

EFFECT OF EVAPORATION PRESSURE ON THE PERFORMANCE OF A CLOSED CYCLE OTEC USED FOR ELECTRICITY IN NIGERIA

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ABSTRACT

The study of the effect of evaporation pressure on the performance of a closed cycle OTEC used for electricity in Nigeria has been performed. Fundamental thermodynamic principles will undergird the governing equations, with detailed analyses performed using advanced simulation software tools like ASPEN HYSYS and MATLAB was employed. The simulations were performed using MATLAB v8.5a and Aspen Hysys v11 software, employing various input conditions such as sea surface water temperatures, pressures, mass flow rates, cooling water temperatures, and pressures. It was observed that as the evaporation pressure increases from 800 KPa to 1000 KPa: in the Hysys simulation, the net power output increases from 14.88 KW to 28.76 KW, while in the MATLAB simulation, it increases from 15.08 kW to 28.93 kW; The efficiency increases from 39.15% to 40.02% in the Hysys simulation and from 39.16% to 40.03% in the MATLAB simulation and the evaporator heat duty also increases, from 1133 kW to 1173 kW in the Hysys simulation and from 1134 KW to 1175 KW in the MATLAB simulation. It is recommended that the evaporation pressure should be allowed to rise up to 1000KPa for optimum performance since better cycle efficiency and net power output is achieved at higher evaporation pressure.

Keywords: Evaporation Pressure, OTEC, Performance, Close Cycle, Electricity.

I. INTRODUCTION

Africa's largest economy, Nigeria is witnessing rapid growth in energy consumption. Per capita power use remains low relative to peer developing countries. However, energy demand is rising steadily, around 6-7% annually, as economic prospects improve after a recent recession. National electricity consumption reached over 22 TWh in 2018, mostly from fossil fuels. The total installed grid- connected capacity stands at 12,500 MW, bolstered recently by additions from large hydropower projects like Zungeru (700 MW). However, only about 7,500 MW generation capacity is available currently with persistent gas supply and infrastructure issues [1]. The gap between supply and ever-increasing electricity demand causes daily power outages and reliance on expensive backup diesel generators that constrain productivity [2]. Energy security concerns also loom in the future as domestic oil production wanes. These motivate the need to diversify supply by aggressively pursuing renewable sources like solar, wind, and ocean energy. While research exists on tidal, wave, and OTEC potential globally, minimal studies focus specifically on Nigeria to concretely evaluate technical feasibility and how such technologies could be integrated within the existing infrastructure. Precisely, developing alternative clean energy that will solve this gap becomes imperative [3].

The OTEC appraisal was performed and how bright this type of renewable energy technology is utilized for the generation of electrical energy coupled with fresh water, seawater air-conditioning, and marine culture together with chilly soil agriculture [4]. The investigation was accompanied by a wide summary of the technique, marketable regions, and technological aspects, together with an economical appraisal of the technique. The effect of the environment of the technique doubles with comparable levelization expenditures of power of this technique with the ones that are already being completed. The study revealed that the present technique subsists to design ocean thermal energy conversion systems, with the exception of some constituents like a coldwater pipe that represents an engineering question when a high energy supply is required, and the technique is awfully expensive.

Also, the precursory appraisal of OTEC as a means of global energy fountains, and how the system was assessed with a one-dimensional time domain framework of the thermal structure of the ocean has been done [5]. Currently, the result of a steady state work where segmenting the possible ocean thermal energy conversion generation is in one-degree by one-degree squares doubled with the permission of the adjustable operation of ocean thermal energy conversion. It increases the valued maximum steady state ocean thermal energy conversion electrical energy from around three trillion kilowatts to five trillion kilowatts, and further revelation portrayed that the ocean thermal energy conversion can provide energy of the order of a few terawatts.

Practically, the work on the OTEC strategic design together with the assessment of the present difficulties has been conducted [6]. Their work proffers various fountains of OTEC designs coupled with impediments encountered in terms of the efficiency and the economics of the ocean thermal energy conversion systems. The transformation design was initially based on closed cycle, open cycle, and hybrid systems with the efficiency evaluation, which is principally slant about the impact of the system distance together with thermal gradient as regards the system efficiency. While the appraisal of the economical aspect is based on the influence of per unit cost of the ocean thermal energy conversion system and different vital considerable things like the plant factor coupled with the offshore distance, which decides the energy production cost. Precisely, the study proved that offshore distance, together with the thermal gradient, directly affects the system efficacy, and the economic appraisal indicates that the system should preserve a system factor of at least 0.9 where the system is 25 megawatts (MW) capacity to attain a production economy in comparison to the energy system that is not renewable energy.

The research on OTEC with a view to the development regarding the capable efficiency consequences has been performed [7]. The work did reemphasize that the consequential issues associated with the OTEC should be thoroughly studied to develop ocean thermal energy conversion plants that are efficaciously operative. The work further highlighted that ocean thermal energy conversion plants could be a possible avenue of cost-operative renewable energy in tropical coastal regions like the Niger Delta of Nigeria.

The numerical appraisal of an OTEC: prefatory results in which the ASPEN PLUS simulation modeling software was used for the creation of a functional model of the ocean thermal energy conversion plant together with the appraisal of the collectable data for the determination of the power output and the efficiency of the plants has been performed [8]. Also, the work used the ideal Rankine cycle in which reliable operational conditions remain the same: constant for the prediction of the efficiency and the power output of the ocean thermal energy conversion plant. Meanwhile, once the simulation models were formed and functional, the performance for verifying the modeling methods was done utilizing numerical computations before the acquisition of any data. It was discovered that the power output and the efficiencies of the two models improve appropriately.

The investigation of the OTEC system together with its offshoot results for Indonesia's island seawater has been conducted [9]. The work looks at the region of the sea on the small island in Indonesia that can produce electrical energy, and it discovered that the monthly temperature gradient is 200°C to 230°C for the warm seawater surface and the deep cold seawater, which implies that with that temperature gradient, a reasonable amount of energy can be generated, thereby advancing another power generation avenue in the small island. Also, the cold-water discharge is affluent in nutrients.

The optimal development of hybrid renewable energy plants which is a summary of various approachable techniques in which they looked at hybrid plants as being used to solve the problem of dependable energy provision doubled with the protection of the environment, unlike fossil fuels, which are highly hazardous to the environment was done by [10]. Also, regarding the description of the location, energy resource potentiality accessible together with the kind of energy needed, and the hybrid energy plants can be designed and optimized to adapt to that particular location. Furthermore, the choice of the appropriate method may vary because of the kind of usage and utilizer needs, and each designed-sized approachable technique has the potential to substantially advance the pertinence of renewable energy plants.

Precisely, the thermodynamic economic capability investigation of a 20 MW OTEC system has been performed. The work looked at the design of a thermal fluids plant modeled closed cycle ocean thermal energy conversion for the aim of appraising the influence of cardinal development parameters on the system performance.

Precisely, the appraisal from the various models hinted that ocean thermal energy conversion is unquestionably achievable from the angle of engineering, but the economical attainability for the 20 MW system will probably be restricted to remote areas.

Furthermore, the investigation the thermodynamic economic appraisal of an OTEC system that will be sited in the coastal region of Nigeria has been conducted [12]. The geographical conditions are latitude $4^{\circ}00'$ to $4^{\circ}16'$ N together with longitudinal values of $7^{\circ}16'$ to $7^{\circ}19'$ E, whose power capability is between 22 and 24K over 1000m from the seawater upper part amid rainy and dry periods separately. However, ammonia was used as the working fluid of the closed-cycle ocean thermal energy conversion system that was developed to steadily provide electric power in the area throughout the year. The results of the appraisal are comparably good with those same systems, and its initial cost is extremely high, so it is solely excessively big companies that can embark on such a design. Harnessing ocean thermal gradients could provide consistent clean power to boost capacity [13][14]. Thus, this study addresses the research gap through evaluating a Close Cycle Conventional OTEC plant tailored to Nigerian sea conditions.

II. METHODOLOGY

Modeling the Conventional Ocean Thermal Energy Conversion Plant

Modeling the baseline conventional OTEC system encompasses the following elements:

Working Principle of Conventional OTEC

The fundamental principle behind conventional ocean thermal energy conversion is to exploit the warm surface seawater to heat a working fluid and vaporize it. This phase change, accompanied by increasing vapor pressure, impinges on turbine blades, imparting mechanical rotation and generating electrical power. The key components of the conventional OTEC cycle are illustrated in **Figure 1** condenser, evaporator, turbogenerator, pumps, and interconnected piping [15][16].

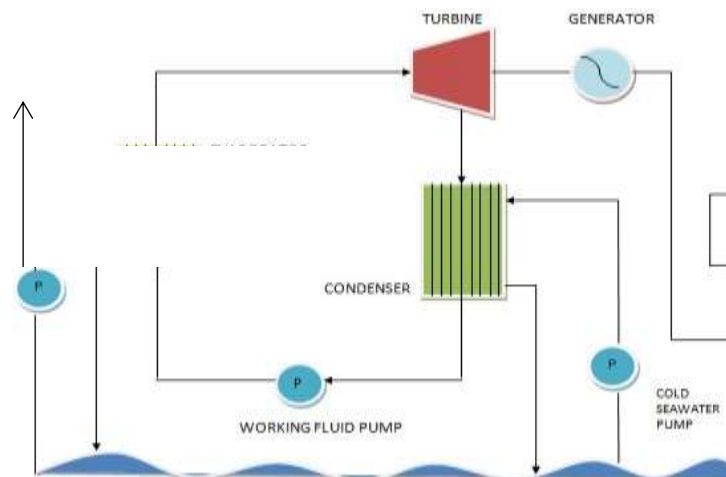


Figure 1: Conventional Ocean Thermal Energy Conversion Plant [14][17]

Performance Analysis

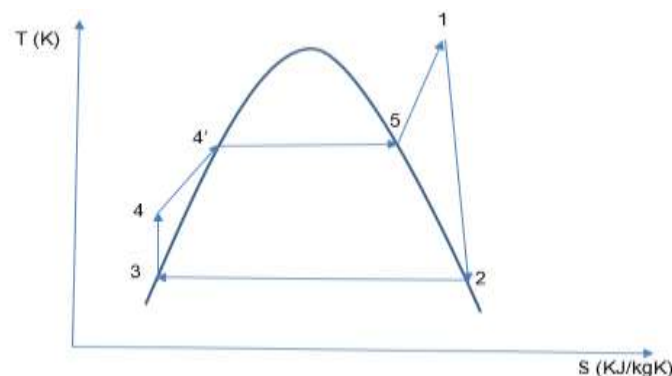


Figure 2: Temperature-Entropy Diagram of the Ocean Thermal Energy Conversion Plant[14]

Thermodynamic Performance Analysis of the Key OTEC System Equipment Rigorous thermodynamic analysis of the principal OTEC system components is performed by evaluating the thermodynamic state points mapped onto a temperature-entropy (T-S) diagram as depicted in **Figure 2**.

$$Q + m(\text{internal energy} + \text{Flow work} + K.E + P.E) = W + m(\text{internal energy} + \text{Flow work} + K.E + P.E) \quad (1)$$

$$Q + m \left(U_1 + P_1 V_1 + \frac{C_1^2}{2} + gz_1 \right) = W + m \left(U_2 + P_2 V_2 + \frac{C_2^2}{2} + gz_2 \right) \quad (2)$$

$$Q - W = m \left[(U_2 + P_2 V_2) - (U_1 + P_1 V_1) + \frac{C_2^2 - C_1^2}{2} + g(z_1 - z_2) \right] \quad (3)$$

When

$$h = U + PV \quad (4)$$

Substituting equation (4) into (3) gives:

$$Q - W = m \left[(h_2 - h_1) + \frac{C_2^2 - C_1^2}{2} + g(z_1 - z_2) \right] \quad (5)$$

Equation 5 is the Steady Flow Energy Equation (SFEE) and can also be written as:

$$Q - W = m[\Delta h + \Delta K.E + \Delta P.E] \quad (6)$$

The energy equation for the evaporator

The energy equation for the evaporator using the steady flow energy equation {(equation (6) and **Figure 1**) can be expressed as:

$$\Delta h = C_p \Delta T$$

$$\Delta K.E = \Delta P.E = W = 0$$

Tube side

$$Q_{Ets} = \dot{m}_{ws} C_p \Delta T_{ws} \quad (7a)$$

Tube side

$$Q_{Ess} = \dot{m}_f (h_1 - h_5) \quad (7b)$$

Where

$\dot{m}_{ws}$ = the mass flow rate of the warm seawater,

C_p = the specific heat capacity of seawater,

ΔT_{ws} = the temperature difference between the inlet and the outlet of warm seawater in the evaporator,

$\dot{m}_f$ = the mass flow of working fluid,

h_1 and h_5 = enthalpies of working fluid at the outlet and the inlet of the evaporator respectively.

The work output equation for the turbine can be expressed as:

$$W_t = \dot{m}_f (h_2 - h_1) \quad (8)$$

The energy equation for the condenser can be expressed as:

Tube side

$$Q_{cts} = \dot{m}_{cs} C_p \Delta T_{cs} \quad (9a)$$

Tube side

$$Q_{css} = \dot{m}_f (h_3 - h_2) \quad (9b)$$

Where

$\dot{m}_{cs}$ = the mass flow rate of the cold seawater,

C_p = the specific heat capacity of seawater,

ΔT_{cs} = the temperature difference between the inlet and the outlet of cold seawater in the evaporator,

$\dot{m}_f$ = the mass flow of working fluid,

h_3 and h_2 = are enthalpies of working fluid at the outlet and the inlet of the evaporator respectively.

The work consumed by the working fluid pump, warm sea water pump and the cold sea water pump are expressed in equations (10) - (12) respectively.

$$W_{p,f} = \frac{\dot{m}_f(h_4 - h_3)}{n_p} \quad (10)$$

$$W_{p,w} = \dot{m}_{wsw} C_p (T_{w2} - T_{w1}) \quad (11)$$

$$W_{p,c} = \dot{m}_{csw} C_p (T_{c2} - T_{c1}) \quad (12)$$

Where

h_4 and h_3 = the enthalpies of working fluid at the outlet and the inlet of the working fluid pump,

$\dot{m}_f$ = the mass flow of working fluid,

n_p = the efficiency of the pump.

Equations 10 and 12 will be given as values.

In the OTEC system, the heat source pumping power is indispensable. The net power of OTEC W_{net} is as follows:

$$W_{net} = W_t - (W_{p,f} + W_{p,w} + W_{p,c}) \quad (13)$$

The thermal efficiency of the Rankine cycle and the OTEC system is defined as

$$\eta_t = \frac{W_{net}}{Q_T} \quad (14)$$

Head loss of the pump

Head loss is the potential energy that is connected to the kinetic energy. It is due to the frictional resistance of the piping system. Head loss due to friction is calculated using the Darcy equation as shown in equation (3.30).

$$h_{fi} = \frac{f_{di} L_i V_i^2}{2 D_i g} \quad (15)$$

Where f_{di} = frictional factor which is function of velocity, roughness factor, viscosity of the fluid and pipe diameter.

The frictional factor in a laminar regime is independent of the wall roughness and inversely proportional to the Reynold's number. It is calculated using the Hagen-Poiseuille equation as shown in equation (16).

$$f_{di} = \frac{64}{Re} \quad (16)$$

Where

L_i = length of pipe (m),

V_i = velocity of water (m/s),

D_i = diameter of pipe (m),

g = acceleration due to gravity.

Pump power loss

The power loss due to the pump at different sections of the OTEC system is calculated.

$$P_{li} = h_{fi} \dot{m}_i g \quad (17)$$

Where $i = 1, 2, 3, \dots, n$ sections

III. RESULTS AND DISCUSSION

Table 1 contains proposed working design data for a 40KW OTEC plant that will be situated in Bonny Island, Rivers State, Nigeria. The daily seawater surface temperatures of Bonny Island obtained from the world seawater temperature chart [16]. and the monthly average is calculated and recorded in **Table 2**. **Table 3** encompasses results obtained from simulating the Ocean Thermal Energy Conversion (OTEC) system. The simulations were performed using MATLAB v8.5a and Aspen Hysys v11 software, employing various input conditions such as sea surface water temperatures, pressures, mass flow rates, cooling water temperatures, and pressures. The influence of evaporation pressure on the OTEC system's performance is analyzed. The results from both Hysys and MATLAB simulations are compared to provide a comprehensive understanding of the system behavior under different evaporation pressures. The evaporation pressure is a critical parameter in the operation of the OTEC system, affecting the thermodynamic cycle and the efficiency of energy conversion.

Table 1: Proposed Working Design Data for the 40 KW OTEC Plant

Parameters	Values	Unit
Working fluid	Ammonia	
Ammonia Density	597.908	Kg/m ³
Ammonia Specific heat capacity	4.87	KJ/KgK
Turbine Efficiency	0.796	%
Turbine Rated Power	40	KW
Generator Efficiency	0.946	%
Pumps Efficiency	0.895	%
Warm seawater inlet temperature	25 and 29	°C
Cold seawater inlet temperature	9 and 10	°C
Pipe length of warm seawater	101	m
Pipe diameter of warm seawater	102	m
Pipe length of cold seawater	670	m
Pipe diameter of cold seawater	101	m
Heat exchangers conductivity	14	W/m K
Surface sea water temperature	29	°C
Deep cold water temperature	9	°C
Water Density	1025	Kg/m ³
Water Specific Heat Capacity	4.182	KJ/KgK
Evaporator Pressure	9.78	Bar
Condenser Pressure	6	Bar
Friction loss factor	0.02	

Table 2: Monthly Average Sea Surface Temperature of Bonny Island Deep-sea River, Rivers State.

S/No.	Year/ Month/ Degree Celcius	2021 (°C)	2022 (°C)	2023(°C)	2024(°C)
1.	January	27.2	27.4	28.3	27.7
2.	Febuary	28.6	28.5	29.2	28.4
3.	March	28.4	29.1	29.0	28.7
4.	April	28.7	29.1	29.1	28.9
5.	May	29.0	31.2	29.0	29.0
6.	June	26.9	28.0	28.3	28.0
7.	July	27.0	27.0	27.3	26.9
8.	August	26.0	26.7	26.5	26.2
9.	September	26.7	26.5	27.0	26.6
10.	October	27.6	26.8	27.9	27.3
11.	November	28.4	26.9	27.4	27.7
12.	December	28.5	27.1	27.5	27.9

Table 3: Data Obtained from Simulation

Evaporator Pressure (Kpa)	Turbine Power (KW)	Pump - Power (KW)	Wnet (KW)- Hysys	Wnet (KW)- Matlab	Thermal efficiency (%) - Hysys	Thermal efficiency (%) - Matlab
800	15.08	0.2037	14.88	16.11538	39.148	39.1593
850	18.5	0.3565	18.14	19.03456	39.069	39.0869

900	21.92	0.5092	21.41	21.66239	39.257	39.2907
950	25.34	0.662	24.68	26.06808	39.573	39.5744
1000	28.76	0.8148	27.95	28.9281	39.985	40.0153

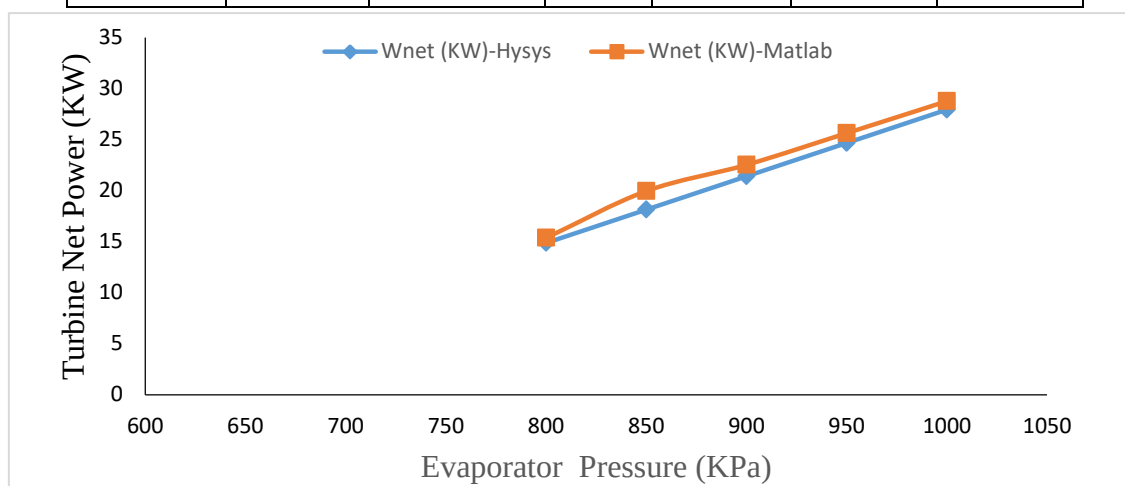


Figure 3: Turbine Net Power against Evaporator Pressure

The turbine net power output is a direct measure of the system's efficiency in converting thermal energy from the ocean into mechanical energy. **Figure 3** illustrates the relationship between turbine net power output and evaporation pressure. As the evaporation pressure increases from 800 KPa to 1000 KPa, there is a significant rise in turbine net power output. In the Hysys simulation, the net power output increases from 14.88 KW to 28.76 KW, while in the MATLAB simulation, it increases from 15.08 kW to 28.93 kW. This trend can be attributed to the enhanced thermodynamic efficiency of the working fluid cycle at higher evaporation pressures. The increase in turbine net power output with rising evaporation pressure can be explained by the improved heat absorption capacity of the working fluid at higher pressures. This results in a greater amount of thermal energy being converted into mechanical energy by the turbine. The slight discrepancies between the Hysys and MATLAB results could be due to differences in the numerical methods and assumptions used in the two simulation platforms. However, the overall trend remains consistent, highlighting the positive impact of increased evaporation pressure on turbine performance.

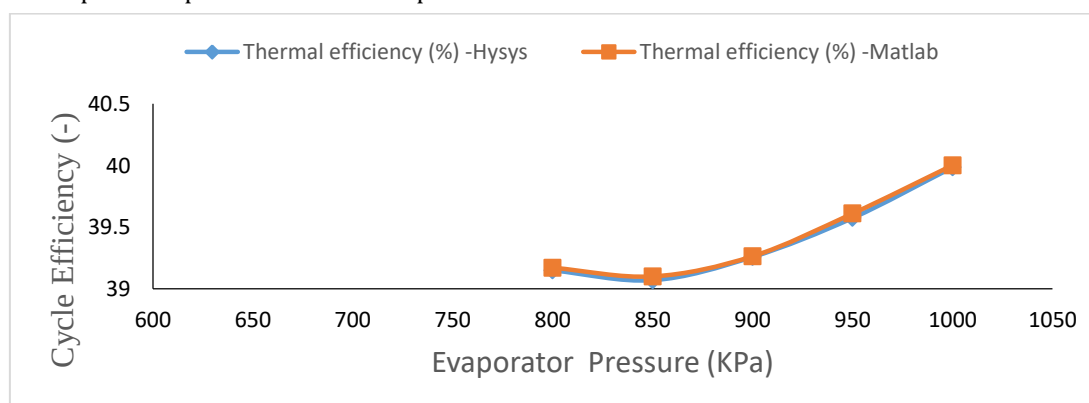


Figure 4: Turbine Cycle Efficiency against Evaporator Pressure

Turbine cycle efficiency is a crucial indicator of the overall performance of the OTEC system. **Figure 4** represents the ratio of the net power output to the total thermal energy input, providing a measure of how effectively the system converts thermal energy into mechanical energy. Also, **Figure 4** shows the effect of evaporation pressure on turbine cycle efficiency. As the evaporation pressure rises from 800 KPa to 1000 KPa, the efficiency increases from 39.15% to 40.02% in the Hysys simulation and from 39.16% to 40.03% in the MATLAB simulation. The improvement in turbine cycle efficiency with increasing evaporation pressure is likely due to the enhanced thermodynamic performance of the working fluid. Higher pressures improve the heat

transfer properties and increase the enthalpy change during the phase transition, leading to better energy conversion efficiency. The close agreement between the Hysys and MATLAB results reinforces the reliability of the findings, indicating that the observed trend is robust and consistent across different simulation platforms.

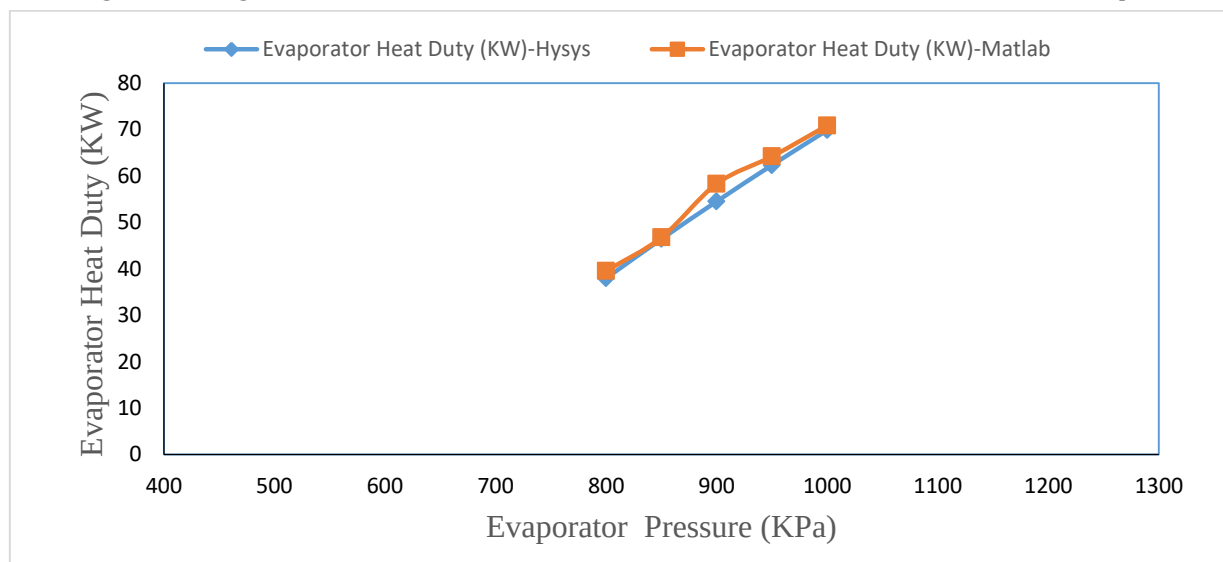


Figure 5: Evaporator Heat Duty against Evaporator Pressure

Precisely, the evaporator heat duty is a measure of the amount of thermal energy absorbed by the working fluid in the evaporator. It directly impacts the overall energy conversion efficiency of the OTEC system. The impact of evaporation pressure on evaporator heat duty is depicted in **Figure 5**. As the evaporation pressure increases from 800 KPa to 1000 KPa, the evaporator heat duty also increases, from 1133 kW to 1173 kW in the Hysys simulation and from 1134 KW to 1175 KW in the MATLAB simulation. This trend indicates that higher pressures facilitate greater heat absorption by the working fluid, enhancing the overall heat transfer efficiency of the evaporator. The increased heat duty at higher pressures is a result of the improved thermal properties of the working fluid, which allows it to absorb more energy from the hot sea water. The close correspondence between the Hysys and MATLAB results suggests that the observed trend is reliable and consistent, further validating the positive impact of increased evaporation pressure on evaporator performance. The analysis of evaporation pressure effects on the OTEC system reveals several key insights. Firstly, increasing the evaporation pressure significantly enhances the turbine net power output, indicating that higher pressures improve the energy conversion efficiency of the system. This improvement is due to the enhanced thermodynamic properties of the working fluid at higher pressures, which facilitate better heat absorption and energy conversion. Accordingly, the turbine cycle efficiency also improves with increasing evaporation pressure, reinforcing the positive impact of higher pressures on overall system performance. The close agreement between the Hysys and MATLAB results suggests that the observed trends are robust and reliable, indicating that the findings can be confidently applied to optimize the OTEC system. Furthermore, the increase in evaporator heat duty with rising evaporation pressure highlights the importance of optimizing the evaporator design to handle higher thermal loads. Ensuring efficient heat transfer at higher pressures is crucial for maximizing the energy conversion efficiency of the OTEC system.

IV. CONCLUSION

The study of the effect of evaporation pressure on the performance of a closed cycle OTEC used for electricity in Nigeria has been performed. Fundamental thermodynamic principles will undergird the governing equations, with detailed analyses performed using advanced simulation software tools like ASPEN HYSYS and MATLAB was employed. The simulations were performed using MATLAB v8.5a and Aspen Hysys v11 software, employing various input conditions such as sea surface water temperatures, pressures, mass flow rates, cooling water temperatures, and pressures. It was observed that as the evaporation pressure increases from 800 KPa to 1000 KPa: in the Hysys simulation, the net power output increases from 14.88 KW to 28.76 KW, while in the MATLAB simulation, it increases from 15.08 kW to 28.93 kW; The efficiency increases from 39.15% to 40.02%

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