

Exergy Analysis of a Liquefied Natural Gas Counter Flow Cooling Tower

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Abstract:

The energy dissipation occurring in a cooling tower coupled with lack of proper system maintenance results in the cooling tower becoming less effective at heat exchange, leading to performance and efficiency losses. This paper presents the exergy analysis of a liquefied natural gas (LNG) counter flow cooling tower. The purpose of this research work was to identify areas of energy dissipation in the components of the cooling tower with a view to carrying out its optimization. The methodology employed in carrying out this research work involves the collection of relevant data from the Nigeria Liquefied Natural Gas (NLNG) plant in Bonny Island, Rivers State and analysis of the data using formulated exergy equations as it applied to a cooling tower. The results of the analysis reveals that as the wet-bulb temperature increased from 21°C to 30°C, this leads to notable improvements in cooling tower efficiency, with enhancements ranging from 23% to 49%. The results also showed that the cooling tower efficiency increased from 45.94% to 46.39%, 46.06% to 46.63% and 46.19% to 46.8% for mass flow rates of air of 946 kg/s, 1583 kg/s and 2216.2 kg/s respectively, with a matching water inlet temperatures of 39.4°C – 41°C. The results also showed that changing the water flow rate, increases cooling tower efficiency from 25.8% to 28.3%, 34.6% to 37% and 40.4% to 42.2% for water mass flow rates of 3257.1 kg/s, 5428.5 kg/s and 7599.9 kg/s respectively. It is important to carry out exergy analysis of a cooling tower in order to identify areas of energy dissipation and determine how to optimize the various components of the cooling tower through efficient maintenance.

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

I. INTRODUCTION

In order for the majority of industrial production processes to run effectively and safely, cooling water is an essential requirement. Paper mills, steel mills, petrochemical production facilities, power utilities and refineries rely significantly on machinery or procedures that need accurate temperature control (Bahadori, 2013).

Thermal systems that use cooling water to absorb heat from heated process fluids and store it, regulate these temperatures. As a result, the cooling water itself heats up and needs to be cooled down or

replenished with a new supply of cold water before it can be used once more. A cooling tower is a heat rejection system that cools a hot water stream inside the tower in order to release waste heat into the atmosphere. The reason this kind of heat rejection is called "evaporative" is that it permits a tiny amount of the water to evaporate into a stream of flowing air, which significantly cools the remaining water stream. After the heat from the water stream is transferred to the air stream, the temperature of the air increases and its relative humidity reach 100%, at which point the air is released into the surrounding space (Hadi, 2015).

Nigeria Liquefied Natural Gas (NLNG) Limited was established in 1989 as a limited liability company with the primary goal of producing liquefied natural gas (LNG) and natural gas liquids (NGL) for export purposes. In November 1995, marked the beginning of the development of an LNG plant situated on Bonny Island, Rivers State (Thompson et al., 2021).

Commonly used water cooling techniques fall into two categories. One is called evaporative or wet cooling (sometimes called open systems), and it works primarily through the evaporation heat-transfer mechanism to effect the transfer of heat from warmer water to cooler air (Hung et al., 2021). The alternative method is referred to as non-evaporative or dry cooling and usually called closed cooling water systems because the water does not come into contact with external air, it uses a sensible heat-transfer method to exchange heat from warmer water to colder air (Kumar et al., 2011). Heat is transferred via a surface that separates the working fluid from the surrounding air in dry cooling towers. Rather than using evaporation, these primarily reject heat from the working fluid by convection heat transfer. Air-cooled exchangers that resemble radiators are used to provide the cooling (Gaurav and Mishra, 2015).

Utilising energy analysis is a practical thermodynamic method to determine and enhance system and process efficiency. The systems' economic and environmental performance can be maximised by looking at the exergy destruction qualities (Zhang and Wei, 2022).

Umit and Mehmet (2018) conducted an exergy analysis of a gas turbine with an inlet air cooling system and came to the conclusion that the performance of combined-cycle power plants is influenced by the state of the climate. The air pressure, temperature, and humidity all have a big impact on the combined cycle's efficiency. The density of the air reduces with rising ambient temperature, which lowers the power produced by the gas turbine. The study's findings indicate that the gas turbine system's net power production rose with decreasing inlet temperatures and that the rates of energy destruction at the combustion chamber (CC),

gas turbine (GT) and air compressor (AC) were highest to lowest, respectively

To identify the primary cause of irreversibility, Saravanan and Renganarayanan (2008), studied the exergy analysis of a power plant in Abu Dhabi, United Arab Emirates (UAE). The combustion chamber accounted for 70.2% of the plant's overall energy destruction, according to the results. The compressor, on the other hand, contributed the least to the destruction of energy (12.4%) The effects of high temperatures and the absolute humidity of the surrounding air on the energy efficiency of the various power plant equipment were simulated in the second section of the inquiry using the equation of state. According to their research, the plant's performance was negatively impacted by ambient air temperature more so than by absolute humidity. Temperature causes the combustor and compressor to lose energy efficiency, but the turbine's energy efficiency increases.

In order to study and improve the efficiency of evaporative cooling towers in heating, ventilation, and air conditioning (HVAC) systems, Jamali (2020) used an exergy analysis technique. Building energy simulation software determines the cooling load and energy requirements for the building. The system's energy efficiency and destruction are computed using theoretical models. The outcome showed that the cooling tower's exergy loss is fairly large and that the temperature of the condensing water and the external environment have an impact on this loss.

In order to determine which parts of a 500 MW steam turbine cycle offer a large work potential savings opportunity, Hui and Wong (2022) delved into the exergy analysis of the cycle. They develop performance standards pertinent to each of the constituent parts of their task. Using plant operation data under various scenarios, energy flows, energy consumption due to irreversibility, and reasonable performance parameters for the turbine cycle with its components are computed. The turbine cycle's derived exergy efficiency is high because of its low exergy rejection, but its energy efficiency is poor because of its high energy rejection.

The aim of this work was to carry out the exergy analysis of a liquefied natural gas counter flow

cooling tower with the purpose of identifying areas of energy dissipation in order to carry out optimization of the components.

The data used for investigating the energy dissipation in the LNG counter flow cooling tower was collected from the operations and maintenance department of the plant and analysed using exergy technique. The schematic diagram of the cooling tower integrated to some operating equipment of the LNG is shown in Fig. 1.

II METHODOLOGY

2.1 data collection

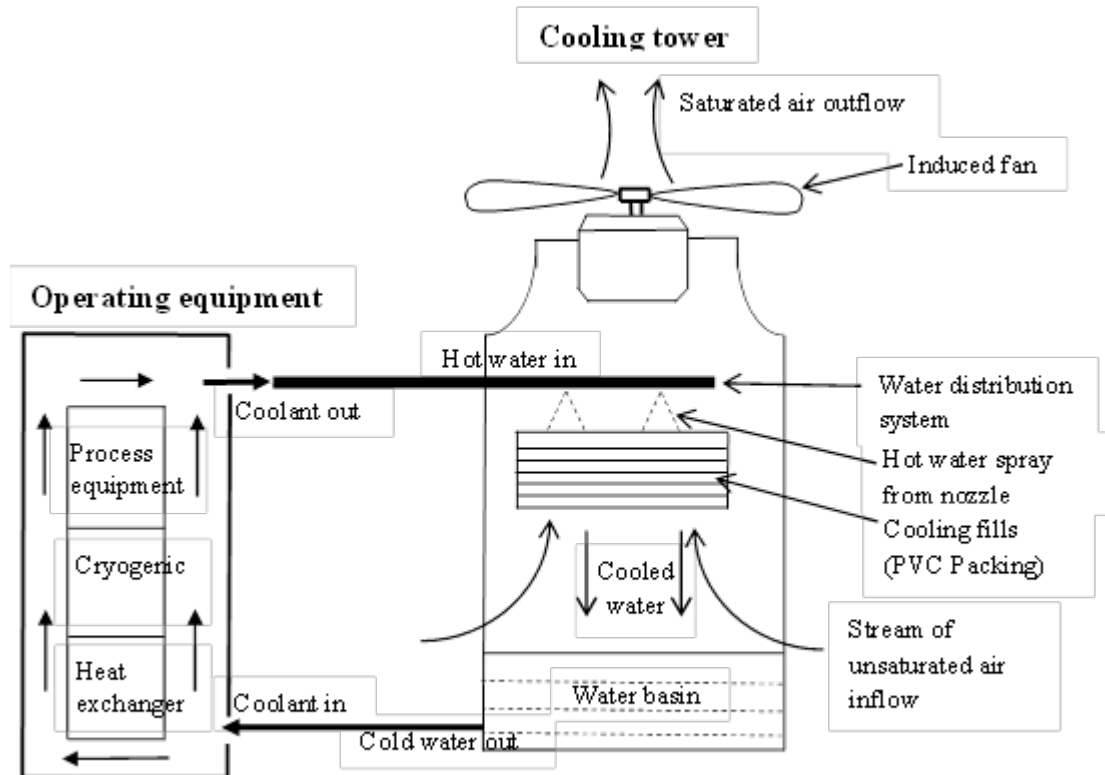


Figure 1: LNG Cooling Tower Integrated to Process Equipment

Table 1 shows the water and air temperatures with corresponding values of the wet bulb temperatures while Table 2 shows the cooling tower parameters.

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

Table 1: Water, Air and Wet Bulb Temperature

S/N	HWT (°C)	CWT (°C)	I TA (°C)	OTA (°C)	WBT (°C)
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

HWT Hot Water 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

In processing the data used for carrying out this research work, the following parameters were obtained: (1) cooling tower range, (2) cooling tower approach, (3) cooling tower effectiveness, (4) exergy destruction and (5) exergy efficiency.

1) Cooling Tower Range (R)

The temperature differential between the cooling tower's hot inflow water and cold output water is known as the cooling tower range. Equation 1 expresses the range.

$$R = T_{w1} - T_{w2} \tag{1}$$

T_{w1} Inlet hot water temperature of the cooling tower

T_{w2} Exit cold water Temperature of the cooling tower

2) Cooling Tower Approach

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

$$Approach = T_{w2} - T_{wb} \tag{2}$$

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

3) Cooling Tower Effectiveness

Cooling tower effectiveness or efficiency is the ratio of the range of a cooling tower to the ideal range

to be obtained. Equation 3 provides an expression for it in terms of percentage.

$$Cooling\ tower\ effectiveness = \frac{R}{R + Approach} \times 100 \tag{3}$$

4) The Heat Load

The heat load is the amount of heat energy that is removed from the circulating water in order to reach a desired temperature. Equation 4 gives the expression for the heat load.

$$Q_{out\ ct} = \dot{m}_{w1} \times C_{pw} (T_{w1} - T_{w2}) \tag{4}$$

\dot{m}_{w1} 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 reaches thermodynamic equilibrium with its surroundings, its maximal work capacity is known as its 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.

$$E_{xair\ in} = \dot{m}_{a1} (h_{a1} - h_0) - T_0 (S_{a1} - S_0) \tag{5}$$

where

\dot{m}_{a1} mass flow rate of air at the inlet of the cooling tower

h_{a1} 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_{a1} 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.

$$E_{xair\ out} = \dot{m}_{a2} (h_{a2} - h_0) - T_0 (S_{a2} - S_0) \tag{6}$$

\dot{m}_{a2} 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

8) Exergy of Water 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

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

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

9) 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

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

\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

10) Net Exergy at the Inlet of the Cooling Tower

The net exergy at the inlet of the cooling tower is expressed by equation 9.

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

11) Net Exergy at the Outlet of the Cooling Tower

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

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

12) Exergy Destruction

Exergy destruction identifies the components of the system where destruction is taking place and serves as a metric for resource degradation. Equation 11 is used to express this.

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

13) Exergy Efficiency

Exergy efficiency (ϵ) by definition is the ratio of total exergy output to total exergy input, this can be expressed by equation 12.

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

ϵ = exergy efficiency

III. RESULTS AND DISCUSSION

3.1 Efficiency of Cooling Tower Under Various Conditions

Table 3 shows the efficiency of the counter flow cooling tower under various conditions of wet bulb temperature (WBT), range and approach. The table reveals that the highest efficiency (49.1%) that could be attained from the cooling tower was when the WBT, range and approach are at the following values of 30°C, 5.40°C and 5.60°C respectively. The Table also reveal that as the WBT increases the efficiency of the cooling tower also increases. The results showed a substantial improvement in cooling tower efficiency – ranging from 23% to 49%, as the wet bulb temperature increased from 21°C to 30°C. This improvement underscores the importance of considering ambient conditions and water flow rates in optimizing cooling tower performance. The WBT is the critical design variable because the cooling tower cells cool water by evaporation. If the wet bulb temperature is 25°C, then an evaporative cooling tower will likely supply cooling water between 28°C and 29°C. In general, an evaporative cooling tower can provide cooling water 3°C to 4°C higher than the current ambient wet bulb condition. The highest wet bulb temperature in the region must be used when choosing a cooling tower cell. Summertime brings the highest wet bulb temperatures because of the highest humidity and air temperatures.

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

S/N	WBT (°C)	Range (°C)	Approach (°C)	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 presents the exergy analysis results of the induced draught counter flow-cooling tower of the LNG plant in Bonny Island. The exergy destruction rate was calculated as 12.7 kW, this was due to energy dissipation in components like the parking fills and spray nozzles. As water and air pass through the polyvinyl chloride (PVC) packing, friction between the packing material and the fluids causes pressure losses. The ability of PVC to maintain a wetted surface affects the heat and mass transfer efficiency, influencing energy dissipation. The initial contact between the incoming air and the water stream caused temperature and humidity changes that brought about energy dissipation.

Table 4: Exergy Analysis Results

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

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

Exergy destruction occurs due to various inefficiencies and losses in a system. The data in Figure 2 demonstrates that the exergy destruction within the cooling tower increases as the inlet water temperature increases. This relationship highlights the impact of higher inlet water temperatures on the potential for exergy destruction.

Essentially, higher water temperatures lead to higher exergy destruction within the system. Additionally, Figure 2 shows that the exergy destruction also increases with an increase in the water flow rate. This suggests that higher water flow

rates contribute to higher levels of exergy destruction within the cooling tower. The increased flow rate may lead to greater friction losses and other inefficiencies, contributing to higher irreversibility. The data provided in Figure 2 includes specific values for total exergy destruction corresponding to different water flow rates. For example, the total exergy destruction increased from 10.1 to 10.6 kW, 11.4 to 11.65 kW and 12.6 to 12.7 kW for water flow rates of 3.2571 kg/s, 5.4285 kg/s and 7.5999 kg/s respectively. These values represent the increase in exergy destruction as water flow rates increases, highlighting the importance of optimizing flow rates to minimize irreversibility.

Understanding the factors contributing to exergy destruction in a cooling tower is essential for optimizing its efficiency. Engineers can use this information to identify areas where improvements can be made to reduce energy losses and enhance overall system performance. Strategies such as better insulation, control of water flow rates and improved heat exchange designs can help mitigate exergy destruction and improve the overall efficiency of cooling towers.

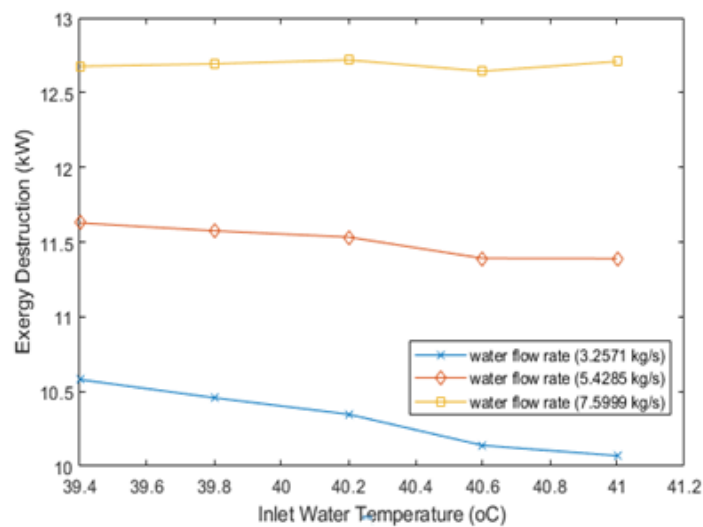


Figure 2: Exergy destruction with changes in water flow rate

3.3 Impact of Mass Flow Rate of Water on Exergy Efficiency

Figure 3 presents the relationship between the mass flow rate of water and the inlet water temperature in the cooling tower. The data indicates that as the inlet water temperature increases, the mass flow rate of water also increases. This observation is crucial because it reflects how the cooling tower responds to changes in water temperature by adjusting the water flow rate.

Concurrently, Figure 3 also demonstrates that as the inlet water temperature rises, the cooling tower effectiveness increases. This correlation between inlet water temperature, mass flow rate of water and cooling tower effectiveness is fundamental for understanding the overall performance of the cooling system.

The data in Figure 3 provides specific effectiveness values corresponding to different mass flow rates of water and inlet water temperatures. When the water flow rate changes, the cooling tower effectiveness increases from 25.8% to 28.3%, 34.6% to 37% and 40.4% to 42.2% for mass flow rates of water of 3257.1 kg/s, 5428.5 kg/s, and 7599.9 kg/s respectively. These values indicate a substantial improvement in cooling tower performance as both the mass flow rate of water and inlet water temperature increase.

The insights from Figure 3 have implications for the design and operation of cooling systems. Engineers can use this information to optimize the mass flow rate of water based on inlet water temperature, aiming for higher cooling tower effectiveness. Adjusting water flow rates in response to changing operating conditions can lead to improved thermal performance and energy efficiency in cooling systems.

IV. CONCLUSION

By quantifying exergy losses and identifying inefficiencies, the study offers insights on optimizing operating conditions and design parameters for optimal results.

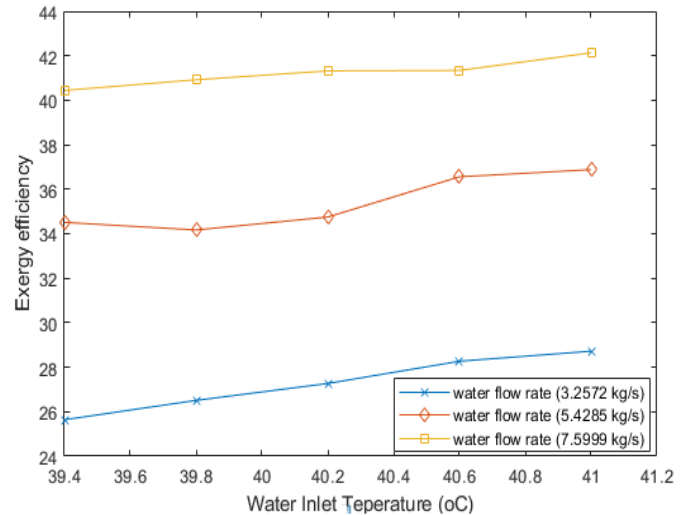


Figure 3: Exergy efficiency with Changes in mass flow of water

To maintain and reduce energy dissipation in cooling tower components for optimal performance, it is essential to increase the frequency of cleaning and maintenance schedules, carefully select component materials and ensure proper filtration and regular maintenance to prevent debris from entering the cooling tower.

This approach reduces blockages and fouling, ensuring long-term performance and system reliability. Additionally, upgrading the induced draught fans and adjusting the fan speed from the initial 106 rpm to an optimized 95.4 rpm will reduce power consumption by 15%, contributing significantly to energy savings and leading to a more energy-efficient cooling system

V. RECOMMENDATION

Every engineering equipment needs to operate as efficiently as possible, hence it is important to periodically identify and reduce areas of energy dissipation by doing an energy analysis of the plant. Additionally, more research can be done in the following areas: energy and exergy analysis of counter flow wet cooling towers; optimal thermal management of server cooling systems under varying ambient temperatures; and parametric study

of induced draft counter flow rectangular cooling towers based on exergy analysis.

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