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ASSESSMENT OF THE PERFORMANCE OF OTEC HEAT EXCHANGER

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ABSTRACT

The performance assessment of OTEC heat exchanger has been conducted. The data was sourced from the World Seawater Temperature for the surface sweater temperature and the map of Nigeria coastal depth in order to ascertain the deep seawater temperature. A reference surface seawater temperature of 27^0C and 6^0C for colder deep seawater temperature with corresponding pressures of 9.78bar and 6.0bar respectively. Simulations were performed utilizing MATLAB software, with input conditions including seawater surface temperatures, pressures, mass flow rates, and cooling seawater temperatures. The key performance indicators were analyzed as follows: a mass flow rate of 1.694 x $10^3$$m^3$/s, heat rejected at the condenser of

2.01 x10^3kJ, an evaporator heat transfer area of 2.2702 x $10^6$$m^2$, and 42,412 tubes in the condenser and 70,148 tubes in the evaporator. OTEC systems need an extensive number of long tubes to achieve the necessary heat transfer surface area. These tubes make up some of the largest components of the system. The substantial number of tubes is a direct result of the very small temperature gradients available in the ocean, which necessitate a large heat transfer area to transfer sufficient heat. Consequently, optimizing the LMTD becomes a crucial task for achieving an economically viable OTEC plant and it also recommended that the use of chromium alloys should be employed in the manufacturing of OTEC heat exchanger because of the corrosive nature of ammonia refrigerant commonly used.

KEYWORDS: Assessment, Performance, OTEC, Heat Exchanger.

1. INTRODUCTION

Renewable energy plays a crucial role in fostering sustainable infrastructural development, with OTEC plants emerging as an important source. The Ocean Energy Conversion system harnesses the thermal energy from the ocean's vertical temperature gradient to generate electricity. This technology holds great potential for providing stable, baseload power to the island nations or remote grids. Additionally, the byproducts of Ocean Thermal Energy Conversion like deep seawater can be used in different industrial applications such as aquaculture, agriculture, and air conditioning (Takaheshi, 1930; Martin *et al.*, 2016).

However, the thermal efficiency of OTEC plants remains relatively low due to the limited temperature difference between the warm surface seawater and the colder deep seawater. To address this problem, different cycle designs has been proposed like open cycle, hybrid cycles combining OTEC with desalination and advanced ammonia plus water mixtures like the Kalina and Uehara Cycles (Claude, 1930; Kalina, 1982; Marson, 1990; Avery & Wu, 1994; Uehara *et al.*, 1995).

Precisely, as worldwide energy consumption continues to increase with economic development, traditional energy sources like petroleum together with coal has contributed significantly to the greenhouse gas emissions and climate change. The Ocean Thermal Energy Conversion is a renewable energy ocean bases technology that offers promising solution particularly in tropical regions, by exploiting the ocean's vertical temperature gradient to power a heat engine (Avery & Wu, 1994). This enables the continuous production of electrical energy, unaffected by weather fluctuations, with the added benefit of utilizing the thermal discharge for desalination and industrial processes like aquaculture and cosmetics (Martine *et al.*, 2016). Demonstration systems has been established in the countries like Japan, the United States, and the South Korea, where a 1 MW plant generated 338kW with a temperature difference of 18.7^{0}C in 2019 (IEA – OES, 2019).

Given the limited temperature difference in Ocean Thermal Energy Conversion systems, the design principles diverge significantly from those of conventional power systems. Optimizing heat and mass balance is crucial for maximizing power output, requiring careful consideration of heat transfer rates and the operating temperature range of the heat engine (Yasunaga & Ikegami, 2020a). The performance of the Ocean Thermal Energy Conversion plants is highly dependent on their heat exchangers, which facilitate heat transfer between the warm surface seawater and the colder deep seawater of the ocean. The heat exchangers typically utilize warm surface seawater to vaporize ammonia under pressure, with the resulting vapour driving a turbine generator.

This study focuses on the evaluation of heat exchanger performance in OTEC plants particularly in terms of the evaporator heat transfer surface, condenser heat transfer surface, number of tube in the condenser and log mean temperature difference (LMTD). This research also aim to address common challenges faced by heat exchangers in OTEC plants such as fouling, corrosion, and maintenance issues, and their influence on the performance and longevity. The findings from this study will contribute to advance OTEC technology, paving the way for more efficient and sustainable energy generation.

2. LITERATURE REVIEW

A. Overview of the Development OTEC Heat Exchanger

The Ocean Thermal Energy Conversion plants use the temperature gradient between warm surface seawater and colder deep seawater to produce electrical energy. Central of the Ocean Thermal Energy Conversion plants are the heat exchangers, which facilitate the transfer of heat from the seawater to the working fluid, typically ammonia. Different heat exchanger types are employed in the Ocean Thermal Energy Conversion Systems, each designed to handle the unique demands of the ocean based thermal energy conversion (Igoma, 2024).

The development of the OTEC heat exchangers dates back to the 1970s with the creation of the vertical spout evaporator by George J. Clark under NELHA. This design was critical for open cycle OTEC systems, where warm seawater was pumped into a low pressure container, causing it to boil and produce steam that drove a turbine for electrical power production. The evaporator's design achieved an impressive steam conversion efficiency of up to 97%.

In the 1980s, the National Renewable Energy Laboratory introduced a more effective heat exchanger design. This system utilized ammonia and water mixture, significantly enhancing the efficiency of the power cycle. A known case is this improvement is the Ocean Thermal Energy Conversion plant on Kume Island in Okinawa Prefecture, Japan, which used a titanium plate heat exchanger. Despite the small temperature difference between warm and cold seawater, this design efficiently transferred heat, marking a significant development in OTEC plants. The Japanese Ministry of the Environment has recognized this titanium based heat exchanger in its technology development and carbon neutrality projects (Igoma *et al.*, 2024).

B. Recent Review on OTEC Heat Exchangers

Recent studies on OTEC heat exchangers focus on optimizing their efficiency and performance under challenging operational conditions. Researchers like Anderson &

Anderson (1996) have investigated the effectiveness of staging closed cycles to increase the available temperature difference between the turbine inlet and outlet, thus enhancing power production ability (Morisaki & Ikegami, 2014). Furthermore, solar boosted cycles have been proposed to further optimize the efficiency of the OTEC systems by augmenting the temperature differential. Performance optimization of heat exchangers in OTEC plants is critical due to the small temperature differences between the warm and cold seawater. The pressure drop caused by the heat exchangers significantly impacts the performance of seawater feed pumps, which in turn influences the overall efficiency of the OTEC plant. The challenge lies in the finding a balance between minimizing pressure drop and maximizing the heat transfer performance. Additionally, studies on the degradation of power generation due to the performance components, such as the back work ratio associated with seawater feed pumps, have emphasized the importance of evaluating the heat exchanger's role in the overall plant performance. The tradeoff between heat transfer performance and pressure drop is a key consideration in OTEC design (Yasunaga *et al.,* 2018; Fontaine *et al.*, 2019)

Conclusively, OTEC heat exchangers play a pivotal role in the performance together with the efficiency of the ocean base renewable energy plants. The titanium plate heat exchanger, despite its higher cost, is the most preferred due to its enhanced heat transfer efficiency and resistance to corrosion.

3. MATERIALS AND METHODS

A. Materials

The following materials were used for the study:

i. Daily Surface Seawater Data (WST, 2024)
ii. MATLAB
iii. Ocean Profile
iv. Steam Table

B. Modeling of the OTEC Heat Exchanger

The model for the Ocean Thermal Energy Conversion system includes the heat engine as depicted in **Figure 1**. The model conceptualization was done according to thermodynamic processes encompassing the irreversibilities related with the working fluid pressure drop as shown in **Figure 2**.

In OTEC plants, heat is transferred from hot seawater to the heat engine, where it is converted in to useful work. Subsequently, heat is transferred from the engine to the colder seawater. This process is central to the performance analysis, which is essential for the determination of the energy efficiency together with the forecasting the needful maintenance intervals to sustain effective performance as shown in **Figure 3**(Adumene *et al.*, 2016).

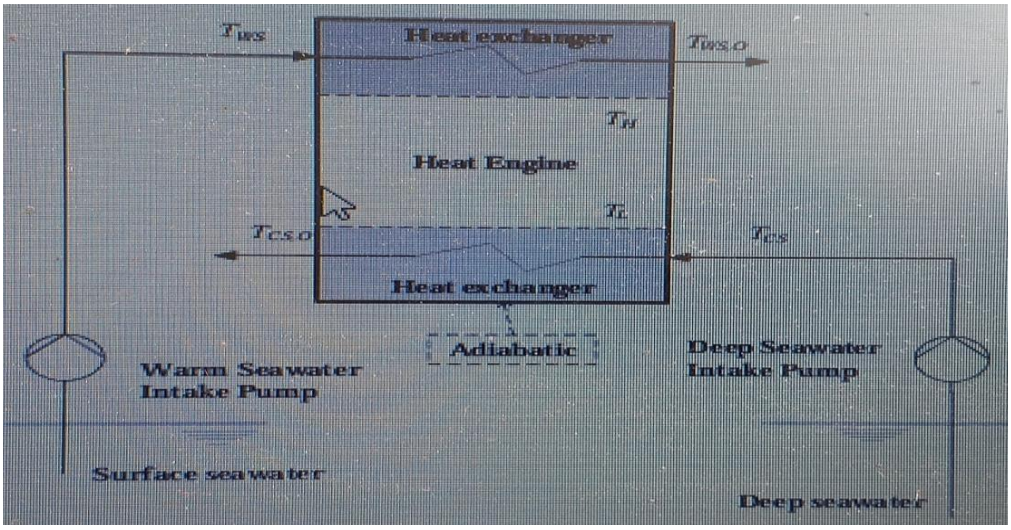

Figure 1: Model of an OTEC Power Generation Plant Involving a Heat Engine (Yasunaga *et al.*, 2021).

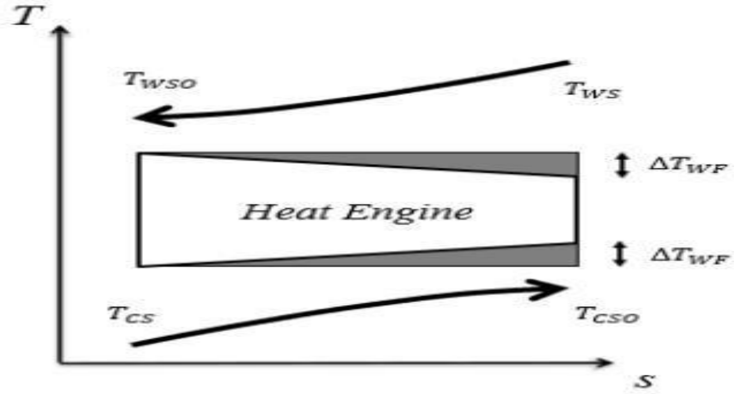

Figure 3.2: Conceptualized Diagrammatic Depiction of the Irreversibility in an OTEC Heat Engine Related with the Working Fluid Pressure Drop (Yasunaga *et al.*, 2021).

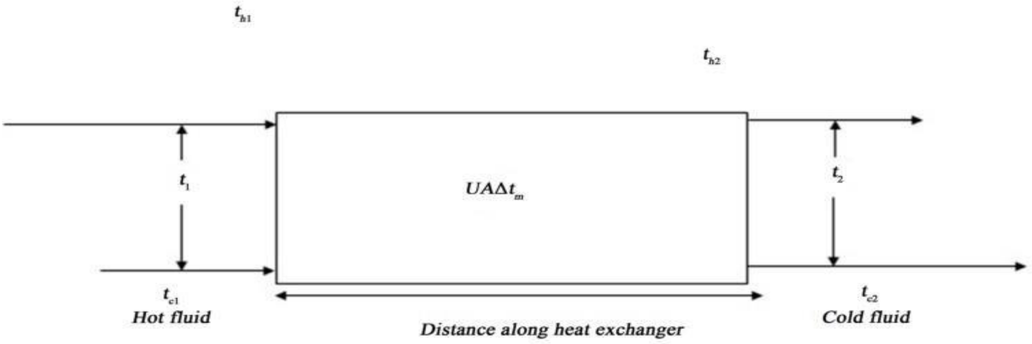

Figure 3: Depiction of a Block diagram of a heat exchanger (Adumene *et al.,* 2016).

The heat loss by the hot seawater

$$Q_{hsw} = m_{hsw}C_{phsw}(t_{h1} - t_{h2}) \tag{1}$$

The Heat Gain by the Cold Seawater

$$Q_{csw} = m_{pcsw}C_{psw}(t_{c1} - t_{c2}) \tag{2}$$

Total Heat Transfer Rate

$$Q = UAt_m \tag{3}$$

The Log Mean Temperature Difference (LMTD)

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln(\frac{\Delta T_1}{\Delta T_2})} \tag{4}$$

Overall Heat Transfer Coefficient

$$U = \frac{1}{\frac{1}{h_i}+\frac{\;}{k}+\frac{1}{h_o}} \tag{5}$$

For the fluid flowing inside and outside the tube:

Overall Heat Transfer Coefficient:

$$\frac{1}{\frac{1}{h_i}(\frac{r_o}{r_i})+\frac{\;}{k}+\frac{r}{k}\ln(\frac{r_i}{r_o})+\frac{1}{h_o}} \tag{6}$$

The effect of the scale or heat flow: thermal resistance to the scale formation on t surface which is also known as the overall heat transfer coefficient - (R_{si}) together outside surface (R_{so}) are expressed as:

$$R_f = \frac{1}{h_s} \tag{7}$$

Where: h_s is the reciprocal of scale heat transfer coefficient.

$$O = \frac{t_i - t_o}{\frac{1}{A_ih_i}+\frac{1}{A_ih_{si}}+\frac{1}{2\pi lk}\ln(\frac{r_i}{r_o})+\frac{1}{A_0h_{so}}+\frac{1}{A_oh_o}} \tag{8}$$

Heat Exchanger Effectiveness

$$\varepsilon = \frac{\text{Actual Heat Transfer}}{\text{Maximum Possible Heat Tranfer}} = \frac{Q}{Q_{max}} \tag{9}$$

Number of Transfer Units (NTU)

$$NTU = \frac{UA}{C_{min}} \tag{10}$$

The negligible fluids viscosities and pressure losses coefficient:

$$\Delta P_t = 4f\left(\frac{l}{d_i}\right)\left(\frac{h^2}{2gp}\right) \tag{11}$$

A Heat Transfer Area (m2)

C_{phsw} Specific Heat Capacity of Hot Seawater C_{pcsw} Specific Heat Capacity of Cold Seawater R_f Fouling Factor

m_{csw} Mass Flow Rate of Cold Seawater (kg/h) m_{hsw} Mass Flow Rate of Hot Fluid (kg/h)

Q_{hsw} Heat Duty of Hot Seawater (kW)

Q_{csw} Heat Duty of Cold Fluid (kW) ε Effectiveness

t_1 & t_2 Wall Temperatures ˚C

t_{h1} Inlet Temperature of Hot Seawater ˚C t_{h2} Outlet Temperature of hot Seawater ˚C t_{c1} Inlet Temperature of Cold Seawater ˚C t_{c2} Out Temperature of Cold Seawater ˚C

Δ_{tc} Change in Cold SewaterTemperature

Δ_{th} Change in Hot Seawater Temperature U Overall Heat Transfer Coefficient

U_{clean} Overall Heat Transfer Coefficient from Design (kW/m2K) U_{dirty} Overall Heat Transfer Coefficient from Operation (kW/m2K) LMTD Log Mean Temperature Difference

Δ_{Pt} Pressure Loss Coefficient

R_{si} Thermal Resistance to Scale Formation on the Inside Surface R_{so} Thermal Resistance to Scale Formation on the Outside Surface.

C. Simulation Process

The simulation was carried out by modeling of the OTEC heat exchanger. The MATLAB was employed to evaluate the performance of the OTEC heat exchanger, and the results contribute to the optimal design of OTEC heat exchanger. The temperatures of both the shallow together with the deep were measured and serve as a reference for analyzing the heat exchanger's performance, which was then compared to the findings of Igoma *et al.*, (2025). **Table 1** entails the design data of the OTEC Heat exchanger. **Table 2** includes the enthalpy of ammonia, used as the working fluid and the average surface seawater temperature values from daily readings taken between January 2021 and December, 2024 for four years (WST, 2024) and compared to Igoma, 2024. Finally, the reference input data are: the inlet temperature and pressure are 27°C and 9.78bar, and the output temperature and pressure are 6°C and 6.0bar respectively.

Table 1: Heat Exchanger Design Data.

Parameter	Units	Plant Data
Heat Duty	KW	3390.32
Overall Heat Transfer Coefficient (U)	KW/m^2K	0.6545
Capacity Ratio		1.966
Fouling Factor	m^2K/KW	7.5967
LMTD		57.689

Table 2: Enthalpies of Ammonia.

h_1 (KJ/Kg)	h_2 (KJ/Kg)	h_3 (KJ/Kg)	h_4 (KJ/Kg)
1624.7	1564.8	378.03	378.59

4. RESULTS AND DISCUSSION

Influence of the Surface Seawater Temperature on the Log Mean Temperature Difference (LMTD) of the OTEC Heat Exchanger

The LMTD is a key driver of heat transfer in an OTEC heat exchanger, determining the effective temperature gradient that transfers heat from warm seawater to the ammonia working fluid in the evaporator, and from the working fluid to the cold seawater in the condenser. As shown in **Figure 4**, a 2^0C increase in the surface seawater temperature results in a proportional increase of the log mean temperature difference. Unlike a simple average temperature difference, the log mean temperature difference accounts for the temperature variations along the length of the heat exchanger, providing a mathematically accurate mean value as depicted in **Figure 4**.

The log mean temperature difference is the design and operation of large scale heat exchangers used in OTEC plants. It serves as an indicator of the system performance, where a sudden drop in the log mean temperature difference can suggest issues such as bio-fouling, where marine growth on the pipes reduces heat transfer efficiency by acting as an insulating layer. Thus, monitoring the LMTD is important for scheduling cleaning and maintenance.

Precisely, for phase changing fluids, the LMTD formula simplifies but remains crucial in accurately calculating the heat transfer driving force. As illustrated, the effective LMTD is typically higher than 0^oC and lower than 9^0C thereby reflecting the true average heat transfer capacity along the heat exchanger.

These findings are consistent with those presented by Boukai *et al.*, (2020), who emphasize the importance of LMTD in optimizing heat exchanger efficiency and its role in identifying performance issues. Similarly, Lee *et al.*, (2018) discussed how bio –fouling can significantly affect heat exchanger performance thereby further validating the need for LMTD monitoring.

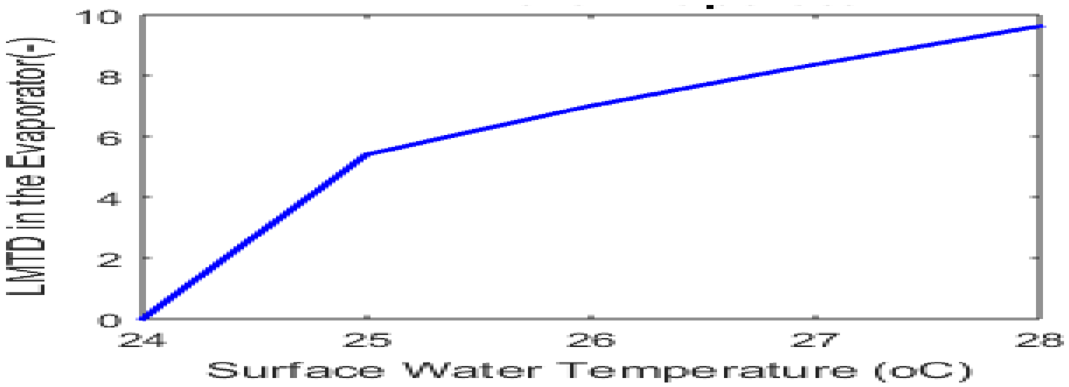

Figure 4: LMTD in the Evaporator versus Surface Seawater Temperature.

Influence of the Deep Seawater Temperature on the on the Log Mean Temperature Difference (LMTD) of the OTEC Condenser

Practically, in Ocean Thermal Energy Conversion condenser, the LMTD is the key factor driving heat transfer from the ammonia working fluid into cold seawater. Due to the low temperature of the cold seawater (around 4 – 6ºC), the log mean temperature difference is inherently small, necessitating a large surface area to reject the required heat. This feature makes OTEC condensers, similar to evaporators, large and costly components of the plant. Operators must optimize the cold seawater flowrate to balance turbine output with pumping power, seeking the optimal point where the net power gain is maximized. The log mean temperature difference plays a crucial role in this optimization.

Figure 5 illustrates the influence of the deep seawater on the OTEC condenser. It shows that for every 2ºC rise in the deep seawater temperature, the LMTD decreases by 2ºC, highlighting its role in the heat rejection from the working fluid. The LMTD is not merely a mathematical value but a central factor influence the economics, efficiency, and operational strategy of the entire OTEC plant, with its impact on the condenser being especially significant.

This aligns with findings from Koyama *et al*. (2018), who emphasize the importance of LMID in OTEC plants, noting that small temperature variations at the condenser require large heat exchange areas. Additionally, they discussed the operational challenges posed by the low LMTD and the critical role of optimizing the seawater flowrate for efficiency.

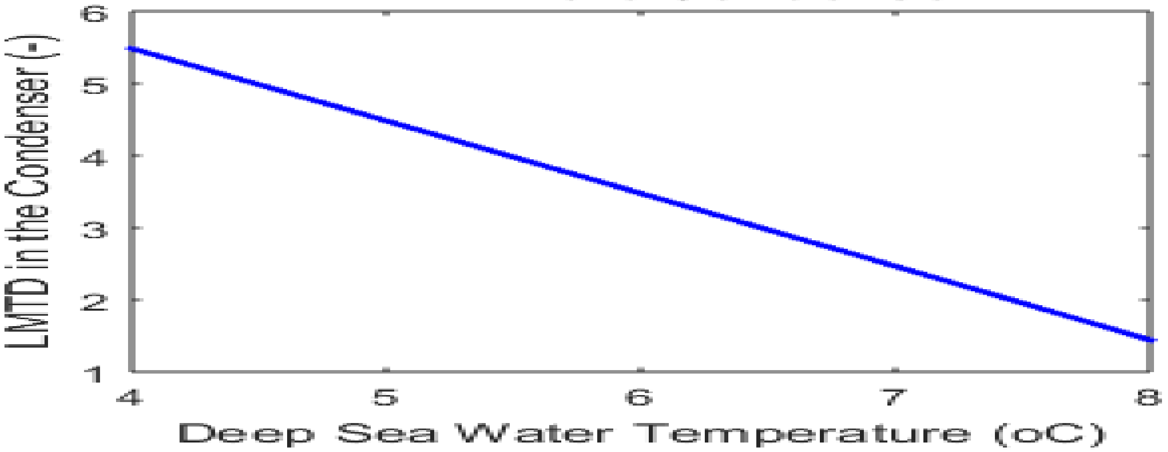

Figure 5: LMTD in the Condenser versus Deep Seawater Temperature.

Influence of the Log Mean Temperature Difference (LMTD) in the OTEC Heat Exchanger on the Evaporator Heat Transfer Surface

The relationship between the LMTD and the required evaporator heat transfer surface area in an OTEC heat exchanger is inversely proportional, playing a critical role in determining the size, cost, and feasibility of the evaporator. **Figure 6** illustrates this relationship, showing that for every 2ºC change in the log mean temperature difference; the evaporator surface area rises by 5.0 x 10^7m^2. This explains why the OTEC evaporators are among the largest components of the system. The LMTD not only influences but essentially dictates the size of the evaporator. The small temperature gradients in the ocean water force OCTEC designers to construct large heat exchangers, making LMTD optimization crucial for achieving an economically viable plant.

These findings align with the work of Koyama *et al*. (2018), who highlight the inverse relationship between the LMTD and the heat exchanger surface area thereby emphasizing the significant impact of small temperature variations on the design and operational cost of OTEC plants. They also stress the importance of optimizing LMTD to improve the economic feasibility of such systems.

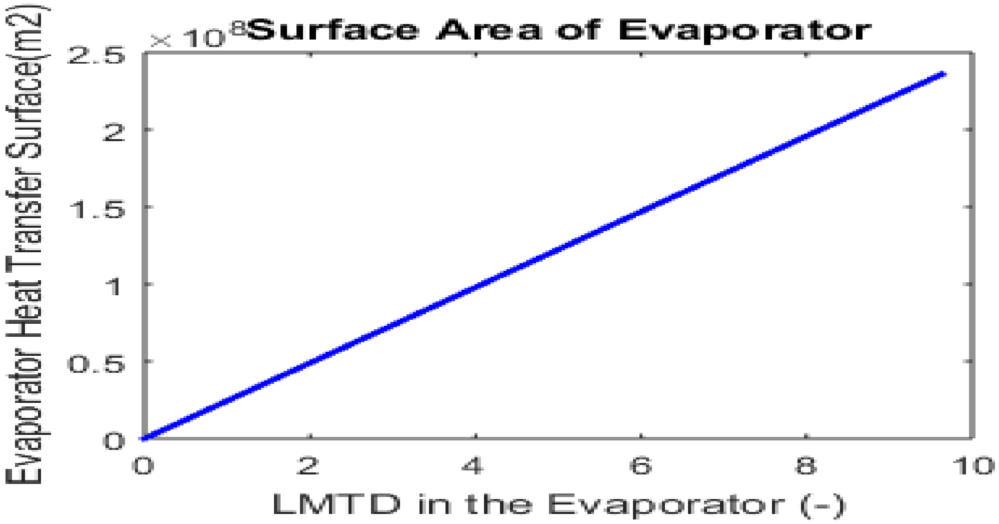

Figure 6: LMTD in the Evaporator versus Evaporator Heat Transfer Surface.

Influence of the Log Mean Temperature Difference (LMTD) in the OTEC Condenser on the Condenser Heat Transfer Surface

Figure 7 illustrates the relationship between the LMTD in the OTEC condenser and the required heat transfer surface area. The Figure shows that for every 1°C change in LMTD, the condenser surface area increases by 2 x $10^7 m^2$, highlighting the inverse relationship – a smaller LMTD requires a larger condenser surface area, and vice versa. The OTEC system operates with a temperature difference of only 20 – 24°C, which is split between the evaporator and condenser. Cold seawater from the deep ocean, typically at 4 – 6°C, interacts with ammonia vapour entering the condenser at temperatures just below its turbine expansion temperature (around 8 – 10°C).

For condensation to occur, the vapour must be cooled to its saturation temperature, which is slightly higher than the cold seawater inlet temperature to maintain the LMTD. This results in a small LMTD like 2 – 4°C, which directly determines the size and cost of the OTEC condenser. The limited temperature difference forces designers to build large heat exchangers, and optimizing the LMTD is crucial for making OTEC technology economically viable and it align with the findings of Koyama *et al*. (2018).

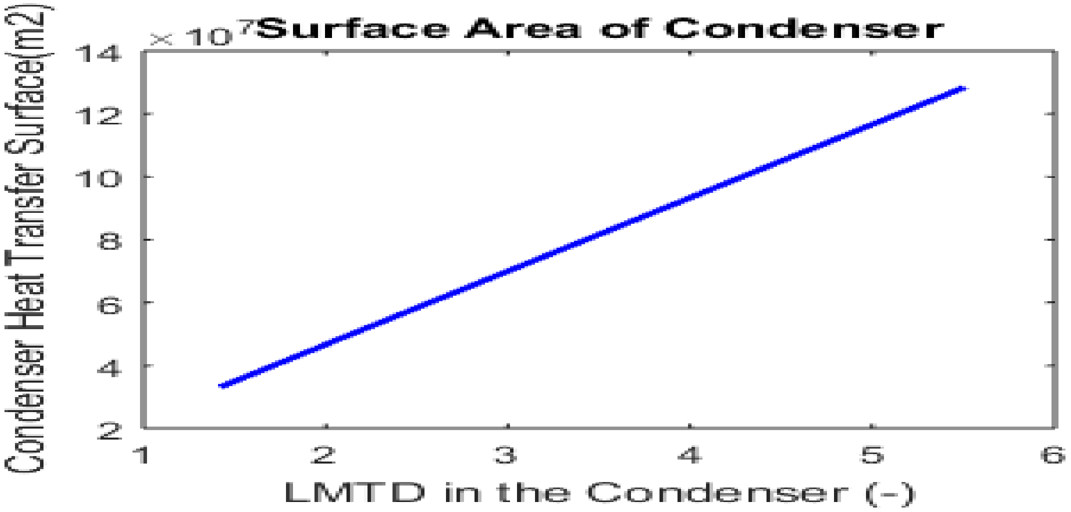

Figure 7: LMTD in the Condenser versus the Condenser Heat Transfer Surface.

The Relationship between the number of tubes of the Evaporator and Condenser of the OTEC and their Heat Transfer Surfaces

The number of tubes in the OTEC evaporator and condenser is directly proportional to their heat transfer area, with a linear relationship. However, the simple correlation is influenced by the more complex requirement of achieving a sufficient total surface area, dictated by the small LMTD in the OTEC plants. Precisely, once the diameter together with the length of the tubes is obtained, doubling the number of tubes results in doubling the heat transfer surface area.

Figures 8 and **9** depict this linear relationship for the evaporator and condenser, respectively. The **Figure 8** shows that for every 5.0 x $10^7 m^2$ of evaporator heat transfer surface, 2000 tubes are required. Similarly, Figure 9 indicates that 1000 tubes cover the same surface area in the condenser. Due to the small LMTD in the ocean environments, OTEC plants require thousands of long tubes to achieve the necessary surface area, leading to heat exchangers that are physically large and among the largest components of the system. The number of the tubes is thus a direct multiplier for the heat transfer surface area, driven by the need to compensate for the small LMTD and efficiently transfer heat and it align with the findings of Koyama *et al.* (2018). They discussed the linear relationship between the tube count and heat transfer surface area in the heat exchangers and their work confirms that optimizing the number of tubes is essential for ensuring effective heat transfer in OTEC system.

5. CONCLUSION

The performance assessment of OTEC heat exchanger has been conducted. The data was sourced from the World Seawater Temperature for the surface sweater temperature and the map of Nigeria coastal depth in order to ascertain the deep seawater temperature. A reference surface seawater temperature of 27^0C and 6^0C for colder deep seawater temperature with corresponding pressures of 9.78bar and 6.0bar respectively.

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