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Performance Evaluation of a Counter Flow Wet Cooling Tower Using Latin Square Design

Adenuga, Peter, Wordu, Animia A., Ehirim, Emmanuel O. and Adenuga, Ronke

Department of Chemical Petrochemical Engineering,
Rivers State University, Port Harcourt, River State-Nigeria
E-mail: macpeter360@gmail.com, wordu.animia@ust.edu.ng, ehirim.emmanuel@ust.edu.ng

ABSTRACT

The design and operating conditions of cooling towers in re-circulating cooling-water systems have been the focus of manufacturers and process engineers with a concern for energy conservation process as main objective. The question of how to improve a cooling tower's effective performance is still getting much of attention. The cooling tower's efficiency is great when the incoming cooling water has moderate temperature and a low flow rate; in other words, the cooling tower removes more heat from the water. In this research an existing model was applied, simulated and then optimize by varying some parameters using Latin Square Design to show the influence of the re-circulating cooling-water inlet temperature, air outlet temperature, water flow rate and the air flow rate on the effectiveness of the cooling tower operation. It was discovered that as the water/air mass flow ratio, L/G, and the outlet air temperature increases, the cooling water range, R and cooling tower efficiency, η*, decrease. Water cooling was best achieved at moderate inlet water temperature, low outlet air temperature, low water mass flow rate, and high air mass flow rate, higher efficiencies are obtained at lower inlet water temperatures for the same water/air mass flow ratio, and the greater the range of the cooling water, R, the higher the cooling tower efficiency.*

KEYWORDS: Design, Simulate, Optimize, Latin Square Design, Water/Air Mass Flow, Cooling Tower Efficiency

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1. INTRODUCTION

A cooling tower is a continuous flow device that cools water by exposing it to the atmosphere as an extended surface using a combination of mass and energy transfer (Akter *et al.*, 2017). Filling increases the surface area of the water, resulting in a film surface or droplets (Ramakrishnan & Arumugam, 2012). Mechanical mechanisms, convection currents, or natural wind can generate cross-flow or counter-flow air movement. One or more mechanically driven fans move air in mechanical draft towers to maintain a consistent air-flow (Ramkumar & Ragupathy, 2015). A cooling tower is a device that cools water while also releasing heat into the atmosphere (Hosoz *et al.*, 2007). Cooling towers can drop water temperatures more effectively than devices that merely use air to reject heat, such as a car's radiator, and are thus more cost-effective and energy efficient (Kumar & Yadav, 2021). They are commonly utilized in the HVAC industry. Cooling towers come in a variety of shapes and sizes. The most popular cooling towers used in HVAC applications are forced draft cross flow and counter flow cooling towers (Mahmud *et al.*, 2013).

A forced draft cooling tower is a mechanical draft cooling tower with a blower fan at the air intake. The fan is more prone to difficulties owing to freezing conditions when it is on the air intake (Siddiqui & Haque, 2013). The capacity to work with high static pressure is a benefit of the forced draft design (Engelbrecht *et al.*, 2017). Such arrangements can be used in tighter settings, as well as in some indoor scenarios (Hossain & Soh, 2015). Blow-through is another name for this fan shape (Adekanye & Babaremu, 2019). The fan forces air into the tower, resulting in high air velocity entering and low air velocity exiting (Tamnar, 2015). The low departing velocity makes recirculation considerably more likely (Verschaeren *et al.*, 2014).

A condenser is a device used in heat transfer systems to chill the fluid passing through it and convert it from a gaseous to a liquid state (Bao *et al.*, 2015). The fluid going through a condenser is cooled using a cooling tower (Wen *et al.*, 2012). Cooling towers can also be used to cool fluids used in manufacturing processes (Afanasenko *et al.*, 2007). As a result, cooling towers are used in a wide range of applications (Ho *et al.*, 2010).

i. Manufacturing; to keep the production line cool
ii. Electric power plants; provide cooling for the condenser.
iii. Use HVAC to reject the heat from chillers (Heating, Ventilation, and Air Conditioning).

A cooling tower's functionality revolves around evaporative cooling and sensible heat exchange (Liu *et al.*, 2013). A little amount of chilled water is evaporated in a flowing stream of air during evaporative cooling in a cooling tower to cool the remaining water (Yang *et al.*, 2019). When heated water comes into touch with cooler air, sensible heat transfer occurs, causing the water to cool (Hasan, 2012). Evaporative cooling accounts for the majority of heat transfer to the air, with sensible heat accounting for just roughly a quarter of the total (Anbazhaghan *et al.*, 2021). A counter-flow cooling tower is seen in Figure 1 (Mulyandasari, 2011).

Shah and Rathod (2012) did thermal design of an industrial cooling tower and determination of all performance parameters with provided intake and exit circumstances and many potential losses. They discovered that as the air flow rate increases, cooling tower performance increases, while cooling tower characteristics decrease as the water to air mass ratio rises.

Pushpa *et al.* (2014) adjusted the water input temperature, air inlet temperature, and water mass flow rate, the performance of a cooling tower in a thermal power plant was investigated. It was discovered that raising the water input temperature, air inlet temperature, and water mass flow rate boosts cooling tower efficiency while decreasing it.

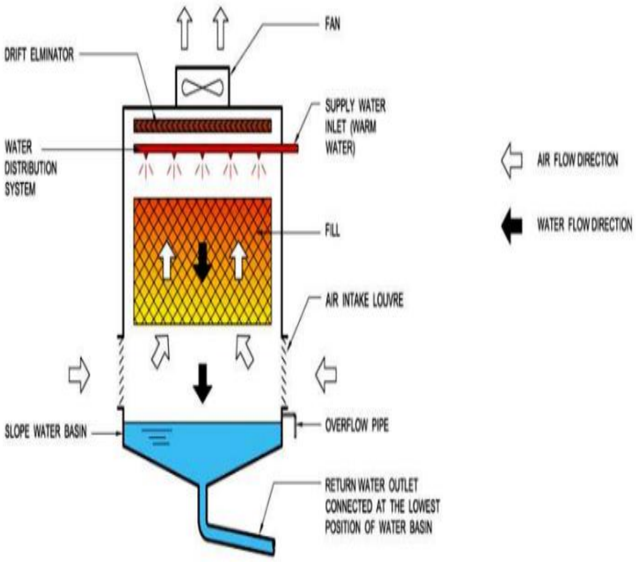

Figure 1: Schematic of a Typical Counter Flow Cooling tower

Murugaveni and Shameer (2015) investigated a forced draft cooling tower by altering air inlet parameters and air inlet angles in both the horizontal and vertical directions. The cooling tower model was created in Solid works 2013, and it was meshed with ICEM CFD 14.5 software, and the mesh models were analyzed with FLUENT software. Based on the temperature contours collected, it was discovered that when the air inlet angle increases, the water exit temperature rises, resulting in a loss in effectiveness.

Chopra and Kumar (2017) performed analysis on a counterflow cooling tower using CFD software. The model was built in CREO and then meshed and analysed in ANSYS 12.1. The optimization was carried out by changing three parameters at the same time: inlet water flow rate, inlet air rate, and fills porosity, and using the Taguchi method. They discovered that cooling towers function best when the water mass flow rate is low, the air mass flow rate is high, and the fill porosity is 50%.

Chitale *et al.* (2018) in their study, they developed a precise approach for designing a counter-flow cooling tower based on input process parameters and taking into account several sorts of probable losses. The performance of the planned cooling tower was then evaluated using CFD software.

ANSYS 16.1 Software was used to mesh and analyze the model. They researched and found that as the angle of the air inlet increases in either direction, the temperature of the exit water rises, reducing cooling efficacy.

Kumar and Mathew (2018) in their research showed that the performance of cooling towers can be improved by raising the mass flow rate of air, according to a research paper. All performance parameters improved, including cooling water range, efficacy, and tower characteristic ratio. The efficiency of the cooling tower rose by about 20%. The result was good when the (L/G) ratio was reduced from 3.25 to 2.60. The cooled water's output temperature was decreased to 2K. When the influence of inlet water temperature on cooling tower performance was investigated while other parameters such as mass flow rate, injection height, and fill area were held constant, it was discovered that effectiveness decreased by 8%. The influence of water mass flow rate was also investigated, and it was discovered that by optimizing both water and air mass flow rates, efficacy can be increased. However, lowering the mass flow rate of water lowers the cooling tower's output, and the temperature of the incoming water is dependent on the plant's operations.

Wordu and Nsin (2021) focused on the design criteria for typical cooling water–pond size of capacity 10,000 gallons/min equivalent (630.8 of L/s) of water from 48.9 to 32.2^0 C in a spray-type cooling pond if the average wet-bulb temperature is 15.6^0 C (288.6K) was designed with specific parameters to give 10,000 gallon/min (50 gallon/min per nozzle) giving rise to 200 nozzles, for 6 nozzles totaling 33.33 sprays, approximating to 34 spray to compensate for partial spray group, surface area required was found to be $1858m^2$, spray pond dimensions overall length was found to be 79.2 meters, water depth in the pond ranged from 0.6 to 0.9 meters, and length of header was 62.2 meters for each header for 17 headers gave 1057.4 meters. The overall width of the cooling water pond was 25.9 meters. Finally, the total pumping-head expressed in meters of water i.e., static-head + friction head + required nozzle head was 14.8 meters of water equivalent to 145.0 kPa delivering pressure. For purpose of allowance a pump having a total head of at least of water 15.2 meters was advised to be chosen for the process operations.

Wordu and Fredrick (2021) the research, which was focused on the development of four models to explain the performance of a cross flow cooling tower and then simulated using MATLAB. These models are given as follows (Wordu & Fredrick, 2021):

$$T_{w2} = \frac{F_A \rho_A Cp_A}{F_w \rho_w Cp_w}(T_{A1} - T_{A2}) + T_{w1} \quad (1)$$

$$V_c = \frac{H_L V_{s1}}{[H_{a2} - H_{a1}] - [(W_2 - W_1)] \times Cp_A T_{A2}} \quad (2)$$

$$n = \frac{T_{A1} - T_{A2}}{T_{A1} - WBT} \quad (3)$$

Where; WBT = wet bulb temperature

$$Q_A = V_c \rho Cp_A T_{A2} \quad (4)$$

On simulation these where discovered:

i. It was seen that there is a decrease in the outlet temperature of the water [Outlet Temperature of Water (T_{w2})] correspondently to the increase in the independent variable which is the exit air temperature [Outlet Temperature of Air (T_{A2})], which correlate with the fact that any increase in the outlet temperature of the independent variable alternatively increases the cooling rate of the water sent through the cooling tower hence promoting the functionality of the cooling tower.

ii. Increase in T_{A2} of the system brings pseudopodia increase in the Velocity cooling rate (Vc) of water in the system, which could be explained as the increase in the temperature of the outlet air comes as a result of heat transfer from water to air via convection and conduction which in turns leads to the reduction in the temperature of the water over contact time.

iii. Increase in the T_{A2} of the system brings a direct proportional increase in the rate of process cooling efficiency (n) of the system over contact time, this proves the functionality of the developed model on the cooling tower process with respect to the operative parameters.

iv. Increase in the heat gained by exit airQ_A of the system brings a direct proportional increase in the rate of process cooling efficiency (n) of the system over contact time, proves the functionality of the developed model on the cooling tower process with respect to the operative parameters with bases that a cooling system or tower operation at $n = 30\%$ efficiency will exit to the environment thermodynamically a heat value of $Q_A = 0.3652$, hence the increase in the system efficiency leads to promote the eco-heating of the environment due to the increase in the Outlet Temperature of Air [T_{A2}] with respect to the model equation.

This study was aimed at evaluating the performance of a counter flow wet cooling tower and this was achieved through the following objectives:

i. By simulating an existing cooling tower model using Latin Square Design and Microsoft Excel to ascertain the performance of a cooling tower

ii. Optimizing by varying the water inlet temperature, water inlet flow rate, air inlet flow rate and air outlet temperature using Latin Square Design to ascertain the best working performance of a cooling tower

iii. By studying the effect of the water inlet temperatures, water inlet flow rates, air inlet flow rates and air outlet temperatures on the Range and efficiency of a cooling tower.

2. MATERIALS AND METHODS

Modelling and simulation are used to get the design equations for any chemical engineering system, for a variety of reasons, either physical modelling or mathematical modelling and simulation can be utilized; nevertheless, mathematical modelling and simulation is preferred since it can be reduced to obtain the system's design performance equations. Latin Square Design and Excel was used to simulate an existing cooling tower model. Also, optimization was carried out using Latin Square Design by varying some parameters which includes; water inlet temperature, water inlet flow rate, air inlet flow rate and air outlet temperature to ascertain the effectiveness of the cooling tower.

Assumptions

i. The cooling tower was assumed to be in a steady state, when the calculations were carried out.

ii. The properties of the hot and cold streams are considered to be equivalent to the properties of the steams at their average temperature.

iii. A viscous fluid has a viscosity that is much higher than that of water.

iv. Assume a constant rate of heat transmission throughout the cooling tower (perfectly insulated).

Table 1: Process data for simulation

Parameters	Values
L	300 kg/h
T_{A1}	84.2 ^{o}F
WBT	80.6 ^{o}F
H_{a1}	43.57 Btu/Ib
H_{a2}	50.47 Btu/Ib
G	500 kg/h
T_{A2}	122 ^{o}F
T_{w1}	158 ^{o}F

Source: (Ataei *et al.*, 2008;Keshtkar, 2017; Murugaveni & Shameer, 2015; Ovat & Anyandi;

Ramkrishnan & Arumugam, 2013; Ramkumar & Ragupthy, 2011, 2015)

Optimization using Latin Square Design

A	B	C	D
B	A	D	E
C	D	E	A
D	E	B	C

Table 2: Water inlet temperature T_1

T°C	T°F
60	140
70	158
80	176
90	194

It is not possible to keep the temperature of the air exiting the cooling tower constant, but is very possible to keep the inlet temperature of the air running through the cooling tower constant, hence the temperature of the outlet water at variant exit temperature of the air was studied with an expectation that the outlet water temperature will increase with respect to the increase in the air outlet temperature

Table 3: Air inlet temperature T_{A1} (^{0}C to ^{0}F) and itsenthalpy atthe wet bulb temperature (T_{wt} = 27^{0}C => 80.6^{0}F)

T°C	T°F	H_1 (Btu/lb)
29	84.2	43.57

Table 4: Air outlet temperature T_{A2} (^{0}C to ^{0}F) and Enthalpy at those temperatures

T°C	T°F	H_2 (Btu/lb) @ 30^{0}C (86^{0}F)
40	104	50.50
45	113	50.49
50	122	50.47
55	131	50.46

Psychometricis a field of study concerned with the theory and technique of measurement. The psychometric calculator is a software that assist in estimating the properties of moist air**.** We can define humid or moist air conditions using the temperature parameters like the wet bulb temperature, dry bulb, and dew point temperature**.** In addition, the specific humidity and relative humidity are also useful to convey the condition of air and weather. Psychometric chart can as well be used to determine the above properties The enthalpies were gotten using a psychometric calculator.

2.1 Models Solution Techniques

(i) $$T_2 = T_1 - \frac{G}{L}(h_2 - h_1) \quad (5)$$

Where:
T_1 = Inlet water temperature (hot water), ^{o}C
T_2 = Outlet water temperature (cold water), ^{o}C G = Mass flow rate of the inlet air, kg/h
L = Mass flow rate of the inlet water, kg/h
h_1 = Enthalpy of the inlet air (cold air), Btu/lb
h_2 = Enthalpy of the outlet air (hot air), Btu/lb

(ii) $$CoolingTowerEfficiency(\eta) = \frac{T_1 - T_2}{T_1 - T_{wb}} \quad (6)$$

Where, T_{wb} = Wet bulb temperature, ^{o}C

(iii) Model Optimization design

Figure 2 shows the design and arrangement of four variables (inlet water temperature, inlet air flow rate, inlet water flow rate and outlet air temperature) which were varied in 16 different mediums to generate 256 data of the cooling water temperature (T_2) of the cooling tower to ascertain its best working performance.

The first solution model (Equation 5), an existing cooling tower model was simulated and also, inserted into the third solution model by varying four set of parameters in it, such as; water inlet temperature (T_1), outlet temperature of air which was converted to enthalpy (h_2), water mass flow rate (L) and air mass flow rate (G) to ascertain the best working performance of the system. Model 2 was used to calculate the efficiency of the system.

The data in Table 1 would be used in the mathematical model simulation. Some set of data in Figure 2, like the water inlet temperature, water inlet flow rate, air inlet flow rate and the air outlet temperature were also varied to see if there would be changes in the results.

3. RESULTS AND DISCUSSION

This section presents the findings of the cooling tower simulation and optimization using Latin Square Design and excel. The effect of inlet water temperature on the cooling tower efficiency, that of the Liquid/gas flow rate (L/G) on the inlet water temperature and ascertaining the best inlet temperature of water and the outlet temperature of air that is best fit for the process. Figure 3, 4, 5, 6, 7, 8, 9 and 10 contains the 3D surface plot, plotted from the data calculated using the existing cooling tower model (Equation 5) and Latin square design for the purpose of optimization. Table 5, 6, 7 and 8 contains the result of relationship between the outlet air temperature of a cooling tower and that of the outlet water temperature when the inlet liquid to gas flow ratio and inlet air temperature are kept constant at a particular water inlet temperature.

3.1 Model Optimization Results from Latin Square Design

The 3D surface plot shows the optimization result of the dependent variable (water outlet temperature) against the independent variable (water inlet temperature), liquid/gas flow ratio, gas flow rate (kg/h) and liquid flow rate (kg/h) which was plotted to obtain the points at which response value is optimum. This will help in subsequent experiment to obtain a maximum desired product. Fig 3 – 10 shows the 3D surface plot of the water outlet temperature (^{0}C) against the water inlet temperature (^{0}C), liquid/gas flow rate ratio, gas flow rate (kg/h) and liquid flow rate (kg/h). This showed that the optimum water outlet temperature of a cooling tower is gotten at a low water inlet flow rate and a high air inlet flow rate.

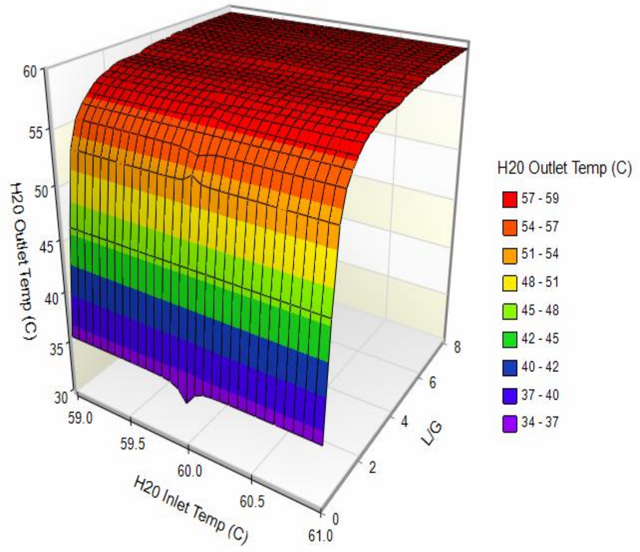

Figure 3: 3D surface plot of water outlet temperature (°C) against water inlet temperature (⁰C) and the liquid/gas flow ratio for an inlet temperature of 60°C

Figure 3 shows that the optimum value of the water outlet temperature between 34 – 37 (°C) was obtained when the range of the water inlet temperature was between 59.5 – 60.5 (°C) and the liquid/gas flow ratio was between 0 – 2.

Figure 4 shows that the optimum value of the water outlet temperature between 33 – 36 (°C) was obtained when the range of the gas flow rate (kg/h) was between 600 – 800 and the liquid flow rate (kg/h) was between 0 – 200.

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	Type	M 1	M 2	M 3	M 4	M 5	M 6	M 7	M 8	M 9	M 10	M 11	M 12	M 13	M 14	M 15	M 16
H_2O Inlet Temp T_1 (^{0}C)	60	60				60				60				60			
	70		70				70				70				70		
	80			80				80				80				80	
	90				90				90				90				90
Gas Flow rate (kg/h)	100	100						100						100			
	300		300				300		300				300		300		
	500			500		500				500		500				500	
	700				700						700						700
Liquid Flow rate (kg/h)	700	700				700				700				700			
	500		500				500				500				500		
	300			300				300				300				300	
	100				100				100				100				100
Air Outle TempT_2(^{0}C)	40	40	40	40	40												
	45					45	45	45	45								
	50									50	50	50	50				
	55													55	55	55	55

Figure 2: Model Optimization Design

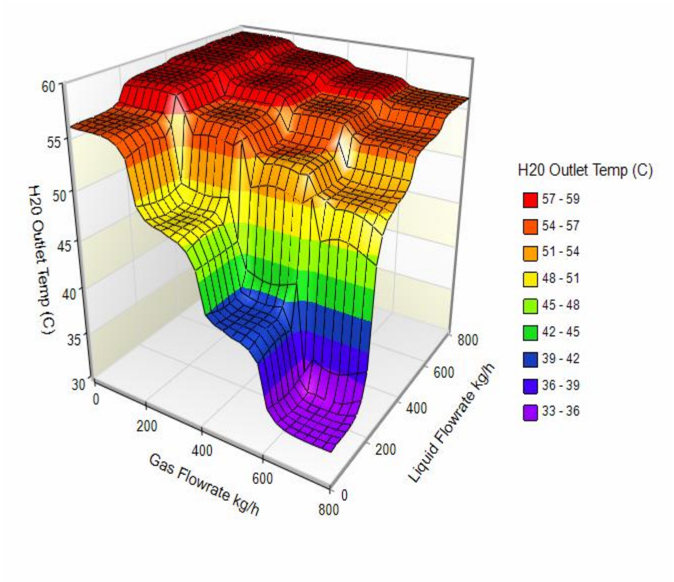

Figure 4: 3D surface plot of water outlet temperature (^oC) against gas flow rate (kg/h) and the gas flow rate (kg/h) for an inlet temperature of 60^oC

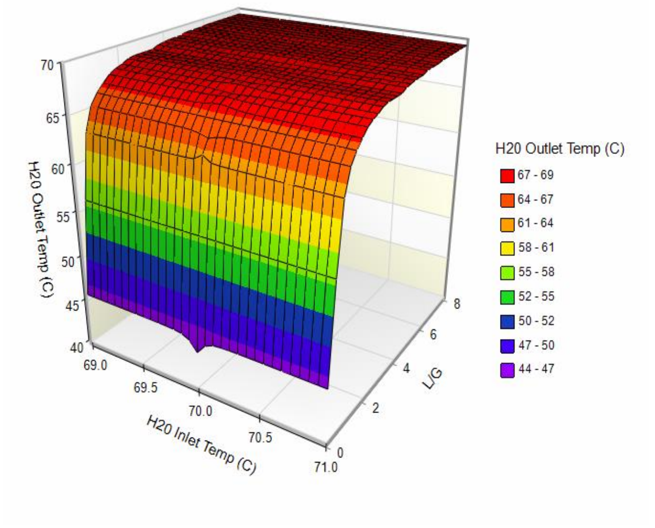

Figure 5: 3D surface plot of water outlet temperature (^oC) against water inlet temperature (^oC) and the liquid/gas flow ratio for an inlet temperature of 70^oC

Figure 5 shows that the optimum value of the water outlet temperature between 44 – 47 (^oC) was obtained when the range of the water inlet temperature was between 69.5 – 70.5 (^oC) and the liquid/gas flow ratio was between 0 – 2.

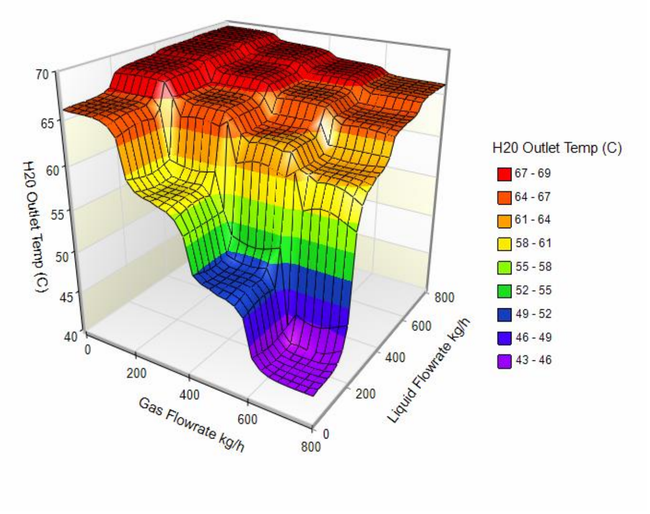

Figure 6: 3D surface plot of water outlet temperature (^oC) against gas flow rate (kg/h) and the gas flow rate (kg/h) for an inlet temperature of 70^oC

Figure 6 shows that the optimum value of the water outlet temperature between 43 – 46 (^oC) was obtained when the range of the gas flow rate (kg/h) was between 600 – 800 and the liquid flow rate (kg/h) was between 0 – 200.

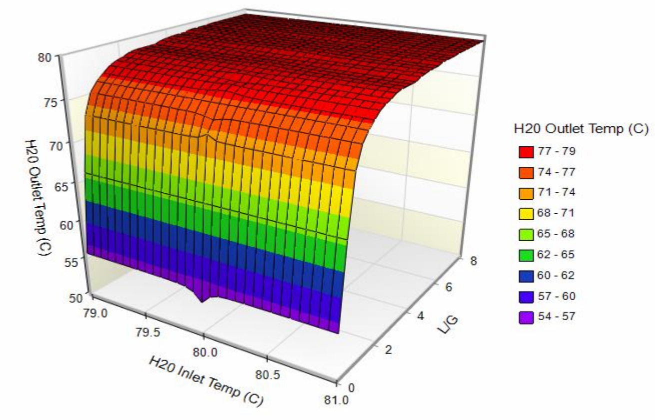

Figure 7: 3D surface plot of water outlet temperature (^0C) against water inlet temperature (^0C) and the liquid/gas flow ratio for an inlet temperature of 80^0C

Figure 7 shows that the optimum value of the water outlet temperature between 54 – 57 (^oC) was obtained when the range of the water inlet temperature was between 79.5 – 80.5 (^oC) and the liquid/gas flow ratio was between 0 – 2.

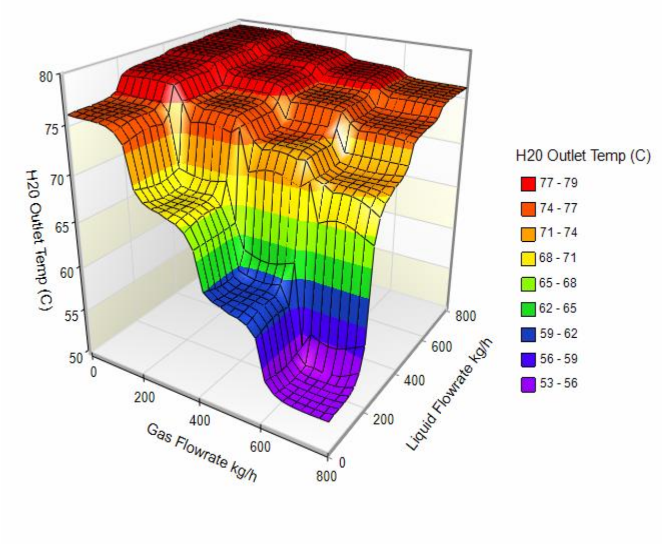

Figure 8: 3D surface plot of water outlet temperature (^{o}C) against gas flow rate (kg/h) and the gas flow rate (kg/h) for an inlet temperature of $80^{o}C$

Figure 8 shows that the optimum value of the water outlet temperature between 53 – 56 (^{o}C) was obtained when the range of the gas flow rate (kg/h)is between 600 – 800 and the liquid flow rate (kg/h) was between 0 – 200.

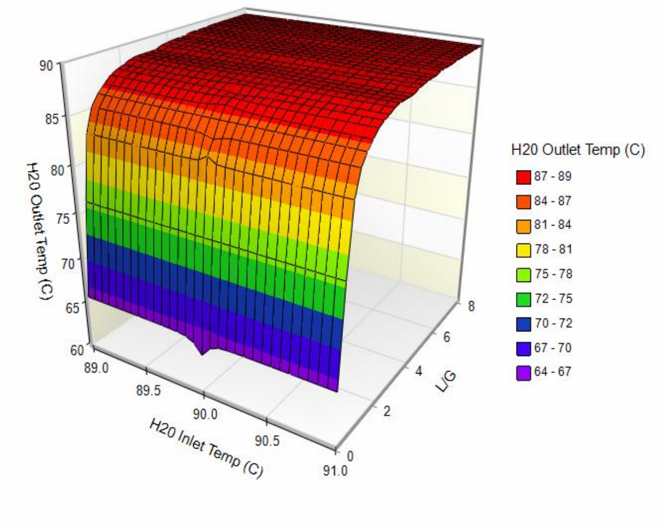

Figure 9: 3D surface plot of water outlet temperature (^{o}C) against water inlet temperature (^{0}C) and the liquid/gas flow ratio for an inlet temperature of $90^{o}C$

Figure 9 shows that the optimum value of the water outlet temperature between 64 – 67 (^{o}C) was obtained when the range of the water inlet temperature was between 89.5 – 90.5 (^{o}C) and the liquid/gas flow ratio was between 0 – 2.

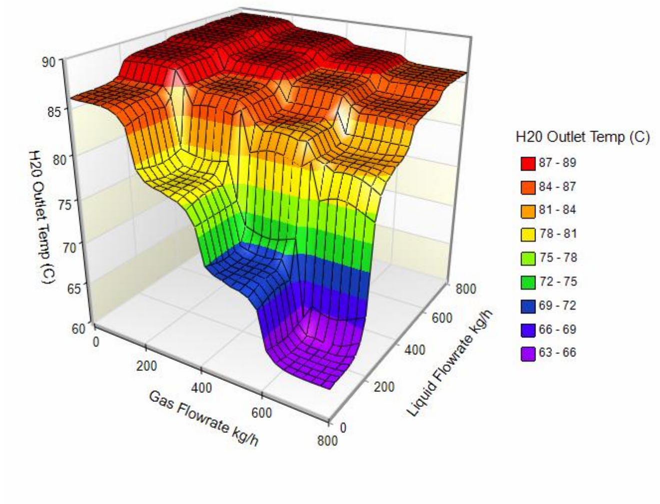

Figure 10: 3D surface plot of water outlet temperature (^{o}C) against gas flow rate (kg/h) and the gas flow rate (kg/h) for an inlet temperature of $90^{o}C$

Figure 10 shows that the optimum value of the water outlet temperature between 63 – 66 (^{o}C) was obtained when the range of the gas flow rate (kg/h)is between 600 – 800 and the liquid flow rate (kg/h) was between 0 – 200. Ramakrishnan and Arumugam (2013) in their experimental investigation, found that cooling tower's effectiveness is higher in the lower L/G ratio and sharply reduced with an increase in the L/G ratio, just as seen in Figure 3 to 10 of this research. When the L/G ratio is smaller, more air comes into contact with less water. The amounts of air and water are reversed in larger L/G ratios, though. Consequently, smaller L/G ratios result in improved cooling tower efficiency.

Kong *et al.* (2019) in their study with the input water temperatures of 32, 35, and 38 °C, showed how the cooling water range, R, varies with the water/air mass flow ratio, L/G. The cooling water range rapidly narrows with rising L/G for all inlet

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water temperatures, as was evident from the data. Additionally, it was found that the cooling water range increases as the inlet water temperature rises while maintaining the same water-to-air mass flow ratio and that the decrease is more pronounced at higher inlet water temperatures than at lower ones. Aside from that, the variation in cooling tower efficiency (e) with water/air mass flow ratio (L/G) at input water temperatures of 32, 35, and 38°C was also shown. For all intake water temperatures, it was noted that the cooling tower efficiency falls as the water/air mass flow ratio rises. The lowest values of L/G, which actually pertain to the optimal cooling of the flowing water, have higher efficiency. However, for the same water/air mass flow ratio, better efficiencies are obtained at higher inlet water temperatures under similar ambient air and operational parameter circumstances.

However, the result summary of this research work tally with that of Kong *et al.* (2019) except for these two statements ‘‘cooling water range increases as the inlet water temperature rises while maintaining the same water-to-air mass flow ratio and for the same water/air mass flow ratio, better efficiencies are obtained at higher inlet water temperatures under similar ambient air” which this research had an opposite result looking at Figure 11, 12, 13 and Table 9.

Table 5 – 8 shows the relationship between the outlet air temperature of a cooling tower and that of the outlet water temperature when the inlet liquid to gas flow ratio and inlet air temperature are kept constant at a particular water inlet temperature. This was done at different inlet water temperature (60, 70, 80 and 90^{o}C) and that of outlet air temperature (40, 45, 50 and 55^{o}C). The test was carried out varying the four-outlet air temperature at a particular inlet water temperature and liquid to gas flow ratio to see the effect on the outlet water temperature of the cooling tower. It can be seen from the Table 5, 6, 7 and 8 below that the outlet water temperature increases as the outlet air temperature increases correspondently. This implies that the efficiency or performance of the cooling tower decreases as the outlet air temperature of the cooling tower increases.

Table 5: Relationship between the outlet air temperature and outlet water temperature of the cooling tower when the inlet air temperature and the liquid to gas ratio (L/G) was kept constant for an inlet temperature of 60^{o}C

S/N	L/G	Inlet Temp T_1 (^{o}C)	h_2	h_1	Outlet Temp T_2(^{o}C)
1	0.142857	60	50.50	43.57	33.05
2	0.142857	60	50.49	43.57	33.08889
3	0.142857	60	50.47	43.57	33.16667
4	0.142857	60	50.46	43.57	33.20556

Table 6: Relationship between the outlet air temperature and outlet water temperature of the cooling tower when the inlet air temperature and the liquid to gas ratio (L/G) was kept constant for an inlet temperature of 70^{o}C

S/N	L/G	Inlet Temp T_1 (^{o}C)	h_2	h_1	Outlet Temp T_2(^{o}C)
1	0.142857	70	50.5	43.57	43.05
2	0.142857	70	50.49	43.57	43.08889
3	0.142857	70	50.47	43.57	43.16667
4	0.142857	70	50.46	43.57	43.20556

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Table 7: Relationship between the outlet air temperature and outlet water temperature of the cooling tower when the inlet air temperature and the liquid to gas ratio (L/G) was kept constant for an inlet temperature of 80ºC

S/N	L/G	Inlet Temp T_1 (ºC)	h_2	h_1	Outlet Temp T_2(ºC)
1	0.142857	80	50.5	43.57	53.05
2	0.142857	80	50.49	43.57	53.08889
3	0.142857	80	50.47	43.57	53.16667
4	0.142857	80	50.46	43.57	53.20556

3.2 Cooling water range and cooling tower efficiency:

The cooling efficiency of the counter-flow wet cooling tower is usually evaluated by the heat exchange efficiency η, which can measure the degree of evaporative cooling in the cooling tower. Heat exchange efficiency is determined as the ratio of actual to maximum water temperature drop:

$$\eta = \frac{T_1 - T_2}{T_1 - T_{wb}}$$

In the formula above, the inlet temperature of the spray water T_1 and the inlet wet bulb temperature of the air T_{wb} are the main factors affecting the cooling efficiency of the cooling tower.

Table 8: Relationship between the outlet air temperature and outlet water temperature of the cooling tower when the inlet air temperature and the liquid to gas ratio (L/G) was kept constant for an inlet temperature of 90ºC

S/N	L/G	Inlet Temp T_1 (ºC)	h_2	h_1	Outlet Temp T_2(ºC)
1	0.142857	90	50.5	43.57	63.05
2	0.142857	90	50.49	43.57	63.08889
3	0.142857	90	50.47	43.57	63.16667
4	0.142857	90	50.46	43.57	63.20556

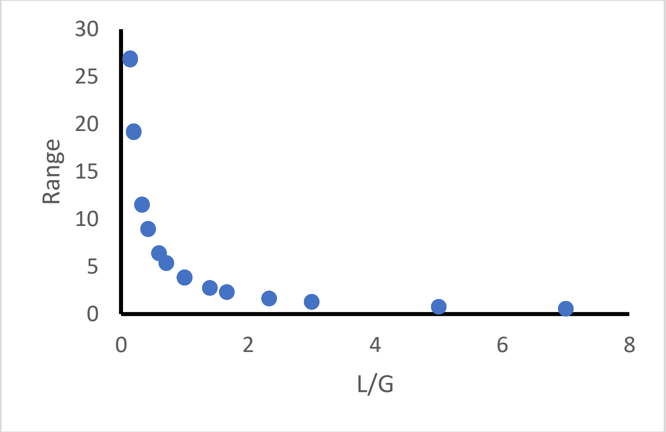

Figure 11: Plot of cooling tower Range against the liquid/gas flow rate ratio

Figure 11 shows the variation of the cooling water range, *R*, with the water/air mass flow ratio, L/G, for an inlet water temperature of 60, 70, 80, and 90ºC. It is apparent from Figure 11 that the cooling water range decreases gradually with an increase in the L/G mass flow ratio for all inlet water temperatures. The reason for this change trend can be included as the increase of L/G mass flow ratio enables the per unit mass of inlet air stream to contact with more volume of spray water inside the cooling tower and the increase of the heat exchange resistance on the water side weakens the effect of contact heat transfer and the evaporation heat transfer at the same time.

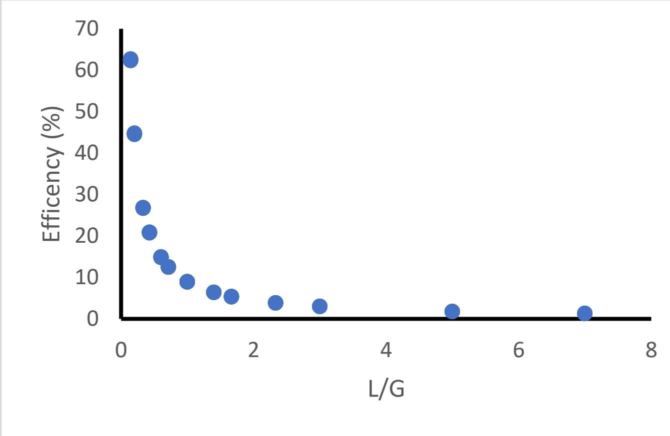

Figure 12: Plot of efficiency against liquid/gas flow rate ratio

Figure 12 shows the variation of the cooling tower efficiency, η, with the water/air massflow ratio, L/G, for an inlet water temperature of 60, 70, 80 and 90°C. It was observed that the cooling tower efficiency increases with increasing the water/air mass flow ratio for all inlet water temperatures. The efficiency is higher for the lowest values of L/G, which in fact refers to the best cooling of the circulating water.

Table 9: Maximum efficiencies of the optimized inlet temperatures

S/N	Inlet Temp. (°C)	L/G	Efficiency (%)
1	60	0.142857	81.66667
2	70	0.142857	62.67442
3	80	0.142857	50.84906
4	90	0.142857	42.77778

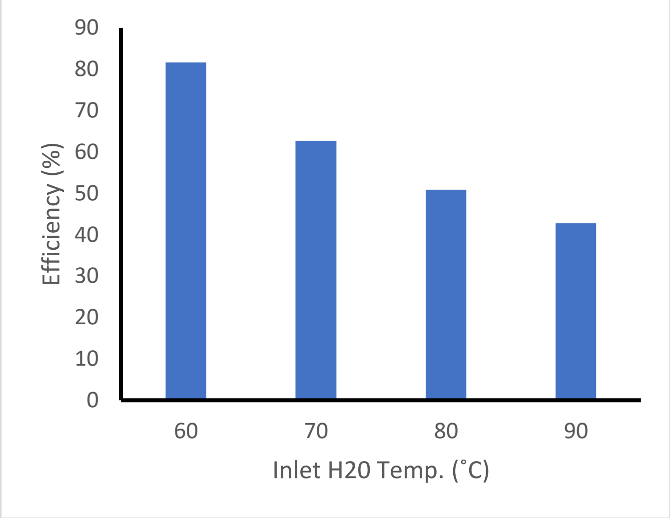

Figure 13: Plot showing the effect of water inlet temperature (°C) on the efficiency

However, under similar conditions of ambient air and operating parameters, higher efficiencies are obtained at lower inlet water temperatures for the same water/air mass flow ratio. Such evolution can be attributed to the efficiency formula, it can be seen from Figure 13 and Table 9 that the lower the inlet temperature, the higher the efficiency of the cooling tower when the inlet water temperature and the inlet air wet bulb temperature is certain, that is, for the same inlet conditions, the greater the range of the cooling water, *R*, the higher the efficiency of cooling tower. Also, from the above analysis of the variation rule of the cooling water range, the cooling water range decreases with increase in the water/air mass flow ratio, the efficiency of cooling tower decreases too.

4. CONCLUSION

Performance evaluation of counter flow wet cooling tower using Latin Square Design was investigated, the following conclusions was made:

i. The cooling water range, *R* and the cooling tower efficiency, η, decrease with the increase in water/air mass flow ratio, *L*/*G*. The higher values of *R* and η are obtained at lower values of *L*/*G*.
ii. The outlet water temperature T_2 increases correspondently with the decrease in the

outlet temperature of air T_{A2}, which correlate with the fact that any increase in the outlet temperature of air alternatively decreases the cooling rate of the water sent through the cooling tower.

iii. The best water cooling was obtained at low inlet water temperature, low water mass flow rate and high airmass flow rate.

iv. Higher efficiencies were obtained at lower inlet water temperatures for the same water/air mass flow ratio.

v. The greater the range of the cooling water, *R*, the higher the efficiency of cooling tower.

Most research on cooling tower focused on software like MATLAB, ANSYS, etc., for simulation and optimization. However, this study has proven that Latin Square Design and Microsoft Excel can be used for cooling tower simulation and optimization to ascertain the best working performance of the cooling tower.

5. RECOMMENDATIONS

The following recommendations are submitted to further enhance the studies of the performance of a wet cooling tower:

i. The analysis should be carried out by simultaneous varying of four parameters; inlet water flow rate, inlet air rate, fills types (material) and fills porosity.

ii. Investigation should be carried out on the effect the air inlet angle has on the outlet water temperature and the cooling tower effectiveness.

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NOMENCLATURE

Symbol	Definition	Unit
R	Range	°C
WBT, T_{wB}	Wet bulb temperature	°C, °F
T_{w2}, T_2	Water outlet temperature	°C, °F
T_{w1}, T_1	Water inlet temperature	°C, °F
T_{A2}	Air outlet temperature	°C, °F
T_{A1}	Air inlet temperature	°C, °F
η	Efficiency of the Cooling tower	-
L	Water inlet flow rate	kg/h
G	Air inlet flow rate	kg/h
L/G	Water to air mass flow ratio	