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4E (ENERGY, EXERGY, ECONOMIC AND ENVIRONMENTAL) ANALYSIS OF THE NOVEL DESIGN OF WET COOLING TOWER

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ABSTRACT

This study aims to calculate the performance of the novel design of wet cooling tower (NDWCT) using first law (energy) and second law (exergy) of thermodynamics. Moreover, it determines the economic feasibility (cost savings and payback period) and sustainability of the NDWCT using the life-cycle cost (LCC) and environmental assessment method. An appropriate mathematical model is developed and simulated in Engineering Equation Solver to calculate water savings, performance and payback period of additional investment. The simulation results have a good agreement with the experimental outcomes (error 2.6%). Simulation results revealed that the NDWCT consumes 34.48% less water than the conventional wet cooling tower (WCT). The installation of heat exchanger improves the performance of WCT by 6% because the consumption of water to air ratio increases. Moreover, the exergy destruction in the NDWCT is 1.23 MW lower than the conventional WCT. Additionally, the heat exchanger costs k$30.7 to save an annual fuel cost of k$72 which could be recovered within a payback period of 0.37 years. Lastly, the environmental assessment proves that the NDWCT relinquishes the particulate matter emission by 0.042 g/s.

Keywords: *Water Consumption, The Novel Design of Wet Cooling Tower, Energy and Exergy Analysis, Life Cycle Cost Analysis,*

INTRODUCTION

Energy demand is increasing globally due to advancements in technology, population growth and change in the human lifestyle. It is mainly fulfilled by using fossil fuels in thermal power plants (TPP), which has caused global warming, rain acidification and ozone layer depletion [1]. In a thermal power plant, fossil fuels conversion into electric power requires 2.6 liters of water to generate a unit of electricity, which has raised the concern about water conservation in agrarian, arid and semi-arid regions [2]. Therefore, increasing the efficiency of TPP is one way to save a significant amount of water [3]. Nowadays, TPP is being used to convert available waste heat into useful heat, wherein the non-renewable energy sources are being replaced by renewable sources such as biomass [4-7]. It causes a significant decline in water consumption but their cost-competency is still challenging as compared to fossil fuels [8].

In Pakistan, TPPs produce around 65% of total electricity using fossil fuels and most of them are not working on their installed capacity. Thereby, electricity generation cost and the auxiliary consumption of TPPs is very high [9]. Among different auxiliary components, the WCT accounts for 2.2-3.4% of total power generation [10]. The function of WCT is to remove the heat absorbed by recirculating water through a condenser to the atmosphere via the evaporation process [11]. The minimum obtainable temperature of recirculating water in the tower is the wet-bulb temperature of ambient air [12].

Cooling towers are of close and open types according to heat and mass transfer mechanisms between circulating water and ambient air. Open cooling tower exchanges heat and mass between circulating water and air with direct contact in packing fill. Consequently, the design of packing fills plays a prominent role in the efficiency of the open cooling tower. It increases the heat and mass transfer between the air and recirculating water [13]. Lemouari et al. [14] investigated the effect of air and water flow rate on the performance of an open cooling tower filled with vertical grid type packing at variable recirculating water temperature. It perceived that air-water contact in a bubble and dispersion region (DBR) promotes efficient heat transfer as compared to the pellicle region contact. Thus, DBR cools more water quantity. Additionally, it was found that DBR has higher thermal performance than others. Khan et al. [15] calculated the impacts of fouling risk in the packing of cooling towers on its efficiency. At the lower risk of

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fouling 0.001, the efficiency of the cooling tower was reduced by 6.0% and the circulating water exit temperature was escalated by 1.2% under given operating conditions.

The closed cooling tower contains a heat exchanger, water distribution system and mechanical or natural draft plant. In a closed cooling tower, only sensible heat transfer takes place between air and water. Here, water is sprinkled over the tubes of the heat exchanger to maximize the cooling effect which enhances the evaporation rate [16]. Stabat and Marchio [17] developed a mathematical model based on Merkel's theory to estimate energy and water consumption of the tower considering saturated air at its exit. Moreover, the developed mathematical model compared with the manufacturer's catalog at various operating conditions. Jovic et al. [18] upgraded the design of prevailing WCT to increase the efficiency of a coal-fired power plant by adding two cells. The up-gradation of the plant had improved its performance by 1.5% and the rehabilitation cost was recovered under the payback period of one year.

The energy and exergy analysis is employed to investigate the thermal performance of the WCT in [19-22]. Khalifa [21] conducted the energy and exergy analysis of induced draft counter flow WCT by fractionating horizontally into 100 equal cells. Each cell assumed at a temperature difference of 0.1 K and the water-air ratio between 1.25 and 1.50. He found that an increase in air humidity raises the exergy destruction in the tower while decreasing the approach temperature reduces thermal exergy destruction. Additionally, Merkel's assumption curved the straight line of the maturation process. Bozorgan [23] conducted an exergy analysis on the WCT and found that the exergy destruction of water was higher than air. Mahdi and Jaffal [22] experimentally investigated that the efficiency of WCT with packing at the bottom and top of the heat exchanger was (40% and 25%, respectively) higher than without packing besides heat exchanger. They determined exergy destruction in WCT around 20% which was lower than its cooling capacity [24]. Topal et al. [25] determined the exergy destruction of a Çan Circulating Fluidized Bed Power Plant (CFBPP) co-fired with olive pits around 295 MW (exergy efficiency of 31.26%). They calculated that the boiler accounts for the largest proportion of exergy destruction (86.05%) in the plant. Taner and Sivrioglu investigated the energy and exergy efficiency of the sugar factory at 72.2% and 37.4%, respectively. They found that optimizing the turbine in a sugar factory rises its energy and exergy efficiency from 46.4 to 48.7 and 27.7 to 31.7%, respectively [26]. They also determined the unit cost of improved turbine power plants around 3.142 $/kW which would be recovered within 4.32 years [27]. Taner et al. [28] calculated the sugar factory energy consumption around 43ktoe performing an energy audit on production processes which had saved the energy cost of the factory by 688.22 $/toe. The factory had to focus on energy management problems to meet the Energy Efficiency of Turkish Law and Directives. Taner conducted energy and exergy optimization analysis for a drying plant. He found that the energetic and energetic performance of the optimizing process is greater than the prevailing drying process. He also investigated that techno-economic optimization reduces the total energy cost of the plant from $98,520 to $84,708 over its expected lifetime [29]. In another study, he estimated the performance of PEM fuel cell in terms of energy and exergy that was found 47.6% and 50.4%, respectively. By varying PEM fuel cell pressure and voltage, he determined that the experimental wastewater was affecting the lifetime of PEM fuel cell considerably [30].

Numerous studies were conducted to improve the thermal performance of WCT considering design modifications. Mostly design alterations were made in packing filled material and location underneath and above the heat exchanger within the cooling tower. However, numerical analysis of cooling towers was examined using the energy, exergy, and techno-economic and simulation results compared with available experimental outcomes. The NDWCT's water savings were experimentally determined using operating parameters [31]. However, the numerical analysis of the NDWCT in terms of energy, exergy, LCC and environmental assessment is not found in the available literature.

This study aims to find NDWCT's (a) thermal performance of the NDWCT using thermodynamic analysis, (b) determine the economic feasibility using LCC analysis and (c) environmental friendliness using environmental assessment methods. Firstly, it develops an appropriate mathematical model using the experimental data available in [31]. The simulation of the developed mathematical model performed in Engineering Equation Solver. The simulation results compared with experimental outcomes with a good fit. It determines the exergy destruction before the economic evaluation of the proposed system. Finally, an environmental assessment is conducted to investigate the reduction in particulate matter emission from NDWCT into the atmosphere.

DESCRIPTION OF NOVEL DESIGN OF WET COOLING TOWER

The WCT is used to dispel the heat absorbed from condenser to the environment via the evaporation process. The recirculating water is sprayed on the top of the tower to ensure proper mixing of water and air. Air is introduced in the tower from the bottom side of louvers by the fan and louvers are sloped downwards to keep water inside the tower. The mixing increases the heat and mass transfer between air and water. As a result, the humidity ratio and dry bulb temperature rise to cool recirculating water. Some quantity of water is removed from the basin to maintain the dissolved solids at an acceptable level (blowdown losses). Makeup water is supplied in the basin to compensate evaporative, drift and blowdown losses in the tower. In NDWCT, a plate type heat exchanger is installed at the top of WCT as shown in Fig. 1. The heat exchanger (plastic) has an overall heat transfer coefficient identical to an aluminum sheet having thickness 100 µm. Its plates spaced at 1.2 cm to keep the minimum pressure drop of air (51Pa) and it sized as 15x15x22 cm. The warm and humid air leaving the tower from the top passes through an air to air heat exchanger. Here, its temperature is reduced by transferring energy to the ambient air. Thus, it causes the condensation of hot and humid air; as a result, evaporative and drift losses are decreased considerably.

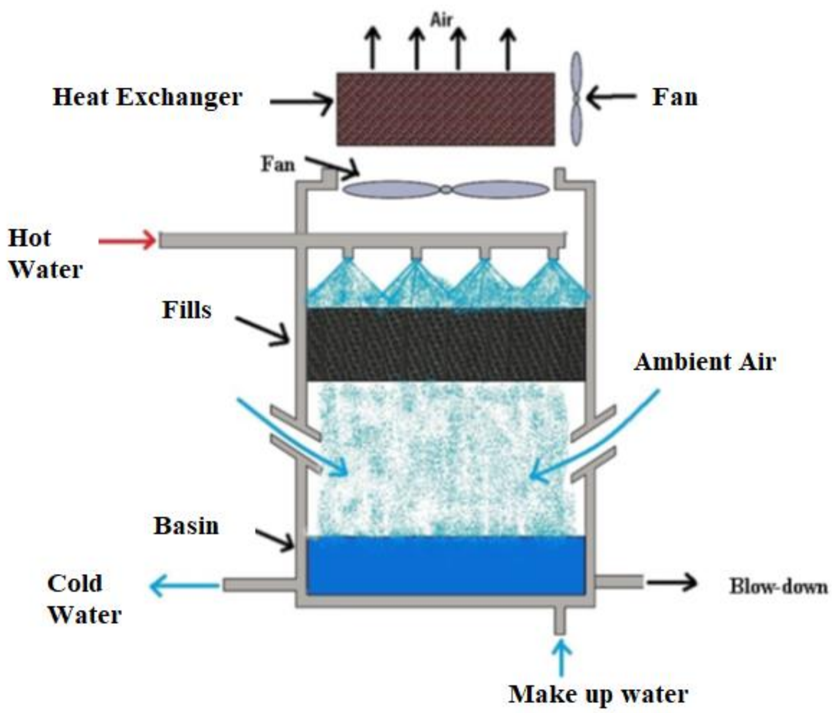

Figure 1: Novel design of a wet cooling tower

THERMAL ANALYSIS OF NOVEL DESIGN OF WET COOLING TOWER

A mathematical model is developed to examine the performance of the proposed novel design of a wet cooling tower. The model considers the tower's different components. The major assumptions that are manipulated to derive the fundamental modeling equations are as follow:

- Steady State condition exists in different components of the proposed wet cooling tower.
- Heat and mass transfer through the tower walls to the atmosphere is negligible [19, 21, 32].
- Merkel's assumption is considered [33].
- Air to air heat exchanger drops humid air temperature and pressure by 2 oC and 5-9 kPa [31, 34]. .
- The pressure drop of air in a wet cooling tower is 1.12-1.16 kPa [35].
- The effectiveness of air to the air heat exchanger is 48% [36].
- The Ratio of water and airflow rate of 1.692 (l/g) [31].
- The temperature difference between inlet and outlet water flow at 10.4 °C [31].

- Mass flow rate of water: 28,500 m3/h [31].

The thermodynamic parameters (temperature and pressure) at the inlet and exit of the NDWCT are given in Table 1. However, other thermodynamics parameters corresponding to the given properties of air and water are determined by Engineering Equation Solver.

Table 1: Design and operating parameters are considered in the analysis [31]

Parameters	Unit	Dead State	Air			Water	
			State 1	State 2	State 3	State 4	State 5
DBT	(°C)	25	29	32.3	30.5	38.2	27.8
WBT	(°C)	15.11	15.14	32	29.9	-	-
Pressure	kPa	101	101	102.4	111.4	279.9	178
Humidity Ratio	g_w/kg_a	6.79	5.97	30.09	21.77	-	-
Relative Humidity	%	34.08	22.71	95.55	96.53	-	-
Enthalpy	kJ/kg	42.4	44.36	109.7	86.31	160.2	116.6
Entropy	kJ/kg-K	5.764	5.782	5.984	5.851	0.5481	0.406
Specific volume	m^3/kg	0.86	0.91	0.90	0.73	0.0011	0.0010

Energy Analysis

The continuity equation and energy balance reveals that during steady flow of ambient air and process water through WCT the mass flow and energy at the inlet and outlet of the tower remains same i.e.

$$\dot{m}_{a,i} + \dot{m}_{w,i} = \dot{m}_{a,e} + \dot{m}_{w,e} \tag{1}$$

$$\dot{W}_f + \dot{m}_{a,i}\, h_{a,i} + \dot{m}_{w,i} h_{w,i} = \dot{m}_{a,e} h_{a,e} + \dot{m}_{w,e}\, h_{w,e} \tag{2}$$

The cooling capacity of tower is estimated by

$$\dot{Q}_C = \dot{m}_{w,i}\,(h_{w,i} - h_{w,e}) \tag{3}$$

An elementary control volume is considered for filled packing of a cooling tower and mass balance for selected control volume is calculated as [37]

$$m_a(1+w) + \left(m_w + \frac{dm_w}{dz} dz\right) = m_a\left(1 + w + \frac{dw}{dz} dz\right) + m_w \tag{4}$$

The humidity ratio is estimated by using Eq. 5 and 6 at the inlet and exit of the tower.

$$\emptyset_i = \frac{C_{pa}}{w_{a(WBT)}}(T_{amb} - T_{wb}) + \emptyset_{sat(WBT)} \tag{5}$$

$$\emptyset_{a,e} = 0.622\,\left(\frac{P_{sat}}{P - P_{sat}}\right) \tag{6}$$

Where $\emptyset_{a(WBT)}$ is given as

$$\emptyset_{a(WBT)} = 2501.3 + 1.82\, WBT \tag{7}$$

The saturated pressure (P_{sat}) of air at the exist of the tower is calculated as [33]

$$LnP_{sat} = \alpha - \frac{\beta}{T+\gamma} \tag{8}$$

The coefficient for the above equation is presented as following: For $0℃ < T < 57℃$, $\alpha = 23.7093$, $\beta = 4111$ and $\gamma = 237$ [33].

The energy balance is employed to NDWCT to calculate the sensible and latent heat transfer that take place between recirculating water and ambient air.

$$\dot{m}_a\, h_a + d\dot{Q}_S + d\dot{Q}_L = \dot{m}_a\, (h + dh_a) \tag{9}$$

The enthalpy transfer associated with the mass transfer in a cooling tower is expressed by

$$d\dot{Q}_L = \dot{m}_{a,i}\, w_{a,i} h_{a,i} - \dot{m}_{a,e}\, w_{a,e}\, h_{a,e} \tag{10}$$

The sensible heat between water and air is given by

$$dQ_s = \dot{m}_{a,i} C_{p,a}\, (DBT_e - DBT_i) \tag{11}$$

The cooling tower's effectiveness is defined as the ratio of actual heat rejected to the maximum obtainable heat rejected.

$$\varepsilon = \frac{Q_w}{Q_{air}} * 100 \tag{12}$$

The evaporative losses of the cooling tower are estimated as

$$E = \dot{m}_{a,i}\, (w_{a,e} - w_{a,i}) \tag{13}$$

The blowdown and make up water consumption is estimated as

$$B = \frac{E}{COC-1} \tag{14}$$

$$M = E\, \left(\frac{COC}{COC-1}\right) \tag{15}$$

The drift losses are estimated as

$$D = 0.006\, \dot{m}_w \tag{16}$$

Exergy Analysis

Conventionally, thermal engineering systems were analyzed using the first law of thermodynamics, in which enthalpy difference at the inlet and exit of the system was taken to determine their performance. Exergy analysis has been conducted to analyze the performance of thermal engineering systems over the last few decades because it investigates the system performance considering the difference of energy loss and internal irreversibility of the system. In wet cooling towers, exergy destruction occurs due to pressure drop (mechanical), heat and mass transfer (thermal) and chemical diffusion for recirculating water treatment (chemical) [19-22, 38].

The exergy of moist air in a wet cooling tower (Ex_a) is estimated as

$$Ex_a = Ex_{me} + Ex_{th} + Ex_{ch} \tag{17}$$

where mechanical, thermal and chemical exergy is represented as Ex_{me}, Ex_{me} and Ex_{ch} respectively, which are estimated as

$$Ex_{th} = \left(C_{pa} + w\, C_{pv}\right) T_{amb} \left(\frac{T}{T_{amb}} - 1 - \ln\frac{T}{T_{amb}}\right) \tag{18}$$

$$Ex_{me} = (1 + 1.608\, w\,)\, R_a T_{amb} \ln\frac{P}{P_{amb}} \tag{19}$$

$$Ex_{ch} = R_a T_{amb} \left\{(1 + 1.608w\,) \ln\left(\frac{(1+1.608\, w_{amb,s})}{(1+1.608w\,)}\right) + 1.68\, w \ln\frac{w}{w_{amb}}\right\} \tag{20}$$

The exergy of water is estimated as

$$\mathrm{ex}_w = (h_w - h_o) - T_{amb}\,(s_w - s_o) \tag{21}$$

And the exergy of water vapor is

$$\mathrm{ex}_v = c_w(T_w - T_{amb}) - T_{amb}\, c_w \ln\left(\frac{T}{T_{amb}}\right) - T_{amb}\, c_w \ln \emptyset_{amb} \tag{22}$$

The exergy destruction in the cooling tower can be estimated as

$$\dot{Ex}_d = \dot{m}_a\left(Ex_{a,e} - Ex_{a,i}\right) + \left((\dot{m}_w - \dot{m}_a\, \emptyset_e)\, \mathrm{Ex}_{w,e} - (\dot{m}_w - \dot{m}_a\, \emptyset_i)\, \mathrm{Ex}_{w,i}\right) + \dot{m}_a\,(\emptyset_e\, \mathrm{Ex}_{v,e} - \emptyset_i\, \mathrm{Ex}_{v,i}) \tag{23}$$

Economic Analysis

The techno-economic feasibility of thermal engineering systems is usually investigated using LCC analysis over their expected lifetime. In life cycle cost analysis, the effect of inflation and interest rate, maintenance ratio, operating and purchase cost of equipment is used to determine the net cost savings and payback period of initial investment on thermal engineering systems [39, 40].

The operating cost of the wet cooling tower without and with heat exchanger are calculated as [33]

$$OC_1 = 2.4094 \times 10 - 3\left(\dot{W}_p + \dot{W}_F\right) + 44\,(\dot{m}_a) + 110(\dot{m}_w) + 2275.132\,(M_1) + 1138(B_1) \tag{24}$$

$$OC_2 = 2.4094 \times 10 - 3\left(\dot{W}_p + \dot{W}_F\right) + 44\,(\dot{m}_a) + 110\,(\dot{m}_w) + 2275.132\,(M_2) + 1138(B_2) \tag{25}$$

where OC represents operating cost, $\dot{W}_p$ and $\dot{W}_F$ denote power consumption of pump and fan are calculated by Eq. 26 and 27 [41], $\dot{m}_a$ and $\dot{m}_w$ are mass flow rate of air and water which are given in Table 1, B is blowdown loss and M is makeup water (Eq. 14 and 15). The subscript 1 and 2 represents conventional WCT and NDWCT.

$$\dot{W}_p = \dot{V}_w\, \Delta P_w \tag{26}$$

$$\dot{W}_F = \dot{V}_F(\,\Delta P_{WCT} + \Delta P_{hx}) \tag{27}$$

where ΔP_w represents a pressure drop of water in WCT, while $\Delta P_{WCT} and\ \Delta P_{hx}$ denotes pressure drop of air in wet cooling and its heat exchanger.

The purchase equipment cost of a wet cooling tower is estimated as [42]

$$PEC_{WCT} = 746 \times \dot{m}_w + 70.5 \times \dot{Q}_{ct} \times (-0.6936 \times ln(T_{cw.abs} - T_{wb}) + 2.1898) \tag{28}$$

The purchase equipment cost of heat exchanger (PEC_{Hx}) is calculated as [43]

$$PEC_{Hx} = C_{Hx}\ (A)^{0.6} \tag{29}$$

where C_{Hx} denotes the cost of heat exchanger per unit area ($20 /m2) and A is the surface area of heat exchanger which is calculated as

$$A = \frac{\dot{Q}_{Hx}}{U \times LMTD} \tag{30}$$

where $\dot{Q}_{Hx}$ is the energy recovered in a heat exchanger, U is the overall heat transfer coefficient of heat exchanger (7.9 W/m^2.K) and LMTD is log mean temperature difference which is calculated as [44]

$$LMTD = \frac{(T_2 - T_4) - (T_3 - T_4)}{\ln\frac{(T_2 - T_4)}{(T_3 - T_4)}} \tag{31}$$

The purchase equipment cost of NDWCT is the sum of wet cooling tower and heat exchanger

$$PEC_{NDWCT} = PEC_{WCT} + PEC_{Hx} \tag{32}$$

The present worth of net amount of savings is determined using LCC analysis. In which, P1 relates operation cost with inflation rate (d=7%) [40], interest rate (i=5%) [40] and lifetime (N) of the equipment 20 years. P2 is the ratio of increase in capital investment during the life cycle of WCT to the initial investment. The P_1 and P_2 are determined by

$$P_1(N, i, d) = \sum_{j=1}^{N} \frac{(1+i)^{j-1}}{(1+d)^j} = \begin{cases} \frac{1}{d-i}\left[1 - \left(\frac{1+i}{1+d}\right)^N\right] & if\ d \neq i \\ \frac{N}{1+i} & if\ d = i \end{cases} \tag{33}$$

$$P_2 = 1 + P_1 MR - SV(1+d)^N \tag{34}$$

where MR is the ratio of annual maintenance (0.04-0.1) [42] and operation cost to the initial investment, SV is the ratio of salvage value to initial investment. The total life cycle cost of the wet cooling tower without and with heat exchanger is estimated as

$$C_{WCT} = OC_{WCT} P_1 + PEC_{WCT}\ P_2 \tag{35}$$

$$C_{NDWCT} = OC_{NDWCT} P_1 + PEC_{NDWCT}\ P_2 \tag{36}$$

Life cycle cost savings ($/year) is calculated as

$$CS = C_{WCT} - C_{NDWCT} \tag{37}$$

The simple payback period is calculated as [39]

$$PP = \frac{C_{NDWCT}}{\mathrm{CS}} \tag{38}$$

Environmental Assessment

In WCT, thermal energy transfer takes place due to direct contact between circulating water and air passing through the tower. Besides, a very little amount of water around (0.6%) is carried out of the tower as drift droplets [45]. These droplets contain some particulate matters which entrains from heat exchanger tubes (condenser). The entrained particulate matters in droplets considered as PM10 emission because the size of particulate matters is below 10 µm [46], and they are calculated as

$$PM10 = \frac{D*TDS}{\rho_w} \tag{39}$$

Where, TDS represent total dissolved solid (360 mg/l) [31] and ρ_w denotes the density of water.

RESULTS AND DISCUSSION

This study presents the numerical solution of the proposed novel design of wet cooling tower. It conducts thermodynamic and economic analysis using energy, exergy, and life-cycle cost analysis to determine the decrease in make water consumption, effectiveness, exergy destruction and economic benefits of the proposed design. Additionally, it uses an environmental assessment method to calculate the environmental impacts of the proposed design. The preliminary data regarding design and operating parameters obtained from [31]. Using the preliminary data, an appropriate mathematical model is developed to determine water consumption, efficiency and exergy destruction in NDWCT. The developed mathematical model is then simulated in EES. After that, the simulation outcomes are compared to experimental investigations with an error of 2.6%. The loss of water in evaporation, drift, and blowdown in WCT and NDWCT presented in Fig. 2. Fig. 3 gives information about the efficiency of WCT and NDWCT. The comparison of numerical and experimental water savings exhibited in Fig. 4. Moreover, Fig. 5 shows exergy destruction in WCT and NDWCT, while Fig. 6 exhibits capital investment, operation cost and the life-cycle cost incurred on WCT and NDWCT. Environmental outcomes of the present study are shown in Fig. 7.

Energy Analysis of Convention WCT and NDWCT

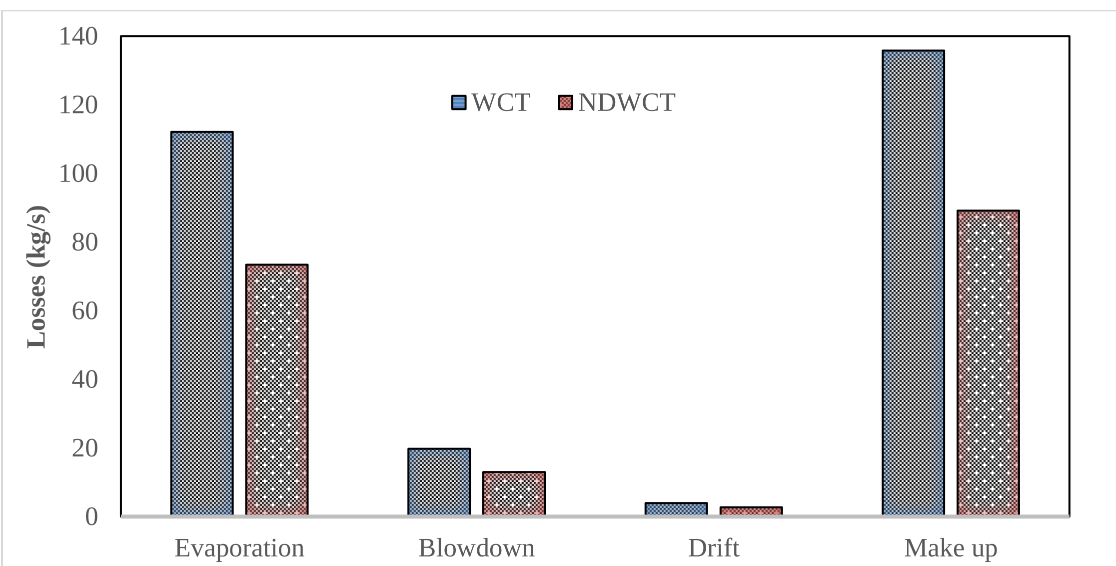

Figure 2: Comparison of circulating water loss (kg/s) in evaporation, drift, blowdown, and total make up water consumed in WCT and NDWCT

Figure 2 exhibits the circulating water loss in WCT and NDWCT through evaporation, blowdown, and drifts which directly affects its total make up water requirement. Water evaporates in WCT results in plume which carries a bulk quantity of water into the atmosphere. However, in the NDWCT, hot and humid air leaving the tower passes through the heat exchanger, here, its temperature drops below the dew point temperature of the air at which condensation commences. As a result, the major proportion of evaporation water is condensed back to the tower. Thus, evaporative losses in NDWCT dwindle from 112.1 to 73.43 kg/s. Blowdown losses depend on evaporation losses; therefore, it decreases in a similar proportion to evaporative losses. Blowdown losses occur due to chemical cleaning recirculating water because when water flow through condenser it erodes condenser tube surface and carries the particulates matters towards the tower. These matters are removed from the tower as blowdown. The blowdown losses are estimated around 19.76 kg/s for conventional WCT and 12.95 for NDWCT. In conventional WCT, some quantity of water is carried in the air as an unevaporated drizzle, which is basically reduced by drift eliminator. However, in NDWCT, drift eliminator is not installed because heat exchanger functions alike drift eliminator. Drift losses in conventional WCT tower are 3.931 kg/s which are decreased to 2.729 kg/s in NDWCT.

Total makeup water compensates evaporative, drift and blowdown losses in the cooling tower. It is proportionate of the evaporative losses in NDWCT. Hence, decrement in evaporative losses drops make water consumption. In conventional WCT 135.79 kg/s of makeup water is required to compensate these losses, while in NDWCT around 89.10 kg/s of makeup water is required.

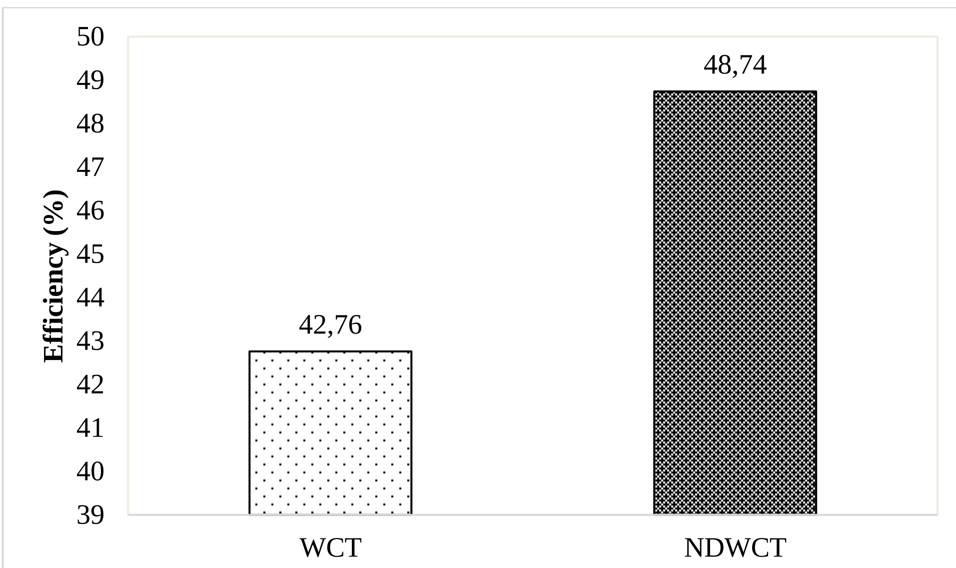

Figure 3. Energy Efficiency of the WCT and NDWCT

Figure 3: shows the efficiency of conventional WCT and NDWCT. The efficiency of WCT (42.76%) is lower than the NDWCT (48.74%) because the less quantity of air is needed to cool given amount of water at constant operating conditions in NDWCT. Thermal performance of WCT increases with the installation of the heat exchanger.

Figure 4 illustrates the percentage of water savings in NDWCT by performing an experiment and conducting a simulation. Water savings are proportional to the reduction in evaporation, blowdown and drift losses in a cooling tower. The water savings are numerically estimated using the developed mathematical model, while it is experimentally obtained from [31]. The results reveal that the evaporative losses calculated from the developed mathematical model were around 34.48% of circulating water, which is deviated by 0.92% from the evaporative loss (35.4%) [31] in the wet cooling tower.

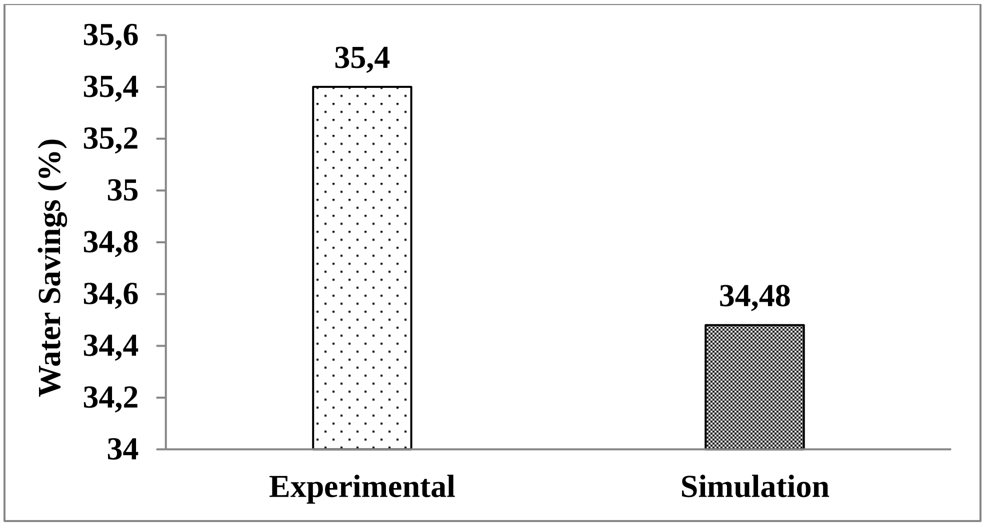

Figure 4: Comparison of the experimentally and numerically estimated proportion of water saving in NDWCT

Exergy Analysis of Convention WCT and NDWCT

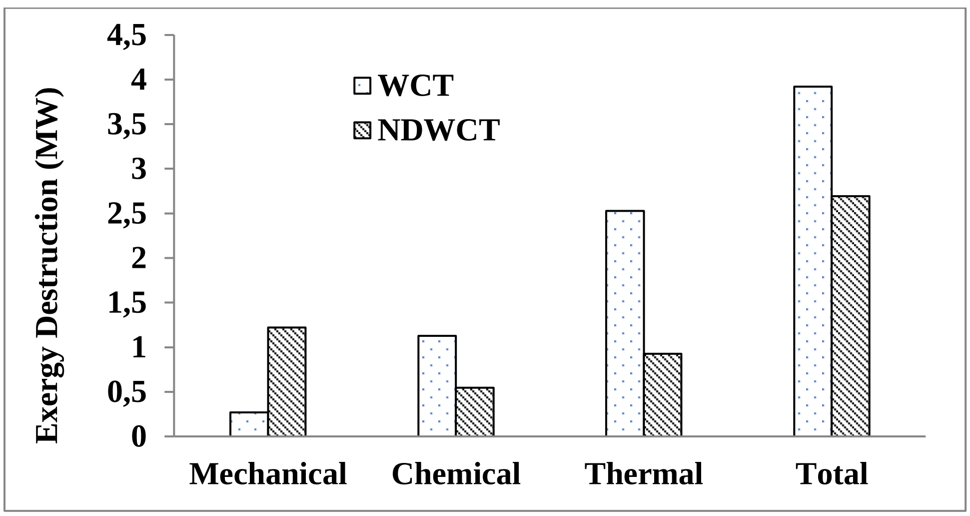

Figure 5: Exergy destruction in WCT and NDWCT

Figure 5 exhibits mechanical (due to pressure changes), chemical (due to moisture transfer) and thermal (due to heat transfer) exergy destruction which is summed up as total exergy destruction in WCT and NDWCT. Mechanical exergy destruction in NDWCT is greater than conventional WCT because installation of heat exchanger drops pressure; as a consequence, cooling tower fan consumes more power to continue airflow. The mechanical exergy destruction in WCT is 0.27 MW while in NDWCT is 1.22 MW. In contrast, chemical exergy destruction in novel design (1.126 MW) is less than WCT (0.54) because less water is treated chemically as compared to conventional WCT. Moreover, thermal exergy destruction is low, in NDWCT, because heat exchanger removes an additional quantity of thermal energy from the cooling tower. As a result, thermal exergy destruction in NDWCT is reduced from 2.53 to 0.97 MW. In NDWCT, total exergy destruction is dropped by 1.23 MW.

Economic Analysis of Convention WCT and NDWCT

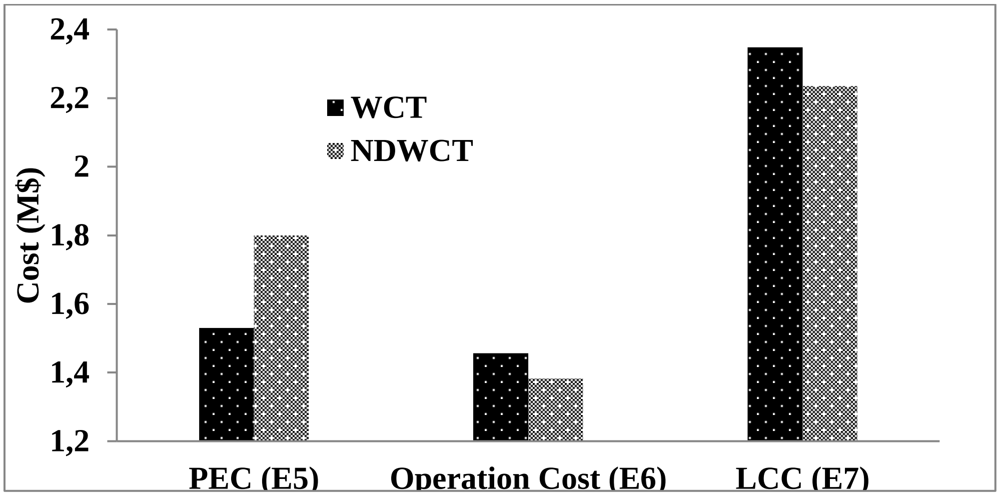

Figure 6: Equipment's purchase, operation, and life cycle cost incur on WCT and NDWCT

Figure 6 exhibits the purchased equipment cost (PEC), operation cost and LCC incurs on conventional WCT and NDWCT. The conventional WCT costs at k$152 which sums up to k$181 with the installation of a heat exchanger (k$30.7) because the installation of heat exchanger has increased heat transfer surface area. It is seen in Eq. 29, the purchasing cost of a heat exchanger is directly proportional to the heat exchanger surface area. In contrast, operation cost is reduced from M$1.4 to M$1.28/year because it drops water treatment cost dramatically which depend on evaporative losses in both cooling tower's types. The LCC of conventional WCT and NDWCT is estimated at around M$23.48 and M$22.35, respectively, over an expected lifetime of the system. The installation of a heat exchanger saves an annual operation cost of k$72 with an additional cost of k$30.7. As a consequence, the payback period of NDWCT is estimated at around 0.37 years.

Environmental Analysis of Convention WCT and NDWCT

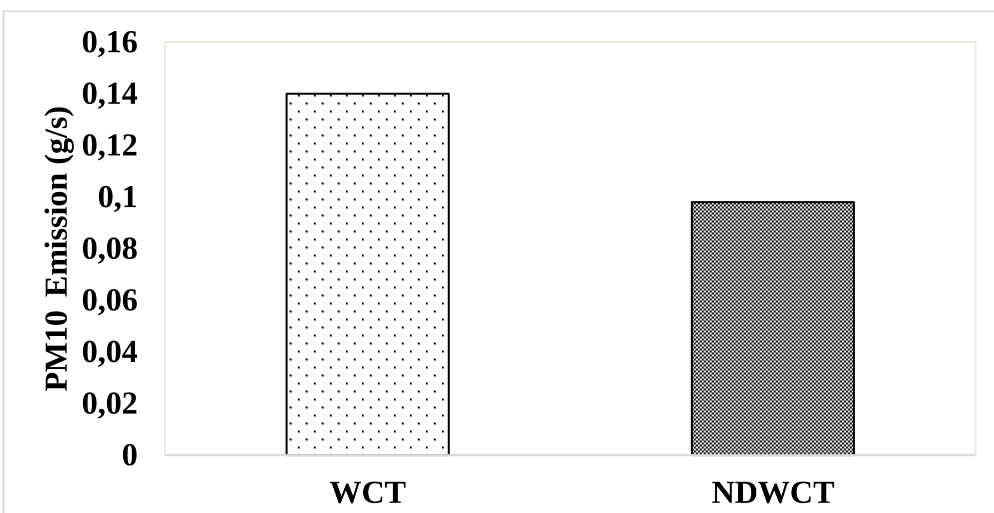

Figure 7: Particulate matters (PM10) emission in WCT and NDWCT

Figure 7 illustrates the emission of particulate matters (PM10) in the conventional WCT and NDWCT. The installation of heat exchanger in WCT improves the thermal performance and reduces the water loss. Thereby, the entrained PM10, which are dispersed in the atmosphere, is reduced from 0.14 to 0.098 g/s in NDWCT. As a consequence, the NDWCT is more eco-friendly as compared to conventional WCT.

CONCLUSION

In this study, a thermal mathematical model is used to investigate the performance of conventional WCT and NDWCT in terms of first law (energy) and second law (exergy) of thermodynamics. Besides, it determines the economic feasibility of NDWCT using LCC analysis. It also estimates the environmental impacts of NDWCT using water-saving and TDS data of the tower. The simulation of a thermal mathematical model is performed using Engineering Equation Solver to investigate the evaporative, blowdown, drifts losses and total makeup water requirement, performance, total exergy destruction, the payback period of initial investment and environmental impacts of the NDWCT. The simulation results are given below

Energetic investigations show that total makeup water consumption is reduced from 135 kg/s to 89 kg/s with the installation of the heat exchanger on conventional WCT.

The performance of conventional WCT increases from 42.76 to 48.74% with the installation of a heat exchanger because it reduces air to water ratio to cool a given quantity of water.

The NDWCT saves 35% of a total make water consumed in conventional WCT.

The mechanical exergy destruction in NDWCT (1.22 MW) is higher than WCT (0.269 MW) because the installation of heat exchanger restricts flow as result maximum pressure drops in NDWCT. In contrast, the chemical and thermal exergy are reduced by heat exchanger because it decreases the humidity ratio and dry bulb temperature of the air at the exit of the cooling tower. Therefore, the chemical and thermal exergy decrease from 1.126 to 0.544 MW and 2.526 to 0.927 MW respectively. Moreover, the total exergy destruction in NDWT is dropped by 1.23 MW because of the decrease in chemical and thermal exergy is higher than the rise in mechanical exergy.

The installation of a heat exchanger increases the cost of the cooling tower by k$30.7, while its operating cost is decreased to k$72. Thus, its additional investment cost recovers within a payback period of 0.37 years. As a consequence, proposed modification in the conventional wet cooling tower is economically feasible.

The use of heat exchanger decreases the PM10 pollutants from 0.14 to 0.098 g/s in NDWCT. Thereby, the NDWCT is more sustainable than conventional WCT.

NOMENCLATURE

A	Area, m^2
B	Blowdown Loss, kg/s
C	Cost per unit area, $\$/m^2$
CS	Cost Savings, $/year
c_p	Specific heat at constant pressure, kJ/kg K
d	inflation rate, %
DBT	Dry bulb temperature, °C
E	Evaporation loss, kg/s
Ex	Exergy, kW
h	Enthalpy (kJ/kg)
i	interest rate (%)
$LMTD$	Log Mean Temperature Difference (°C).
M	Make up water (kg/s)
$\dot{m}$	Mass flow rate (kg/s)
N	Lifetime (years)
OC	Operation Cost ($/year)
P	Pressure (kPa)
$PM10$	Particulate Matters (g/s)
PP	Payback Period (year)
PEC	Purchased Equipment Cost (
$\dot{Q}$	Cooling Capacity (kW)
R	Universal Gas constant (kJ/kg.°C)
T	Temperature (°C)
TDS	Total Dissolved Solids (mg/l)
U	Overall heat transfer co-efficient (W/m2.°C)
$\dot{W}$	Power (kW)
WBT	Wet bulb temperature (°C)

Greek symbols

ε	Efficiency (%)
$\emptyset$	Humidity Ratio (-)

Subscripts

a	Air
act	actual
amb	ambient
ch	Chemical
e	exit
F	fan
Hx	Heat Exchanger
i	Inlet
l	Latent
max	maximum
me	Mechanical
o	Dead state
p	pump
s	Sensible
sat	Saturated
th	Thermal
v	Vapor
w	water

Abbreviations

COC	Cycle of Concentration
EES	Engineering Equation Solver
LCC	Life cycle cost
WCT	Wet cooling tower
NDWCT	Novel Design of Wet Cooling Tower.

REFERENCES

[1] Kumar D, Memon RA, Memon AG. Energy Analysis of Selected Air Distribution System of Heating, Ventilation and Air Conditioning System: A Case Study of a Pharmaceutical Company Mehran University Research Journal of Engineering & Technology. 2017;36(3):745-56. https://doi.org/10.22581/muet1982.1703.29

[2] Leo Samuel DG, Shiva Nagendra SM, Maiya MP. An analysis of operating parameters in the cooling tower-based thermally activated building system. Indoor and Built Environment. 2017;27(9):1175-86. https://doi.org/10.1177/1420326X17704276

[3] Rahġm MA, Erbaġ O, Taner T, Köse R, Topal H. Energy recovery from waste heat of a steam boiler by a sysytem of organic rankine cycle: A case of textile factory. ULIBTK'15 20 Ulusal Isı Bilimi ve Tekniği Kongresi 02-5 Eylül; BALIKESİR2015.

[4] Angeline AA, Jayakumar J, Asirvatham LG, Marshal JJ, Wongwises S. Power generation enhancement with hybrid thermoelectric generator using biomass waste heat energy. Experimental Thermal and Fluid Science. 2017;85:1-12. https://doi.org/10.1016/j.expthermflusci.2017.02.015

[5] Angeline AA, Jayakumar J, Asirvatham LG. Performance analysis of (Bi2Te3-PbTe) hybrid thermoelectric generator. International Journal of Power Electronics and Drives Systems. 2017;8(2).

[6] Angeline AA, Jayakumar J, Asirvatham LG, Wongwises S. Power generation from combusted "syngas" using hybrid thermoelectric generator and forecasting the performance with ann technique. Journal of Thermal Engineering. 2018;4(4):2149-68. https://doi.org/10.18186/journal-of-thermal-engineering.433806

[7] Angeline AA, Jayakumar J. Analysis of (Bi2Te3-PbTe) hybrid thermoelectric generator for effective power generation. 2nd International Conference on Innovations in Information, Embedded and Communication Systems; Karpagam College of Engineering, Coimbatore, India: IEEE; 2015. p. 1-6.

[8] Chow J, Kopp RJ, Portney PR. Energy resources and global development. Science. 2003;302(5650): 1528-31. https://doi.org/10.1126/science.1091939

[9] Rajper MA, Memon AG, Harijan K. Energy and Exergy Analysis of 210 MW Jamshoro Thermal Power Plant. Mehran University Research Journal of Engineering & Technology. 2016;35(2):265-74. https://doi.org/10.22581/muet1982.1602.12

[10] Kumar D, Memon RA, Memon AG, Tunio IA, Junejo A. Impact of Auxiliary Equipments' Consumption on Electricity Generation Cost in Selected Power Plants of Pakistan. Mehran University Research Journal of Engineering & Technology,. 2017;36(2):419-36. https://doi.org/10.22581/muet1982.1702.20

[11] Taghian Dehaghani S, Ahmadikia H. Retrofit of a wet cooling tower in order to reduce water and fan power consumption using a wet/dry approach. Applied Thermal Engineering. 2017;125:1002-14. https://doi.org/10.1016/j.applthermaleng.2017.07.069

[12] Kashani MMH, Dobrego KV. Heat and mass transfer in natural draft cooling towers. Journal of Engineering Physics and Thermophysics. 2013;86(5):1072-82. https://doi.org/10.1007/s10891-013-0930-z

[13] Kaiser AS, Lucas M, Viedma A, Zamora B. Numerical model of evaporative cooling processes in a new type of cooling tower. International Journal of Heat and Mass Transfer. 2005;48(5):986-99. https://doi.org/10.1016/j.ijheatmasstransfer.2004.09.047

[14] Lemouari M, Boumaza M, Mujtaba IM. Thermal performances investigation of a wet cooling tower. Applied Thermal Engineering. 2007;27(5):902-9. https://doi.org/10.1016/j.applthermaleng.2006.08.014

[15] Khan J-U-R, Qureshi BA, Zubair SM. A comprehensive design and performance evaluation study of counter flow wet cooling towers. International Journal of Refrigeration. 2004;27(8):914-23. https://doi.org/10.1016/j.ijrefrig.2004.04.012

[16] Jiang J-J, Liu X-H, Jiang Y. Experimental and numerical analysis of a cross-flow closed wet cooling tower. Applied Thermal Engineering. 2013;61(2):678-89. https://doi.org/10.1016/j.applthermaleng.2013.08.043

[17] Stabat P, Marchio D. Simplified model for indirect-contact evaporative cooling-tower behaviour. Applied Energy. 2004;78(4):433-51. https://doi.org/10.1016/j.apenergy.2003.09.004

[18] Jović M. Improving the energy efficiency of a 110 MW thermal power plant by low-cost modification of the cooling system. 2018; 29(2):pp. 245-59. https://doi.org/10.1177/0958305X17747428

[19] Saravanan M, Saravanan R, Renganarayanan S. Energy and exergy analysis of counter flow wet cooling towers. Thermal Science. 2008;12(2):69-78. https://doi.org/10.2298/TSCI0802069S

[20] Hui SCM, Wong H. Exergy analysis of cooling towers for optimization of HVAC systems. Hunan-Hong Kong Joint Symposium; Changsha, Hunan, China2011. p. 1-10.

[21] Khalifa AH. Thermal and Exergy Analysis of Counter Flow Induced Draught Cooling Tower. International Journal of Current Engineering and Technology. 2015;2868.

[22] Mahdi Q, Jaffal H. Energy and Exergy Analysis on Modified Closed Wet Cooling Tower in Iraq. Al-Khwarizmi Engineering Journal. 2016;12:45-59.

[23] Bozorgan N. Exergy Analysis of Counter Flow Wet Cooling Tower in Khuzestan Steel Co. Journal of Mechanical Research and Application. 2020;2(1):31-7.

[24] Qasim SM, Hayder MJ. Investigation of the effect of packing location on performance of closed wet cooling tower based on exergy analysis. IOP Conference Series: Materials Science and Engineering. 2016;145. https://doi.org/10.1088/1757-899X/145/3/032009

[25] Topal H, Taner T, Naqvi SAH, Altınsoy Y, Amirabedin E, Ozkaymak M. Exergy analysis of a circulating fluidized bed power plant co-firing with olive pits: A case study of power plant in Turkey. Energy. 2017;140:40-6. https://doi.org/10.1016/j.energy.2017.08.042

[26] Taner T, Sivrioglu M. Energy–exergy analysis and optimisation of a model sugar factory in Turkey. Energy. 2015;93:641-54. https://doi.org/10.1016/j.energy.2015.09.007

[27] Taner T, Sivrioglu M. A techno-economic & cost analysis of a turbine power plant: A case study for sugar plant. Renewable and Sustainable Energy Reviews. 2017;78:722-30. https://doi.org/10.1016/j.rser.2017.04.104

[28] Taner T, Sivrioğlu M, Topal H, Dalkılıç AS, Wongwises S. A model of energy management analysis, case study of a sugar factory in Turkey. Sādhanā. 2018;43(3). https://doi.org/10.1007/s12046-018-0793-2

[29] Taner T. Optimisation processes of energy efficiency for a drying plant: A case of study for Turkey. Applied Thermal Engineering. 2015;80:247-60. https://doi.org/10.1016/j.applthermaleng.2015.01.076

[30] Taner T. Energy and exergy analyze of PEM fuel cell: A case study of modeling and simulations. Energy. 2018;143:284-94. https://doi.org/10.1016/j.energy.2017.10.102

[31] Deziani M, Rahmani K, Mirrezaei Roudaki SJ, Kordloo M. Feasibility study for reduce water evaporative loss in a power plant cooling tower by using air to Air heat exchanger with auxiliary Fan. Desalination. 2017;406:119-24. https://doi.org/10.1016/j.desal.2015.12.007

[32] Papaefthimiou VD, Zannis TC, Rogdakis ED. Thermodynamic study of wet cooling tower performance. International Journal of Energy Research. 2006;30(6):411-26. https://doi.org/10.1002/er.1158

[33] Panjeshahi MH, Ataei A, Gharaie M, Parand R. Optimum design of cooling water systems for energy and water conservation. Chemical Engineering Research and Design. 2009;87(2):200-9. https://doi.org/10.1016/j.cherd.2008.08.004

[34] Darici S, Canli E, Dogan S, Ozgoren M. Determination of heat transfer rate and pressure drop performance of an intercooler for heavy duty engines International Journal of Arts & Sciences. 2012;5:43-57.

[35] Viljoen D. Evaluation and performance prediction of cooling tower spray zones. Master of Science, University of Stellenbosch; Stellenbosch, South Africa: 2006.

[36] Guo P, Ciepliski DL, Besant RW. A Testing and HVAC Design Methodology for Air-to-Air Heat Pipe Heat Exchangers. HVAC&R Research. 1998;4(1):3-26. https://doi.org/10.1080/10789669.1998.10391388

[37] Xia ZZ, Chen CJ, Wang RZ. Numerical simulation of a closed wet cooling tower with novel design. International Journal of Heat and Mass Transfer. 2011;54(11):2367-74. https://doi.org/10.1016/j.ijheatmasstransfer.2011.02.025

[38] Kumar S, Kumar D, Memon RA, Wasan MA, Ali MS. Energy and Exergy Analysis of a Coal Fired Power Plant. Mehran University Research Journal of Engineering & Technology. 2018; 37 (4):611-24. https://doi.org/10.22581/muet1982.1804.13

[39] Topal H, Taner T, Altıncı Y, Amirabedin E. Application of trigeneration with direct co-combustion of poultry waste and coal: A case study in the poultry industry from Turkey. Thermal Science. 2017;22(6):3073 – 3082. https://doi.org/10.2298/TSCI170210137T

[40] Kumar D, Memon RA, Memon AG, Ali I, Junejo A. Critical analysis of the condensation of water vapor at external surface of the duct. Heat and Mass Transfer. 2018;54:1937–50. https://doi.org/10.1007/s00231-017-2256-4

[41] Rao RV, Patel VK. Optimization of mechanical draft counter flow wet-cooling tower using artificial bee colony algorithm. Energy Conversion and Management. 2011;52(7):2611-22. https://doi.org/10.1016/j.enconman.2011.02.010

[42] Memon AG, Memon RA. Parametric based economic analysis of a trigeneration system proposed for residential buildings. Sustainable Cities and Society. 2017;34:144-58. https://doi.org/10.1016/j.scs.2017.06.017

[43] Hewitt GF, Pugh SJ. Approximate Design and Costing Methods for Heat Exchangers. Heat Transfer Engineering. 2007;28(2):76-86. https://doi.org/10.1080/01457630601023229

[44] Liang C, Tong X, Lei T, Li Z, Wu G. Optimal Design of an Air-to-Air Heat Exchanger with Cross-Corrugated Triangular Ducts by Using a Particle Swarm Optimization Algorithm. Applied Sciences. 2017;7(6):554-74. https://doi.org/10.3390/app7060554

[45] Reisman J, Frisbie G. Calculating realistic PM10 emissions from cooling towers. Environmental Progress. 2002;21:127-130. https://doi.org/10.1002/ep.670210216

[46] Ruiz J, Kaiser AS, Ballesta M, Gil A, Lucas M. Experimental measurement of cooling tower emissions using image processing of sensitive papers. Atmospheric Environment. 2013;69:170-81. https://doi.org/10.1016/j.atmosenv.2012.12.014