an Evaporative Condenser: A Detailed Review

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Abbreviations

h_w	Film water heat transfer coefficient, (W/m^{2}K)
h_d	Air water mass transfer coefficient, (W/m^{2}K)
G_w	Water mass velocity, (Kg/m^{2}s)
G_a	Air mass velocity, (Kg/m^{2}s)
T_{wm}	Mean deluge water temperature, (°C)
T_{wm}	Water Temperature, (°C)
α_m	Mass transfer coefficient for water vapor, (W/m^{2}K)
α_{spray}	Heat transfer coefficient between tube surface and water film, (W/m^{2}K)
m	Mass flow rate, (Kg/s)
$m_{\max}$	Maximum mass flow rates, (Kg/s)
ε_e	Efficiency of evaporative condenser
L	Flow rate of liquid, (Kg/s)
G	Flow rate of air, (Kg/s)
T_s	Temperature of heating steam, (°C)
T_w	Wet-bulb temperature, (°C)
ε_a	Efficiency of air condenser.
h_o	Outer heat transfer coefficient, (W/m^2 °C)
E	Percentage of evaporated water
b	Empirical constant.
$\dot{m}_p$	Mass flow rate of fluid used, (kg/s)
Δt_p	Cooling temperature range, (°C)
$\dot{m}_{w,i}$	Mass flow rate of water at inlet, (kg/s

1 Introduction

Energy saving, water usage and effluent management are crucial parameters under consideration for a cooling system. Thus, the potential of implementing water uniformity source with a fine dispersion of water and minimum utilization should be put into reality. One of the industrial units that follow all these methods is an evaporative condenser.

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Technically, evaporative condenser is a device that extracts the heat from working refrigerant and transfers it to the surrounding by application of cooling tubes bounded system with water supply sprinkles. Condenser works with air circulation over the surface, which is regulated by an axial or centrifugal arrangement of the exhaust fan.

These condensers are used in water coolers, air conditioning plants and industries. For its working, some general values of parameters are taken as, air velocity from 1.5 to 4 m/s for economic design consideration. Usually, evaporative condensers using a forced type of flow model is used, as it is very important for cooling purpose with the required efficiency. But, the efficiency of condenser unit is still under consideration for improvement.

In this review, the performance improving parameters are first classified as passive and active types for the analysis. Passive techniques generally refer to the characteristic design, tube modification, extended surface area, etc. whereas; Active techniques refer to the change in any external agent that is used like the attachments and adding's. The experimental investigations require a special emphasis and hence they are separately studied along with the condenser losses.

2 Passive Technique

The techniques where main focus is given on the design problems for the evaporative condenser based on of numerical simulation and by the application of software simulations without any external modifications is referred to as passive techniques.

2.1 Numerical Simulation

Working on mathematical simulations [1–3], used different design models with different modification in sizes for increasing the performance and they have put some parameters like heat and mass transfer in calculated technique using empirical formulae. Rana and Haran [4] mainly focused on the heat transfer coefficient for water side without air flow, mass transfer coefficient, evaporative Effectiveness. It was found that heat transfer coefficient for water side deprived of air flow increases along with increase in the coolant and product flow rates, also the calculation was carried out with 20% accuracy of range, $13 < Re_w < 1.7 \times 10^2$. In addition to it, the mass transfer coefficient also increases with increase in flow rates of fluids. Eventually, the effect of flow rate decreases evaporative effectiveness for the flow of cooling water and increases the effectiveness for flow of air. Hsu et al. [5] investigated on the enhancement of system design work for three different wet surface heat exchanger structures. It was found that the air can be cooled below the wet-bulb temperature range by evaporation. Moreover, satisfying the range it can also cooled very close to dew-point temperature. His main focus was on water wetting techniques on heat exchanger which is also another type of evaporative condenser. Zalewski et al. [6] proposed a mathematical simulated model for forced air flow type of evaporative condenser and have shown that it agrees with the empirical data. The computer program, based on this model, for simulation of bare tube condenser may be used to improve the design. Zalewski et al. [7] optimized the operating and geometrical parameters for fluid type evaporative coolers. Besides, mathematical model for the transfer of mass and heat in evaporative coolers, model of evaporative heat exchanger for production costs along with evaluations of air pressure drop have also examined. More attention was on design of heat exchanger for maximum heat capacity with low cost. Searching for economical results, Manske et al. [8] studied on the optimization of industrial based refrigeration system using evaporative condenser for cold storage distribution. The system consists of single screw, an evaporative condenser, reciprocating compressor, evaporators, developing a mathematical model. It was observed that the pressure head, condenser fan and condenser sizing were the key elements that affect the total power expenditure of the refrigeration system. Hasan and Siren [9] performed experiments on two different evaporative coolers to analyze the effect of circular and oval tubes under same operating conditions. Moreover, it was shown that the combined thermal-hydraulic characteristic for the oval tube was found better than the circular tube. Min and Webb [10] worked for the effect of tube geometry on performance of heat exchangers. It was found that the pressure drop and heat transfer coefficient decreases on air side and increases on water side as the aspect ratio of oval tube increases. Qureshi and Zubair [11] have proposed the mathematical model to investigate the scenario for the effective design and rating analysis of an evaporative condensers and coolers, which was validated using numerical and experimental data reported in literature. Risk based thermal performance characteristics were evaluated using the fouling model for these heat exchangers. It was shown that there were about 50% decrease in the effectiveness for both types of heat exchanger and also 5% increment of the fluid outlet temperature. In addition, the effectiveness rose with mass flow ratio for both heat exchangers. While investigating the thermal-flow characteristics Heyns and Kröger [12] evaluated the methodology for the evaporative cooler analysis and derived the governing equations. Performance trials were steered on evaporative cooler with 15 tube rows in 76.2 mm triangular pitch pattern made of galvanized steel having outer diameter of 38.1 mm. The following correlations were developed from the experimental data that is revived,

'Air mass flow rate and deluge water temperature' is

$$h_w = 470 G_a^{0.1} G_w^{0.35} \tag{1}$$

Here, $0.7 < G_a < 3.6 \frac{\text{Kg}}{\text{m}^2\text{s}}$, $1.8 < G_w < 4.7 \text{Kg}/(\text{m}^2\text{s})$ and $35 < T_{wm} < 53°\text{C}$.

'Air mass velocity and deluge water mass velocity' is

$$h_d = 0.038 G_a^{0.73} G_w^{0.2} \tag{2}$$

Here, $0.7 < G_a < 3.6\ \text{Kg}/(\text{m}^2\text{s})$ and $1.8 < G_w < 4.7\ \text{Kg}/(\text{m}^2\text{s})$.

'Air side pressure drop' is

$$\Delta p = 10.2 G_a^{1.8} G_w^{0.22} \tag{3}$$

Here, $0.7 < G_a < 3.6\ \text{Kg}/(\text{m}^2\text{s})$ and $1.8 < G_w < 4.7\ \text{Kg}/(\text{m}^2\text{s})$.

A similar study, Jahangeer et al. [13] have demonstrated extensively on the numerical study of coefficient of heat transfer for an evaporative cooling condenser working with aspects near tropical climatic region. Very high combined heat transfer coefficients were observed for various film thicknesses over the condenser tubes in the evaporative cooled condenser. It was noticed that the performance increased by decreasing temperature lift with the help of water droplets inclusion. By modifying the design slightly, Sun et al. [14] concluded that, by using these all method air pressure drop in elliptical tube bundle decreases by an average of 20–30%. In addition, heat transfer rates found to be increased by an average of 8.3–30.9%. Moreover, by giving the attention on capacity and COP they found to be increased by 21.3–27.5% and an average of 3–7% respectively. Harbyn et al. [15] reviewed the domestic evaporative condensers and presented innovative designs intending to reduce the power consumption and improve the COP. It is reported that the use of evaporative condenser instead of air cooled one may increase the COP by 113.4% and decrease the power consumption by 58%. Xu et al. [16] made some innovative developments in structure of the evaporative condenser to improve the efficiency and other benefits such as reduced wind resistance, expedient cleaning operation and greater energy-efficient fan. The noise level was reduced by changing the spray direction, inorganic fillers were arranged to reduce the cooling water temperature with enhancement of heat transfer, elliptical finned tubes were used in bottom evaporative coils, inlet air temperature was reduced all of which resulted in more efficient and compact device. Anicalliea et al. [17] have proposed the comprehensive experimental thermal investigation with effect of key parameter on condensation heat transfer in ammonia evaporative condensers. It was revealed for the evaporative condensers using ammonia, that the correlations presently accessible in literature describe the processes of heat as well as mass transfer appropriately. Liu et al. [18] have conducted the tentative examination of high efficiency dew-point evaporative operational cooler by modified and effectively optimizing the water and air flow arrangements. It was found that corrugated plates enhance the efficiency of cooling by 10%. The counter flow arrangement also improves the efficiency by more than 30%. The cooling efficiency is enhanced within a practical range by the increase in lengths of channel and air entrance and also by reducing the width and gap of channel. Experiments were performed by Zhu et al. [19] on evaporative condenser with an elliptical tube bundle to study the effect of various parameters, such as inlet wet-bulb temperature, relative humidity, spray density and frontal air velocity on heat and mass transfer performance. Using the experimental data the accurate empirical correlations were obtained for predicting the mean condensation coefficient of heat transfer, wall-film coefficient of convective heat transfer and the film-air coefficient of convective mass transfer.

2.2 Software Simulation

Abbassi and Bahar [20] predicted outcomes of their thermal design on the basis of software. They concluded that PID controller can appropriately replace by the neural network controller to model the thermal behavior of an evaporative condenser with advantage of reduced time for generation of model and minimizing the process error. In search of best satisfactory operating conditions to guarantee the complete wet ability of the heat transfer geometry with minimum pumping cost, Fiorentino and Starace [21] have conducted the pervasive numerical and investigational performance examination of evaporative type condensers. Novel relations were presented for engineers to quantify thermal performance depending on actual working conditions. Fiorentino et al. [22] conducted experiments on a test rig to analyze the combined effect of DBT and RH on performance of evaporative condenser. It was found that the heat transfer rate reduces by 30% with 6% increase in relative humidity at highest DBT. The air process was shown on psychometric chart revealing that the ratio of latent heat to sensible heat decreases with increase in RH.

3 Active Techniques

The techniques where in main focus is given on the attachments, additions, modifications externally rather than focusing on modifying the model itself.

Bykov et al. [23], have defined different heat and mass transfer spaces in evaporative condensers. They have presented a procedure to optimize such spaces, the effect of fins and spray-filled spaces which will result in optimizing the thermal efficiency characteristics and obtaining a better design of evaporative condensers. Goswami et al. [24], retrofitted media pads to the condenser of a 2.5 ton air conditioner as an additive technique to improve the performance which resulted in 20% savings with a remuneration period of two years. Hwang et al. [25] introduced by modifying the normal pump into split heat pump, by putting the tubes immersed down in the water, where the disks fitted near tubes rotate with the help of pump and simultaneously the air is also blown over them. Rejection of heat from tubes takes place in water whereas, heat from the film is extracted in the surrounding. This resulted in increase in capacity of condenser by 1.5–8.3% and also increases COP by 11.1–21.6%. The setup introduced by him consists of copper serpentine laid wrapped by cloth placed in rectangular shaped duct. This cloth soaks the water and reduces the heat inside the tubes and helps in effective transfer of heat. Horacek et al. [26] investigated on the spacing of nozzles, so that every area must come under its dispersing shower. When spray height is nearly 11–14 mm then spray of water will satisfy this situation. Experiment with 2-spray nozzles was performed to improve heat transfer performance. Moreover, attention was provided toward distribution of heat transfer beneath two spray nozzles with revelation of the liquid to solid contact area. For a nozzle, higher transfer of heat was achieved when nozzles were situated directly over the surface area. Also, the heat flux becomes uniform as the distance from nozzle to surface goes on increasing. Hence, it concludes that the heat flux is directly connected to contact length and not the wet area. Royne [27] worked on key factor affecting the performance of cooling device i.e., nozzle configuration. Instead of considering the transfer of heat and the drop in pressure, he investigated various types of nozzle consisting of short (straight), long (straight), sharp edging, contoured, countersunk nozzles. After this experiment it was concluded that:

1. Countersunk nozzles are having average heat transfer at higher rates, preferring them over others.
2. Longer nozzles are having lower pressure drop as compared to smaller nozzles. This makes longer nozzles beneficial than the smaller, on the basis of pumping power.
3. Sharp edging and contoured shape nozzles yield similar results for pump power requirement when compared with straight nozzles but still sharp-edged nozzle is used as it decree lower flow rate.

Nozzles spacing and inclination also matters, this is because all the tubes area must be covered with water spray to shun the expenditure over buying unrequited number of nozzles. Silk et al. [28] investigated on spray cooling methods on various types of enhanced surfaces, nozzle angle and the type of nozzles. Basically, this experiment was performed on cubic pin fin, pyramids and straight fins with working fluid as PF-5060. Moreover, comparison between flat surface and enhanced surfaces was done with inclination angle in the range of 0–45° at highest CHF. It was concluded that straight fins are the best option for increasing performance, multiphase efficiencies, heat flux and also for cost effectiveness. Camargo et al. [29] proposed three methods that can be used as reference for efficient use of evaporative cooling systems. Idrissi et al. [30] mentioned that the implementation of water spraying over condenser will increase the efficiency. The experimental validation was none for the semi numerical model but it was observed that the COP can be increased averagely up to 55%. Vrachopoulos et al. [31] proposed a novel evaporative condenser where his work anticipated on very unique additions like electrical circuit pump and drop clouding computer engaged system for water spraying. It was observed that by using such novel condenser the COP can be enhanced up to 21.1% which is result of reduction in the operating temperature difference of compressor. Tissot et al. [32] investigated the performance improvement of a refrigerator by employing water spray in air near the condenser inlet. The numerical analysis found a rise of 22.4% in COP for the machine with this spraying technique, which was validated experimentally. A detailed study was given by Ndukaife et al. [33] on performance and proposed the mathematical research relevant to the enhancement in performance and diminution in energy consumption of air conditioning system by using evaporative cooling condenser. Contact of the hot air with water on porous medium can yield a result in immediate heat as well as mass transfer. Reduction in the air temperature results in rise in relative humidity interpreted for being a function of thickness of pad. It was accomplished,

1. The lower mass flow rate was obtained by 15 cm pad which ultimately reduces the work of compression up to 20%. Also this thickness of pad increases COP by 44% as compared to other thicknesses.
2. The fall in air temperature of 1 °C causes the fall in condensing temperature by 0.6 °C. In addition to this, it was predicted that about 4% raised in COP occurred due to the drop in condensing temperature by 1 °C.

Wang et al. [34] have reviewed the research status of evaporative condensers and have suggested the use of nano-technology and nano-materials to enhance the performance. Chien et al. [35], carried out the investigational study using various flow rates, spacing of nozzles and its geometric designs to investigate the uniformity of the water spray and collection ratio of sprinkler in an evaporative cooled condenser. It was observed that the uniformity depends upon the flow rate, nozzle opening and properly adjusted flow rate that can prevent the impact and loss of droplet. A smaller spacing of nearly 17 cm and larger opening size of nozzles are preferable to accomplish the task.

4 Experimental Investigations in Evaporative Condenser as a Comparison

This section describes various experiments that result in the formation of new model.

Facao and Oliveira [36] conducted thermal investigation for a new closed wet cooling tower to use with chilled ceiling through different thermal models. Experimental correlations were presented in order to predict augmentation in thermal performance. Better results were obtained using these new correlations by the models, for small towers. The new correlations were,

$$\alpha_m = 0.1703\left(\frac{m}{m_{\max}}\right)^{0.8099}_{\text{air}} \tag{4}$$

$$\alpha_{\text{spray}} = 700.3\left(\frac{m}{m_{\max}}\right)^{0.6584}_{\text{spray}} \tag{5}$$

Ettouney et al. [37] conducted experiments with two different finned-tube heat exchangers which can be arranged in parallel, series and stand alone with water or air cooling. Steam temperature and the water to air mass flow rate ratio (L/G) were under consideration for the analysis. The efficiency was highest for arrangement in series, followed by parallel and then single condenser. It was also shown that the system efficiency increases when L/G ratio is low and steam temperatures are high. Simple correlations were presented for the evaluation of external heat transfer coefficient and efficiency in terms of L/G ratio and temperature of steam.

The efficiency correlation for the evaporative condenser is:

$$\begin{aligned}\varepsilon_e = 98.57 - 1.76\left(\frac{L}{G}\right) - 2.09 \times 10^{-2}(T_s) \\ + 0.27A + 4.83 \times 10^{-2}(T_w)\end{aligned} \tag{6}$$

Similarly, the efficiency correlation for the air condenser is

$$\varepsilon_a = 223.03 + 1.81 \times 10^{-2}(T_s) - 0.31A - 5.29(T_w) \tag{7}$$

The correlation for wet heat transfer coefficient is

$$h_o = 0.16(L/G)^{0.23}(T_s)^{2.13} \tag{8}$$

Hosoz and Kilicarslan [38] conducted a comparative analysis for three types of condensers; viz air cooled, water cooled and evaporative type condenser and revealed that water cooled condensers were superior whereas the air cooled exhibits lower performance. However, in various cases, outcomes of the evaporative type condenser were found equivalent with water cooled type condenser system. To improve chiller efficiency, Yu and Chan [39], installed direct evaporative coolers in front of air cooled condensers so that the outdoor air gets cooled prior to entering the condensers. It was observed that the refrigeration was increased for all operating conditions. Wolfgang, Leidenfrost and Korenic [40] have emphasized that air side heat transfer augmentation can be achieved best with evaporative cooling as heat can be rejected to ambient even when the ambient temperature is greater than the condenser temperature. Complete wetting of the heat transfer surface is sufficient to get maximum performance of the condenser thus amount of water sprayed should be just sufficient rather than deluging the surface which not only saves the power but also reduces the water loss. The air flow rates should be appropriately adjusted to have air water-film interaction just sufficient to remove water film partially by drag force which results in low blower power. Nasr and Salah Hassan [41] suggested an innovative condenser for a small refrigerating system, which was cooled with the help of wick wrapped over the condenser tubes, sucking water from the basin by capillary action and providing the evaporative cooling. The evaporative cooling condenser has 13 times more capacity to reject heat as compared to air cooled type condenser. Eghtedari and Hajidavalloo [42] performed experiments by retrofitting the air cooled condenser with evaporative cooling. They found 20% decrease in the power consumption and 50% increase in the overall performance with this adaption. It was also observed that the increasing ambient temperature has hardly any effect on COP while using evaporative cooling condensers. Patel and Shah [43] optimized the evaporative condenser in two different ways, first by reducing condenser pressure and second, using VFD for fan and pump. It was also observed that for same rate of heat rejection total specific power consumption is less for optimal reduction in condenser pressure comparatively with using VFD for fan and pump. Shen et al. [44] studied the peak power reduction and saving of energy of evaporative condenser cooling. It was found that the energy saving was much higher for HVAC systems, with R-410A as a refrigerant than R-22 refrigerant.

5 Evaporative Condenser Losses and Water Treatment

The very factor that affects the performance of evaporative condenser at greater extent but occurs stagnantly as evaporation losses are generally neglected in thermal design of cooling tower. Nahavandi et al. [45] developed a new technique, including the evaporation losses in the energy balance, leading to conservative design of a cooling tower where accurate results are needed. The Merkel's method, ignoring these losses, introduces up to 12% of error on design conditions. Khan and Zubair [46] developed a fouling model to predict the decrease in the tower performance characteristics and validated it with experimental data. It was found that fouling decreases the NTU, which in turn decreases the effectiveness of the cooling tower and increases the exit water temperature. Fouling allowance factor should be considered in the design procedure of cooling towers for adequately compensating the fouling loss. Qureshi and Zubair [47] developed an empirical relation, considering the thumb rule by Baltimore Air Coil which was a patent based on increasing the uniformity with increased efficiency related to water flow. Calculation of evaporation losses which causes increases in the concentration of dissolved solids and other impurities. The values predicted were in good concurrence with the numerical standards obtained from the calibrated model.

$$E = \left(\frac{b\dot{m}_p \Delta t_p}{\dot{m}_{w,i}}\right).100 \tag{9}$$

Mehrabi and Yuill [48] studied on research about the effects of fouling along air side on the performance of air cooled condensers. They examined nine fouled condensers from field, seven plate fin coils along with that two spine fin coils. On the basis of this, they concluded that the performance of the system was negligible affected by fouling on air side even though it substantially decreases the coil's air side pressure drop. Also, in some cases fouling improved the performance. For cleaning the coil, water was found to be used in most of the cases as compared to detergents that causes reduction in performance. Browning et al. [49] discussed the problems in evaporative condensers related to the water and its treatment. They mentioned that water deposits on condenser tubes not only reduce the heat transfer effectiveness and increase the operating cost but also lead to potential failure. Hence the treatment of water should be an essential operational program.

6 Conclusion

The intent of writing this review paper was to recognize the adaptation workings performed on evaporative condenser as,

- Water cooled type condenser is more effective till now, but the water scarcity and ground space management problem makes evaporative condenser as a better option. However, in some cases, outcomes of the evaporative type condenser are found equivalent with water cooled type condenser system which again justifies their use. Evaporative type condenser has compact structure, small footprint, low investment, easy maintenance, stable performance, clear water saving, low operating pressure which makes it more preferable over others.
- If more than one condenser is used then the efficiency is highest for arrangement in series, followed by parallel and then single condenser.
- Maximum amount of inlet vapor can be processed in parallel configuration whereas, largest degree of sub-cooling is offered by arrangement in series.
- The use of evaporative condenser instead of air cooled one may increase the COP by 113.4% and decrease the power consumption by 58%. At high inlet vapor temperatures and lower L/G ratios the evaporative condenser efficiency increases.
- Elliptical tubes should be preferred over circular tubes as it lowers the pressure drop on air side and increases the heat transfer because of increased surface area.
- Countersunk nozzles and sharp edging nozzles should be used for higher and lower flow rates respectively.
- Allowance data should be added in thermal calculations, as evaporation loss is significantly important for condenser. Also, fouling should be considered.
- Adding techniques, such as media pads and water pads, should be adopted for optimum cooling of the refrigerant and to reduce the power consumption.
- PID controller can be appropriately replaced by the neural network controller to model the thermal behavior of an evaporative condenser with advantage of reduced time for generation of model and minimizing the process error.
- The noise level can be reduced by changing the spray direction, inorganic fillers can be arranged to reduce the cooling water temperature which leads for enhancement of

heat transfer, elliptical finned tubes can be used in bottom evaporative coils all these can result in more efficient and compact device. Additionally, corrugated plates will enhance the performance.

- Novel relations are presented with strong predictive potential for engineers to quantify various parameters against the specific conditions in evaporative condensers which can be used for improving the design and performance.
- The heat exchanger performance of the evaporative condenser is affected by both the inlet relative humidity and the inlet wet-bulb temperature of air. But the effect of change in the inlet WBT is quite larger than that of relative humidity. For each 1 °C increase in the wet-bulb temperature, the total heat exchange decreases by an average of 1.445% whereas, the same decreases by about 12.8% as the relative humidity increases from 0 to 90%.
- The total vapor-to-liquid film heat transfer performance increases with increase in frontal air velocity and spray density.
- The water treatment program for an evaporative condenser system is integral to the operation of an energy, water and resource efficient facility.
- For getting enhanced effect over evaporative condenser performance, nano-material and nano-particles should be added to coil of condenser and working refrigerant respectively.

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