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Design and Construction of a Laboratory Scale Cooling Tower

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***Abstract**: Developing a full-scale system for experimentation has various problems, including greater complexity, high production costs and the possibility of errors when compared to smaller versions. This study presents the design and construction of a laboratory scale counter flow cooling tower, which may be used to test and analyze cooling tower effectiveness in controlled conditions. The approach employed in this study included developing the conceptual design of the cooling tower, doing design calculations and drawings, as well as constructing and evaluating the equipment. The functionality of the cooling tower was tested to identify the effect of flow parameters on its effectiveness. A 40-watt fan was required to deliver 0.066 kg/s air through the cooling tower to produce a total heat transfer of 3,600 kJ/kg across the hot water as well as the air stream, enabling the heat flux of the stream of air to rise from 28.3 kJ/kg on entering to 47.3 kJ/kg on exiting. The performance analysis shows that when the overall flow rate of water increases, the cooling tower's efficiency often decreases. At higher flow rates, the water flows faster up the tower, shortening the contact period between water and air, limiting heat transfer and leading to lower tower cooling efficiency.*

Keywords- Approach, Heat exchanger, Heat transfer, Efficiency, Range, Air stream, Hot water and Cross Flow

1. INTRODUCTION

The primary function of cooling towers as a heat exchanger is to recover waste heat through industrial operations employing circulating water for a cooling agent. It operates on the concept of evaporative cooling, in which the fluid stream distributes the surplus energy of evaporation, causing cooling (Hawlader, 2023) [8]. Thermal engines, chemical reactions, heating and cooling systems, manufacturing processes, manufacturing facilities, crude oil refineries, distillation and a variety of additional chemical reactions are the principal sources of waste heat. The warm water that results from the extraction method is pumped throughout the towers via a closed-loop system as well as cooled with air contact and evaporation.
Recirculating the cooled water into the process requires less energy as well as fresh water (Yogesh et al., 2021) [13]. Cooling towers are employed as process optimization aid to maintain the optimum temperature, which is critical to numerous chemical processes. They guarantee the water utilized in these operations is at the correct temperature, avoiding overheating or chilling (Rosaler, 2005) [12]. The main purpose of cooling towers was to avoid releasing heat into the surrounding atmosphere; they are a vital component of thermal power plants since they provide a constant and reasonably affordable method of receiving heat from any process (Barile and Dengler, 2024) [2].
The lack of cooling towers within a steam-driven plant implies that a large amount of water must be drawn from an adjacent source of water (a sea or a lagoon) and pumped through a condenser before being discharged back into the sea during a relatively high temperature and these may harm aquatic life in the area (Klopper, 2023) [10]. Figure 1 shows the categories of cooling towers.

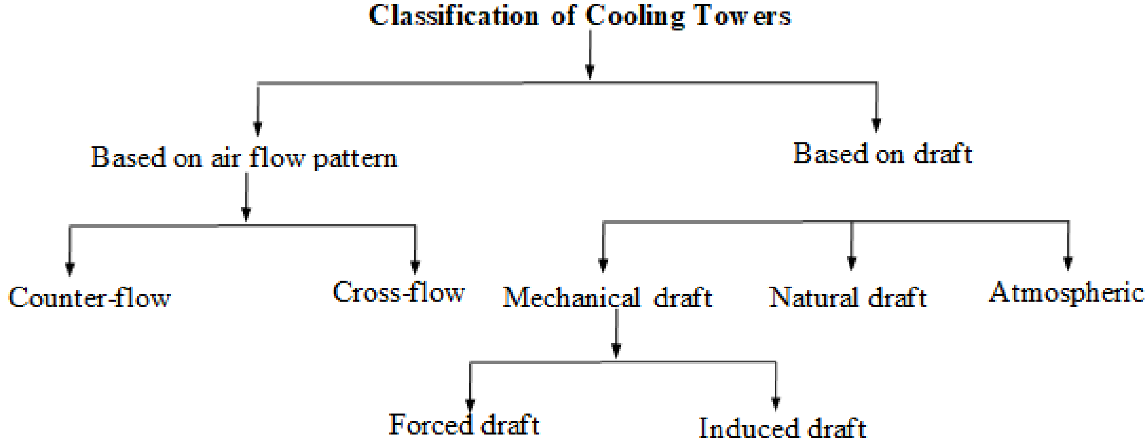

Figure 1: Classification of cooling towers.

One of the key features shared by all cooling tower layouts is the spraying of hot water at the highest point down vertically stacked drains, which is used to increase the air-water interface area. Air flows through the bottom within the tower, cooling the water by immediately transferring heat between the water to the atmosphere and evaporating a portion of it. Overall heat and mass transfer procedures are important in this cooling method because they affect the tower's overall cooling capability (Benton 2023) [4].

A laboratory size cooling tower might serve as a test rig, enabling researchers to investigate and evaluate the efficiency of an actual cooling facility under controlled conditions, by manipulating variables such as the water flow rate, air circulation velocity, along with cooling load to understand how these components influence the cooling effectiveness and other important variables, all in a smaller, more manageable setup rather than a full-scale industrial cooling tower. The measurements acquired from the laboratory model cooling tower could be scaled to predict the performance of a bigger industrial or commercial cooling tower with comparable design principles (Kroger, 2025) [11]. The laboratory setting allows for the testing of different cooling tower filling materials, spray nozzles configurations and air flow patterns in order to optimize design aspects. In comparison to testing using a full-scale cooling tower, the laboratory arrangement is typically less expensive and takes up less room. The purpose of this project was to design and construct an experimental cooling tower that can be used as a test rig apparatus.

EMPIRICAL REVIEW

Kelly (2016) [9] examined the heat transfer and pressure loss characteristics of splash grid-style coolant tower packaging. The researchers found that tower characteristics were influenced by parameters such as water-to-air proportion, packing height, decking design and though to a lesser degree, hot water temperature. They also correlated the water/air velocity with the tower's features. Furthermore, it was revealed that tower properties at a certain water-to-air proportion are unaffected by wet bulb temperatures and air loading, which extends beyond the airborne loading range used in industrial cooling towers.

El-Dessouky (2023) [6] evaluated the hydraulic and thermal capabilities of a three-phase fluid-bed cooling tower. The tower attributes, hot water entrance temperature, dynamic bed height and water/air mass circulation ratio were each linked using 12.7mm-diameter, 375 kg/m3 sponge balls manufactured of rubber as packaging.

Bedekar and Nithiarasu (2018) [3] performed an experiment to assess the effectiveness of a counter-flow packing bed cooling tower using film packing. Their findings were presented in terms of tower features, water output conditions, effectiveness and a measure of the liquid-to-air flow rate ratio (L/G). Their findings revealed that when that L/G ratio grows, tower performance decreases.

Adam et al. (2020) [1] studied the mass transmission along with pressure drop capabilities of various corrugated packing forms, including smooth and irregular surface perforated packaging in air-cooled towers. The investigation was conducted in a 0.15 m x 0.15 m counter-flow test unit with a packing altitude of 1.60 m. Considering their experimental results, they proposed a link between the packing's weight transfer ratio with pressure loss.
Goshayshi (2024) [7] investigated the entropy formation within a cooling tower along with showed that when heat transfer in a cooling tower section approaches homogeneity, its generated entropy is uniform and reaches its lowest value. In addition to proving that the production of entropy is strongest towards the tower's base and increases at its peak, Black et al. (1996) [5] created a model for forecasting the energy features of the water and air surrounding the cooling tower.

2. METHODOLOGY

This section explains the methodology used to design and build an experimental cooling tower.

Conceptual Design

Figure 2 displays a conceptual design for a counterflow cooling tower linked to a thermal power facility's condenser. A cooling tower located in a thermal power plant dissipates heat generated during the production of electricity process and reduces the power station's cooling water consumption by cooling the heated water discharged through the condenser and returning the cool water back to the condenser.

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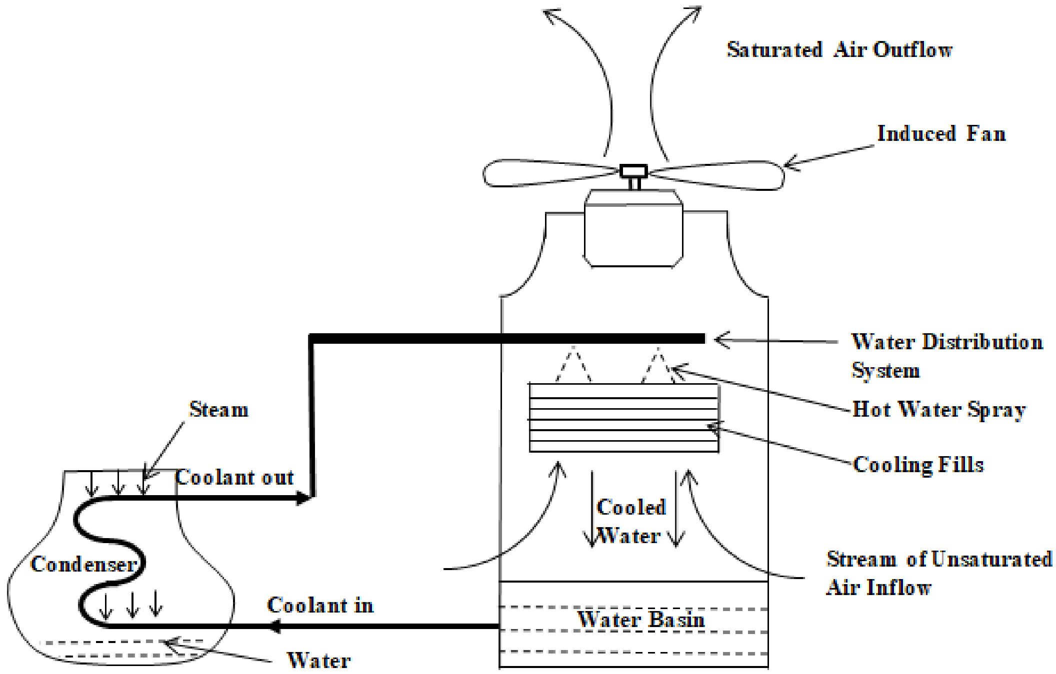

Figure 2: A cooling tower integrated to a condenser of a power plant.

Design Calculations
The design parameters are as follows:
The height of the cooling tower is 1.2 meters.
The diameter that defines the cooling tower is 0.9 meters.
Inlet temperature of cold air stream = 27ºC

The parameters to be calculated are as follow:

i) Enthalpy of Exiting Air

The enthalpy of outbound air is the total of the heat into the air exiting the cooling tower, which is more than what comes in due to the intake of water vapour via the cooling water.
Equation 1 calculates the enthalpy of leaving air.

$$h_{a2} = h_{a1} + \left[\frac{m_{wi}}{m_{ai}} \times [t_{wi} - t_{wo}]\right] \qquad (1)$$

h_{a2}: Enthalpy of incoming air
h_{a1}: Enthalpy of leaving air
m_{wi}: Mass flow rate of intake cooling water
m_{ai}: Mass flow rate of dry air
t_{wi}: Inlet temperature of the hot waters
t_{wo}: Outlet temperature of cold water

ii) Total Heat Transfer to Air

Cumulative temperature transmission from air within a cooling tower is the amount of heat energy passed from the water that circulates to the air moving through the tower, encompassing both latent and sensible heat that the surrounding air receives. This efficiently cools the water leaving the tower. Equation 2 presents a formula for calculating total heat transfer into air.

$$Q_a = m_{ai} \times [h_{a2} - h_{a1}] \qquad (2)$$

Q_a: Total heat transfer to air

iii) Heat Lost by the Hot Water

Equation 3 depicts the procedure of heat loss from hot water in a cooling tower, where just a little of the hot water cycling through the tower evaporate towards the air, cooling the water that remains as it absorbed heat energy.

$$Q_w = m_w[t_{wi} - t_{wo}] \quad (3)$$

Q_w: Heat lost by water
m_w: Mass flow of water entering the tower

iv) Pressure Drop

A cooling tower's pressure loss represents a decrease in water pressure as it passes through the tower due to friction with its internal components such as fill material and pipework. Equation 4 provides the formula underlying the pressure drop.

$$\Delta p = \frac{k\rho V^2}{2 \times g} \; lb/ft^2 \quad (4)$$

Δp: Pressure drop
k: Pressure drop coefficient (ranges from 0.1 – 0.3)
g: Acceleration due to gravity

v) Sizing of the Fan Power

Measuring fan energy in a cooling tower is the process of establishing the proper power rating required for the blade(s) inside a cooling tower to produce an ideal airflow rate. The formula used for calculating the draught system power required for a cooling tower is expressed as equation 5.

$$P = \frac{\Delta p v_i}{3600 \times 1000 \times \eta} \; kW \quad (5)$$

P: Fan power requirement
v_i: Volumetric efficiency of fan
η: Fan efficiency (between 0.75 – 0.85)

vi) Air Velocity

Air velocity in a cooling tower indicates the rate at which the air-vapor combination moves through the tower, or how quickly the air circulates around the cooling tower, this can lead to improved heat transfer and the effectiveness of cooling. Equation 6 calculates the air velocity from a blower fan in a cooling tower.

$$V = \frac{\pi DN}{60} \quad (6)$$

V: Velocity of air
D: Duct diameter

vii) Mass Flow Rate of Air Stream

The mass flow rate of the air stream is given by equation 7

$$m_a = \rho_a Q_a \quad (7)$$

m_a: Mass flow rate of air
ρ_a: Density of air

viii) Mass Flowrate of Hot Water

The mass flow rate of the hot water is given by equation 8

$$m_w = \frac{m_a c_a \theta_a}{c_w \theta_w} \quad (8)$$

m_w: Mass flow rate of water
m_a: Mass flow rate of air
c_w: Specific heat capacity of water
c_a: Specific heat capacity of air
θ_w: Temperature difference between the inlet hot and exit cold water in the cooling tower
θ_a: Temperature difference between the inlet cold and exit hot air in the cooling tower

Design Drawing

The exploded view of the design drawing of the laboratory scale cooling tower is shown in Fig. 3.

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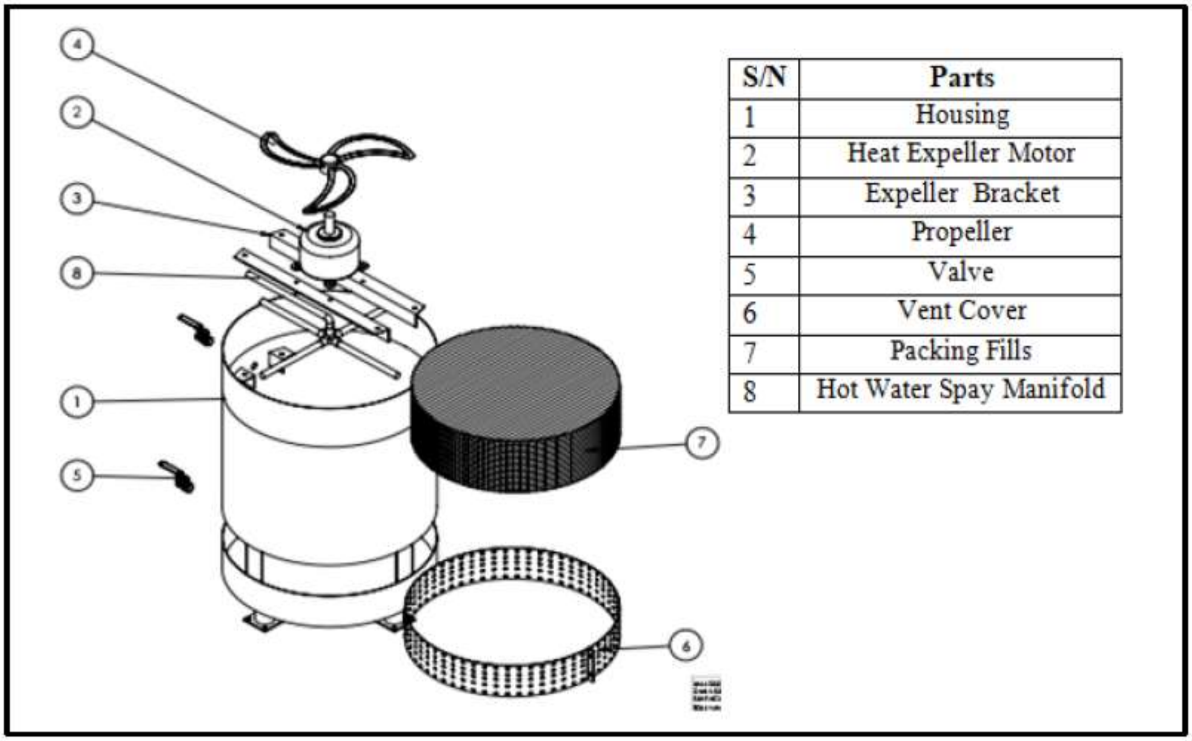

Figure 3: exploded view of the laboratory scale cooling tower

Materials/Equipment Selection and Construction of the Prototype
The process of choosing materials and equipment was carried out prior to the construction process.

Materials/Equipment Selection
The detail overview of components and materials selected for the construction of the equipment is provided in Table 1 while the equipment selection is given in Table 2.

Table 1: Materials Selection.

S/N	Components	Materials	Criterial
1	Water distribution line	PVP pipe	Durability, corrosion resistance, light weight and ease of installation
2	Nozzle	PVC shower	Durability, corrosion resistance, light weight and ease of installation
3	Hot water source	Plastic bucket	Durability, corrosion resistance.
4	Packing or fill material	Marine boards	Resistance to absorbing water
5	Tower inlet/outlet pipe	Carbon steel	High strength, durability, malleability and cost-effectiveness.

Table 2: Equipment Selection.

S/N	Equipment	Specification
1	Forced/Induce draft fan	4 Watts, 9–12-inch, 15 L/S
2	Hot water heater	Ring boiler (1200W)
3	Thermometer	infrared thermometer (20^oC ~ 160 ^oC)
4	Anemometer	Digital anemometer (0.4 m/s ~30 m/s
5	Sling pychrometer	Wet bulb and dry bulb temperature (-20^oC ~ 50 ^oC)

Construction of the Prototype

The cooling tower was constructed with major components such as packing material, a hot water source, a fan, a water circulation line, and a cold-water basin. This tower's design is counter-flow, resulting in water flowing into the fill and air flowing vertically up. Plate 1 and 2 show the exterior and interior views of the fabricated cooling tower, respectively.

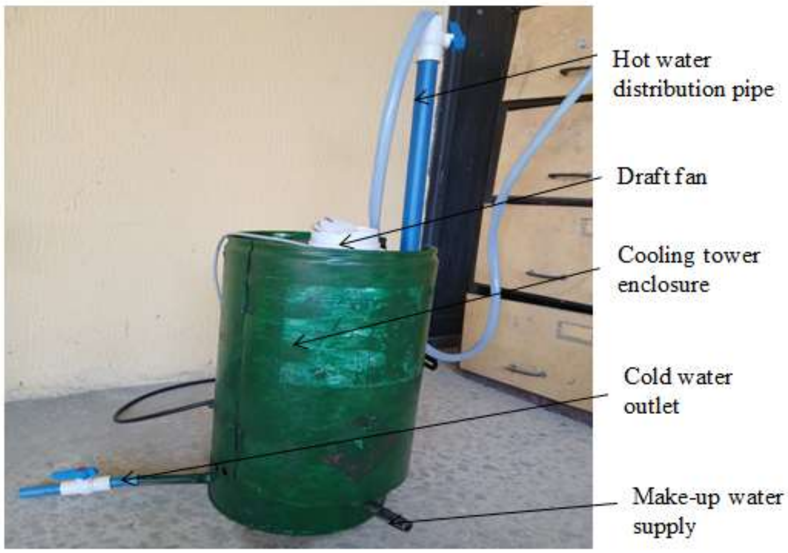

Plate 1: Exterior view of the cooling tower.

Plate 2: Interior View of the Cooling Tower.

Performance Assessment

The efficiency of a laboratory-scale cooling tower is frequently measured by measuring crucial parameters such as water circulation rate, input and exit temperatures, atmospheric damp bulb humidity degree and fan power (mechanical draft). To replicate the process's heat load, a typical heating element was used to heat a 20-liter volume of liquid from 26°C to 61°C at a barometer pressure

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of 101.32 kPa. The water was then allowed to run down through the packing fill after being sprayed from the nozzle at around 61°C. The mass flow rate was adjusted every five minutes, and the water's discharge temperature was tracked during each of the five successive time intervals of the experiment.

Performance Metrics

The following performance metrics were measured:

i) Cooling Range

Equation 9 estimates the cooling range, meaning the difference between the cooling building's water's initial and final temperatures.

$$R = t_{wi} - t_{wo} \qquad (9)$$

ii) Cooling Tower Approaches

The cooling tower approaches is the temperature difference between the cooling tower's outgoing temperature to the input air, as provided in equation 10:

$$\text{Tower approach} = t_{wo} - t_{wb} \qquad (10)$$

iii) Cooling Tower Efficiency

Equation 11 expresses the cooling tower efficiency.

$$\eta_{ct} = \frac{t_{wi} - t_{wo}}{t_{wo} - t_{wb}} \qquad (11)$$

η_{ct}: cooling tower efficiency
t_{wb}: wet bulb temperature of air

3. RESULTS AND DISCUSSION

Results of Design Calculations

Cooling tower design calculations include determining characteristics such as airflow rate, water supply rate, packing fills and dimensions in order to accomplish the required cooling ranges and approach. The findings of these calculations are then utilized to design and assess the tower's effectiveness by comparing estimated values to data from experiments. The key metrics include cooling temperature range, approach, efficiency and heat transfer rate. The design calculations are shown in Table 3.

Table 3: Results of Design Calculations.

S/N	Parameters	Symbols	Values/Units
1	Enthalpy of entry air	h_{a1}	28.3 kJ/kg
2	Enthalpy of exit air	h_{a2}	47.3 kJ/kg
3	Cooling capacity of tower	Cc	0.85 kW
4	Fan power	P	40 Watts
5	Total heat transfer	Q	3,600 kJ
6	Air velocity	V	5.2 m/s
7	Mass flow rate for the air stream	m_a	0.066 kg/s
8	Mass flow rate for hot water	m_a	0.0498 kg/s
9	Evaporation loss	Eva_{loss}	0.89%

In order to introduce 0.066 kg of atmospheric air through the cooling tower, a fan with a rate power of 40 watts was needed, resulting in an overall heat transfer of 3,600 kJ by the hot water to the air, raising the air's enthalpy from 28.3 kJ/kg at entry to 47.3 kJ/kg at exit. The evaporation rate is estimated to be 0.89%, necessitating a make-up water of approximately the same amount to replace the circulating water and ensure that it flows constantly throughout the tower.

Performance Test

The result of the performance test carried out on the cooling tower is shown in Table 4

Table 4: Performance Parameters and Metrics

S/N	Performance Parameters	Performance Metrics

	In-let Temp.	Out-let Temp.	Wet bulb Temp.	Mass Flowrate	Range	Approach	Efficiency
1	60ºC	48.7ºC	24ºC	0.015 kg/s	11.3ºC	24.7ºC	31.4
2	55ºC	43.8ºC	24ºC	0.013 kg/s	11.2ºC	19.8ºC	36.1
3	50ºC	39.2ºC	24ºC	0.011 kg/s	10.3ºC	15.2ºC	40.4
4	45ºC	35.8ºC	24ºC	0.011 kg/s	9.2ºC	11.8ºC	43.8
5	40ºC	32.9ºC	24ºC	0.013 kg/s	7.1ºC	8.9ºC	44.4
6	35ºC	30ºC	24ºC	0.011 kg/s	5ºC	6.0ºC	45.5

Table 4 shows that the cooling tower's best efficiency was 45.5% while the range and approach temperatures were 5ºC and 6ºC, accordingly. While the lowest efficiency occurred when the range and approach temperatures were 11.3ºC and 24.7ºC, respectively. This is due to the cooling tower's substantial mass flow rate, that usually boosts heat transfer and the capacity for cooling. However, it can also reduce cooling efficiency and raise running costs, while increased water flow rate improves heat exchange it also requires more energy to move the water. Overall the water might not be adequately cooled due to shorter contact time with the air, thus restricting evaporation overall heat transfer.

Performance Evaluation

The following performance evaluations were carried out:

i) Variation of Water Flow Rate Versus Outlet Temperature

Figure 4 shows a plot displaying the cooling water output temperature (°C) vs the total flow rate of water (m^3/s). The graph below shows that, the relationship between water's speed and output temperature may not necessarily be linear. The rise in temperature may be large at first as the flow rate increases, but the small rise in temperature gradually decreases while the fan speed stays constant.

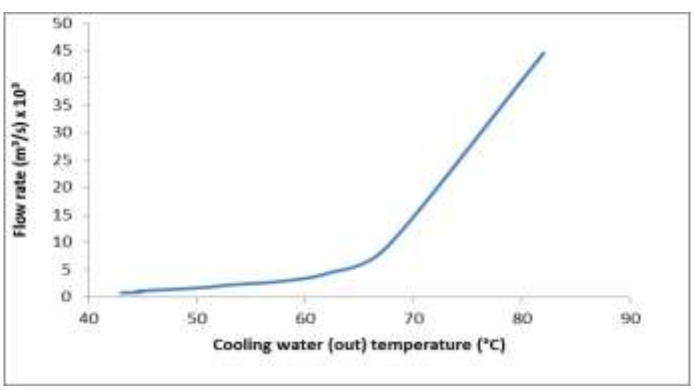

Figure 4: Variation of Water Flow Rate versus Outlet Temperature.

ii Variation of Air Velocity at Different Water Flow Rate Vs Cooling Effectiveness

Figure 5 indicates that increasing the velocity of air in the cooling tower usually boosts cooling efficiency, but raising water flow rate could initially increase cooling capacity yet may gradually decrease efficiency because of reduced contact time with air and water. The relationship is non-linear and is determined by the tower's individual design and operational conditions.

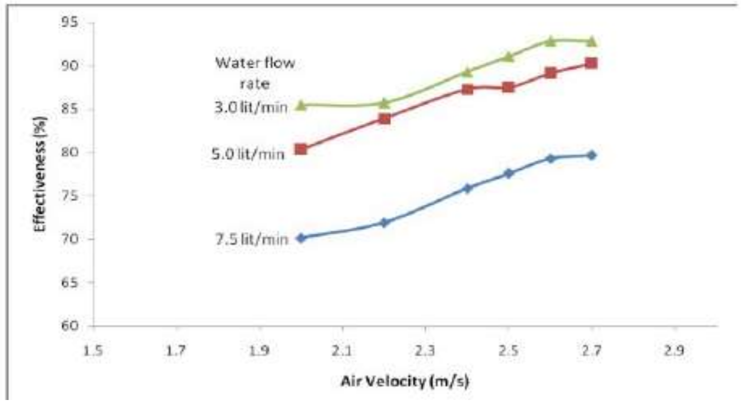

Figure 5: Cooling effectiveness vs air velocity at different water flow rate.

iii) Variation of Air Velocity at Different Mass Flow Rate Vs Cooling Capacity

Fig. 6 illustrates that increasing air velocity typically raises cooling capacity; especially, larger water circulation rates could indicate more hot water is moving via the tower, this can result in greater heat transfer and hence a higher capacity for cooling.

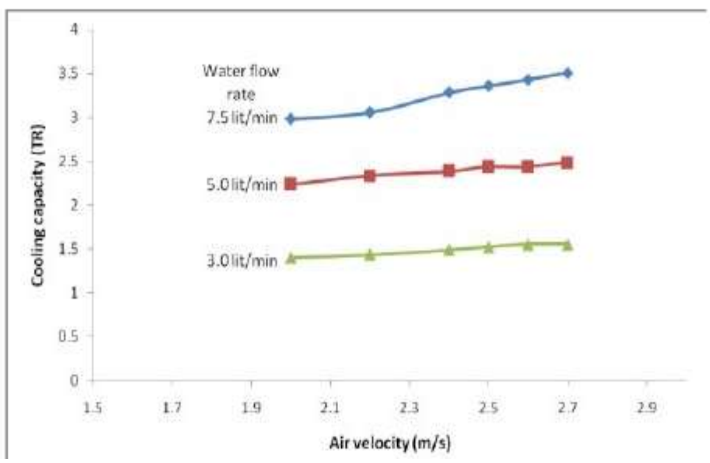

Figure 6: Cooling capacity vs air veocity at Varying mass flow rates.

4. CONCLUSION

An experimental cooling tower was designed and built to function as a test rig, allowing for the testing and validation of innovative designs, materials and operating parameters, resulting in increased effectiveness and reduced expenses in practical applications. It also serves as a platform to study heat transport and fluid dynamics inside cooling towers, which will help us to better understand and optimize their behavior. Additionally, experimental cooling towers are able to assess the impacts of various parameters, such as fill components, air circulation rates, along with overall performance, this is important for developing more sustainable and environmentally friendly cooling systems.

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