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Performance Based Exergy Analysis of a Liquefied Natural Gas Counter Flow Cooling Tower

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Abstract: *A cooling tower's capacity to efficiently exchange heat can be severely diminished by improper maintenance and energy losses, which will ultimately result in lower performance and efficiency. The performance-based exergy analysis of a counter-flow cooling tower utilised in the processing of liquefied natural gas (LNG) is investigated in this work. Identifying the cooling tower's energy-dissipating regions was the primary goal in order to optimize the cooling tower's overall efficiency. Poor management and energy losses may drastically decrease a cooling tower's ability to circulate heat, resulting in reduced performance and efficiency. This article investigates the energy expenditure of a counter-flow cooling structure used in the production of liquefied natural gas (LNG). To maximize the cooling tower's overall effectiveness, the primary goal was to identify its energy-dissipating zones. The data for the study came from the Nigeria Liquefied Natural Gas (NLNG) facility on Bonny Island in Rivers State. The analysis was carried out using exergy equations designed specifically for cooling tower operation. Moreover, altering the water flow rate improved performance. Efficiency improved from 25.8% to 28.3%, 34.6% to 37%, and 40.4% to 42.2% at water volume flow rates of 3257.1 kg/s, 5428.5 kg/s, and 7599.9 kg/s, respectively. These findings highlight the need of doing energy analysis on cooling towers in order to detect inefficiencies and direct maintenance and optimization activities for better performance.*

Keywords—Energy dissipation, Optimization, Cooling load, Range, Approach, Wet bulb temperature, Working fluid, Mass flow rate.

1. INTRODUCTION

The constant supply of cooling water is critical for the effective and secure functioning of the vast majority industrial production systems. Newspaper manufacturing, the manufacture of steel, petrochemicals, electricity generation, and oil refining all rely heavily on temperature-controlled procedures and machinery [1]. Cooling systems assist to regulate temperatures by removing heat from operating fluids. As the energy is taken in, the degree of the cooling water rises. For further use it, the warm water needs to be cooled or replenished with a new source of cooler water. Cooling towers accomplish this by extracting waste heat out of water and releasing it into the sky. This procedure is characterized as "evaporative" chilling because some of the liquid evaporates into a current of flowing air, lowering the temperature of the water that remains. As heat moves from water to air, the air warms and humidifies until it reaches saturate (100% relative humidity), after which point it is discharged into the surrounding atmosphere [2]. Nigeria Liquefied Natural Gas (NLNG) Limited was established in 1989 in order to generate liquefied natural gas (LNG) as well as liquid natural gases (NGL) for export. The development of its LNG production on Bonny Island in Rivers State, Mississippi, launched in November 1995 [3]. Water cooling systems are often divided into two types: evaporating (or wet) chilling and dry cooling.

Evaporative cooling systems, often known as open systems, use evaporated water to transmit heat from warm water to cold ambient air [4]. Conversely, dry cooling systems (also known to be closed systems) prohibit water to come direct contact with the outside environment. Heat is transmitted from heated water to ambient temperature via solid surfaces, rather than evaporation. These systems frequently use radiator-like air-conditioned heat exchangers [5][6]. Exergy analysis is a useful thermodynamic method for evaluating and increasing the efficiency of thermal installations. By assessing where and why exergy (or valuable work potential) is wasted inside a system, including its economic performance nor environmental effect can be improved [7]. For example, [8] investigated gas turbines with an input air cooling system and discovered that environmental parameters such as airflow pressure, moisture, and precipitation had a significant impact on the productivity of combined-cycle nuclear plants. They observed that as temperatures outdoors rise, air density decreases, resulting in a fall in turbine power production. Their research revealed that lower inflow air temperatures improve power output, with the combustion unit seeing the biggest energy losses, thereafter the turbine and expander.

likewise, [9] did an exergy analysis of a power plant in Abu Dhabi, UAE. According to their results, the combustion chamber took responsibility for roughly 70.2% of the total exergy destruction, with the compressor accounting for the least (12.4%). They also employed thermodynamic equations to recreate how extreme temperatures and moisture affect system efficiency. It was discovered that outside temperatures had a greater negative impact on equipment operation than humidity, notably on the combustibility and compression stages, even if it enhanced turbine efficiency. [10]employedexergy analysis to enhance the evaporative cooling towers found in HVAC units. The research investigation used structural simulation software to determine cooling loads and power consumption.

Theoretically modeling helped measure energy losses, demonstrating that cooling towers lose an enormous quantity of energy, which is determined mostly both the temperature within the condensed water and the outside environment. Furthermore, [11] conducted an exergy analysis of a 500 MW steam generation cycle to identify regions with high work-saving potential. They developed benchmark performance indicators for each component and examined data from facility operations under a variety of scenarios. Their findings demonstrated good exergy efficiency due to limited exergy rejection, whereas energy efficiency remained poor due to significant energy losses.

The primary purpose of this study is to conduct a performance-based exergy analysis of a counter-flow cooling tower used in an LNG facility. The purpose is to discover where energy losses happen and to research strategies to optimize the tower's subsystems for improved performance.

2. METHODOLOGY

2.1 Data Collection

Data for this research was gathered from the operations and upkeep department of the NLNG plant. The investigation focuses on determining locations of dissipating energy within the LNG counter-flow cooling tower utilizing exergy-based methodologies. Figure 1 shows an illustration of how the cooling tower is integrated with important equipment in the LNG complex.

Table 1 shows the recorded water and air temperatures, as well as the associated wet-bulb temperatures, while Table 2 lists the cooling tower's essential operational characteristics

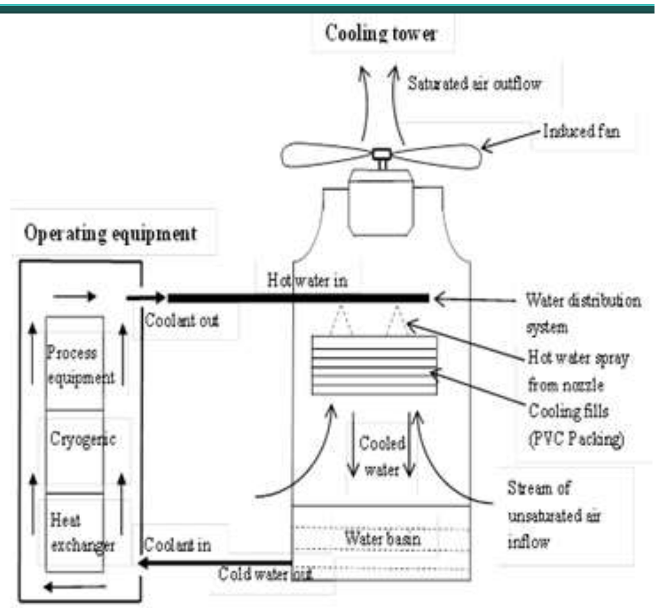

Figure 1: LNG Cooling Tower Integrated to Process Equipment

Table 1: Water, Air and Wet Bulb Temperature

S/N	HWT (ºC)	CWT (ºC)	I TA (ºC)	OTA (ºC)	WBT (ºC)
1	39.4	35.12	35.12	39.4	21
2	39.8	35.24	35.24	39.8	24
3	40.2	35.36	35.36	40.2	25
4	40.6	35.48	35.48	40.6	28
5	41.00	35.60	35.60	41.0	30

Where;

HWT Hot Water Temperature
CWT Cold Water Temperature
I TA Inlet Temperature of Air
OTA Outlet Temperature of Air
WBT Wet Bulb Temperature

Table 2: Cooling Tower Parameters

S/N	Parameters	Values/Unit
1	Entropy of air	8.559 *kJ/kgK*
2	Enthalpy of air	2576.2 *kJ/kg*
3	Mass of air	3166 *kg/s*
4	mass of water	10857 *kg/s*
5	Entropy of water	0.367 *kJ/kgK*
6	Enthalpy of water	104.8 *kJ/kg*
7	Humidity of inlet air	0.78
8	Humidity of outlet air	0.68
9	C_p of water	4.182 *kJ/kgK*

2.2 Data analysis

The following variables were acquired while processing the data utilised in this study work: (1) Cooling tower assortment, (2) Cooling tower strategy, (3) Cooling tower efficacy, (4) Exergy destruction, as well as (5) Energy efficiency.

1) Cooling Tower Range (R)

$R = T_{w_1} - T_{w_2} I$ (1)

The cooling tower's variety is defined as the temperature difference in the heated inflow water and the chilly output water of the cooling tower. The range is defined in Equation 1.

T_{w_1} Inlet hot water temperature of the cooling tower

T_{w_2} Exit cold water Temperature of the cooling tower

2) Cooling Tower Approach

Equation 2 depicts the cooling tower approach as the difference between the ambient wet bulb temperature of the entering air and the temperature of the cold exit water.

$\text{Approach} = T_{w2} - T_{wb}$ (2)

T_{wb} inlet air wet bulb temperature of the cooling tower

3) Cooling Tower Effectiveness

Cooling tower effectiveness or performance is the ratio of a cooling tower's range to the optimal range that can be achieved. Equation 3 expresses it in percentages.

$$Cooling\ tower\ effectiveness = \frac{R}{R + \text{Approach}} \times 100 \quad (3)$$

4) The Heat Load

The heat load is the quantity of heat energy extracted from circulating water with the goal to achieve the target temperature. Equation 4 provides an equation regarding the heat load.

$$Q_{\text{out ct}} = \dot{m}_{w_1} \times C_{pw}(T_{w_1} - T_{w_2}) \quad (4)$$

$\dot{m}_{w_1}$ mass flow rate of hot water at ye inlet of the cooling tower

C_{pw} specific heat capacity of water

5) Exergy

When a system achieves thermodynamic equilibrium with its environment, its maximum work capacity is identified as energy.

6) Exergy of Air at the Inlet of the Cooling Tower

The expression for the exergy of air at the cooling tower's inlet is given by equation 5.

$$E_{\text{xair in}} = \dot{m}_{a_1}(h_{a_1} - h_0) - T_0(S_{a_1} - S_0) \quad (5)$$

$\dot{m}_{a_1}$ mass flow rate of air at the inlet of the cooling tower

h_{a_1} enthalpy of air at the inlet of the cooling tower

h_0 enthalpy of air at the reference state

T_0 temperature of air at the reference state

S_{a_1} entropy of air at the inlet of the cooling tower

T_0 entropy of air at the reference state

7) Exergy of Air at the Outlet of the Cooling Tower

Exergy of air at cooling tower outlet is expressed by equation 6.

$$E_{\text{xair out}} = \dot{m}_{a_2}(h_{a_2} - h_0) - T_0(S_{a_2} - S_0) \quad (6)$$

$\dot{m}_{a_2}$ mass flow rate of air at the exit of the cooling tower

h_{a_2} enthalpy of air at the outlet of the cooling tower

S_{a_2} entropy of air at the outlet of the cooling tower

i. Exergy of W ater at the Inlet of the Cooling Tower

The exergy of the hot water at the inlet of the cooling tower is given by the equation 7

$$E_{\text{xwater in}} = \dot{m}_{w_1}(h_{w_1} - h_0) - T_0(S_{w_1} - S_0) (7)$$

h_{w_1} enthalpy of hot water at the inlet of the cooling tower

S_{w_1} entropy of hot water at the inlet of the cooling tower

ii. Exergy of Water Outlet of the cooling tower

The exergy of the cold water at the exit of the cooling tower is given by the equation 8

$$E_{\text{xwater out}} = \dot{m}_{w_2}(h_{w_2} - h_0) - T_0(S_{w_2} - S_0) \quad (8)$$

$\dot{m}_{w_2}$ mass flow rate of cold water at the outlet of the cooling tower

h_{w_2} enthalpy of cold water at the outlet of the cooling tower

S_{w_2} entropy of cold water at the outlet of the cooling tower

iii) **Net Exergy at the Inlet of the Cooling Tower**

Equation 9 represents the net exergy at the cooling tower intake.

$$E_{\text{xnet in}} = E_{\text{xair in}} + E_{\text{xwater in}} (9)$$

iv) Net Exergy at the Outlet of the Cooling Tower

Equation 10 gives the net exergy at the outlet of the cooling tower

$$E_{\text{xnet out}} = E_{\text{xair out}} + E_{\text{xwater out}} (10)$$

iv) Exergy Destruction

Exergy destruction detects the number of constituents that are being destroyed and acts as a resource deterioration meter. Equation 11 expresses this.

$$E_{xdestruction} = E_{xnet\ in} + E_{xnet\ out} (11)$$

v) **Exergy Efficiency**

Exergy efficiency (ε) is defined as the ratio of total exergy output to total exergy input, which may be stated using equation 12

$$\varepsilon = 1 - \frac{E_{xdestruction}}{E_{xnet\ in}} \times 100 \qquad (12)$$

ε = exergy efficiency

3. RESULTS AND DISCUSSION

3.1 Efficiency of Cooling Tower Under Various Conditions

Table 3 displays the counter flow cooler tower's effectiveness under various parameters of wet bulb temperature (WBT), range, and approach. The Table shows that the cooling tower achieved the best efficiency (49.1%) when the WBT, range, and approach were set to 30oC, 5.40oC, and 5.60oC, respectively. The Table also shows that as the WBT grows, the cooling tower's effectiveness increases. The results revealed an important rise in cooling tower efficiency, with values ranging from 23% to 49%, when the wet bulb temperature climbed from 21°C to 30°C. This improvement emphasizes the necessity of taking into account surroundings and flows of water for enhancing cooling tower performance.

Since cooling tower cells chill water through evaporation, the WBT is an important design parameter. Assuming the wet bulb temperature is 25°C, an evaporative cooling tower will most likely supply cooling water at 28°C to 29°C. Generally, an evaporating cooling tower may provide cooling water 3°C to 4°C hotter than the present ambient wet bulb temperature. When selecting a cooling tower cell, consider the region's greatest wet bulb temperature. Summer generates the highest possible wet bulb temperatures due to increased humidity as well as the temperature of the air.

Table 3: The Efficiency of the Cooling Tower under Various Conditions

S/N	WBT (ºC)	Range(ºC)	Approach (ºC)	Efficiency
1	21	4.28	14.12	0.233
2	24	4.56	11.24	0.289
3	25	4.84	10.36	0.318
4	28	5.12	7.48	0.406
5	30	5.40	5.60	0.491

Table 4 shows the exergy evaluation findings for the LNG plant's generated draught counterflow cooling tower at Bonny Island. The exhaustion rate was computed at 12.7 kW, owing to evaporation of energy in components such as parking fillers and spray nozzles. Whenever water and air flow within the polyvinyl chloride (PVC) packaging, resistance among the protective material and the liquids results in pressure loss. The capability of PVC to keep a wet surface influences mass and warmth transfer efficiency, which influences energy dissipation. The first encounter between the entering air and the water stream altered temperature and humidity, resulting in energy depreciation.

Table 4: Exergy Analysis Results

S/N	Exergy Component	Value/Unit
1	Exergy of air in	7824 kW
2	Exergy of air out	7823 kW
3	Exergy of water in	26832 kW
4	Exergy of water out	26831 kW
5	Exergy Destruction rate	12.7 kW
6	$Q_{out\ CT}$	58177.8 kJ/s
7	Mass flow rate of air	3166 kg/s
8	Makeup water flow rate	316.6 kg/s
9	Water to air ratio (LG)	3.43

3.2 The Effect of Inlet Water Temperature on Exergy Destruction at Various Mas Flow Rate

Exergy destruction arises as an outcome of numerous inefficiencies and impairments in the system. The data in Figure 2 show that the exergy destruction within the cooling tower increases as the incoming water temperature rises. This relationship emphasizes the effect of increasing inlet water temperatures upon the likelihood of exergy degradation. Essentially, greater water temperatures cause more exergy destruction inside the system. Furthermore, Figure 2 indicates that as the water flow rate increases, so doesexergy destruction. This shows that larger water flow rates cause more exergy degradation in the cooling tower. Increased flow rate may result in larger friction losses along with various inefficiencies, adding to higher permanence.

Figure 2 shows particular numbers for total energy loss according to various water flow rates. In this regard, the total exergy destruction rose from 10.1 to 10.6 kW, 11.4 to 11.65 kW, and 12.6 to 12.7 kW with water flow levels of 3.2571 kg/s, 5.4285 kg/s, and 7.5999 kg/s, respectively. These numbers illustrate the increase in exergy destruction as water flow rates rise, emphasizing the significance of adjusting flow rates to reduce irreversibility. Understanding the mechanisms contributing to exergy destruction in a cooling tower is vital for enhancing its performance. Engineers can utilize this data to find areas for improvement that will reduce energy losses and increase overall system performance. Better insulation, management of water flow stages, and enhanced heat exchange designs may all contribute to reduce exergy destruction and increase cooling tower performance.

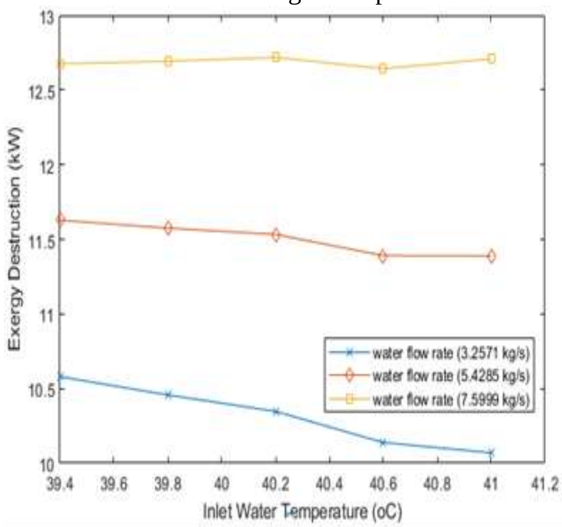

Figure 2: Exergy destruction with changes in water flow rate

3.3 IMPACT OF MASS FLOW RATE OF WATER ON EXERGY EFFICIENCY

Figure 3 depicts the relationship involving liquid mass flow rate as well as incoming temperatures of water in a cooling tower. According to the statistics, as the temperature within the incoming water rises, so does the mass flow rate of water. This finding is critical because it illustrates the manner in which the cooling tower reacts to shifts in water temperature through modifying the water flow. Figure 3 clearly shows that when the incoming water warms up, the cooling tower becomes more effective. The relationship between inflow water temperature, the volume of water, as well as cooling tower efficiency is critical when analyzing a cooling system's efficiency in general.

The information displayed in Figure 3 shows specific efficacy values for various mass flow rates for water and inlet temperatures. Once the water circulation rate changes, its efficacy rises from 25.8% to 28.3%, 34.6% to 37%, and 40.4% to 42.2% at mass flow rates of 3257.1 kg/s, 5428.5 kg/s, and 7599.9 kg/s. These figures show a substantial boost in cooling tower efficiency when both the mass flow rate nor incoming water temperature increase.

Figure 3 provides insights into the design and functioning of cooling structures. Engineers can utilize this information to improve the total velocity of water based on incoming water temperature, resulting in increased cooling tower efficacy. Altering water flow rates within response to changing operational circumstances can enhance thermal performance as well as energy efficiency in cooled systems.

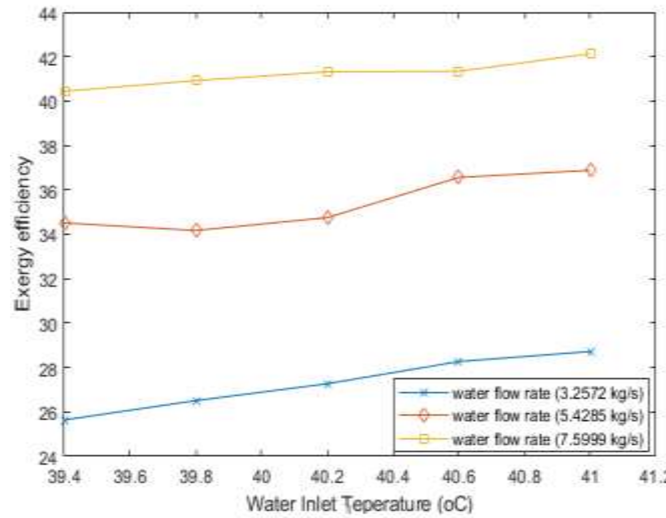

Figure 3: Exergy efficiency with Changes in mass flow of water

4. CONCLUSION

By calculating exergy losses and detecting inefficiencies, this study sheds light on how to optimize operating conditions including design parameters for better performance. To reduce energy dissipation in cooling tower components and improve overall efficiency, language proficiency is critical to increase the amount of maintenance and upkeep routines, meticulously choose appropriate component products in order and install effective filtration systems. Periodic upkeep and adequate filtration aid to avoid debris accumulation, which reduces blockages and fouling while guaranteeing long-term system reliability. Additionally, upgrading as well as adjusting the induced suction fans' speeds from 106 rpm to 95.4 rpm might end up in a decrease of fifteen percent in power usage. This change greatly reduces energy consumption and supports a more effective cooling system

5. RECOMMENDATION

.To achieve optimal performance, every engineering equipment must run at peak efficiency This necessitates periodic assessments to identify and reduce energy losses across the entire facility. These evaluations are critical for improving performance, lowering operational costs, and increasing system reliability. Additionally, there is a need for ongoing research in important fields such as energy and exergy analysis of counterflow wet cooling towers, developed thermal management technologies for server cooling systems operating under varying ambient conditions, as well as parametric examinations of induced draft counterflow rectangular cooling towers using exergy-based methods.

These investigations will help to enhance environmentally friendly and sustainable engineering solutions.

6. References

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