



Design and Performance Appraisal of Proposed OTEC Plant Used For Power Generation

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Abstracts

The design and performance appraisal of proposed OTEC plant used for power generation in the Niger Delta region of Burutu Offshore Deep-sea has been conducted. The approach adopted in this study encompasses the design and modeling together with performance appraisal of close cycle ocean thermal energy conversion plant for power generation. Practically, the design encompasses development of a dependable model via utilization of pertinent data such as surface sea water temperature, sea water temperature at a given depth, mass flow rate of the refrigerant, pressure of the refrigerant etc., and these data are obtained from the Burutu Offshore Deep-Sea and from standard tables and graphs. Also, appropriate thermodynamic principles were also applied in developing the model equations coupled with ASPEN HYSYS and Microsoft Excel software programs that was used to carry out the analysis. The study showed that there is potentiality of citing the proposed OTEC Plant because there is enough temperature difference to give rise to a workable cycle efficiency which also indicates normal operational performance and it was recommended that a solar booster should be incorporated in the heat exchanger so that it can increase the heat generated and thereby increasing the efficiency of the OTEC plant.

Keywords: Design, Performance, OTEC, Plant, Power generation

1.0 Introduction

Ocean energy is a sustainable energy source that has enormous capability for delivering a vast amount of energy demand. It contains a large quantity of energy and it covers over seventy percent of the planet earth's surface (SOPAC, 2009; Ressurreição et al., 2011). The system uses the change in the temperature that exists between the shallow waters together with the deep waters in the ocean to operate a heat or steam engine (Magesh, 2010). The ocean surface behaves like a solar collector and has the potential to capture the heat energy form the sun (Khan et al., 2017). Ocean energy has several merits when compared with other maintainable sources like biomass, solar and wind. It is abundance in nature, preferably accessible, gives a lesser impact on the environment when compared with other renewable sources, and it is predictable. These merits give it a capability for electricity generation (Melikoglu, 2018). Ocean energy could give energy independence, desalination plants together with job creations. However, the rising in global energy consumption, environmental concerns together with the increase in oil prices of the 2010s have strengthen interest in the exploitation of renewable energy. Oceans together with the seas inspired the engineers to use the energy of seawater in different means. Practically, these means can be divided



into two cardinal areas: wave energy coupled with temperature difference. Precisely, nowadays, researchers have in common eyed more in utilizing the temperature differences between warm surface water and colder deep seawater (Thomas, 1993). Accordingly, the International Energy Agency (IEA), there is five various techniques of exploiting the ocean energy. Majorly, these techniques are previously implemented but some are still in the design level and they includes; tidal power, tidal or marine current, wave power, temperature gradient coupled with the salinity gradient. Tidal and wave energy conversion has remarkably gained attention globally coupled with the technology of the generation of portable drinking water through desaltation, hydrogen generation by electrolysis together with the supply of compressed-air to aquaculture (SOPAC, 2009; IEA, 2017).

The position of electrical power production of different kind of renewable energy like wind, solar, hydraulic, geothermal, biomass, and ocean thermal energy conversion which is major concerned of this research work, is constantly chronicled and the design of possible renewable energies are frequently studied (Bouraiou *et al.*, 2020; Kuang *et al.*, 2016; Østergaard *et al.*, 2020). The design of renewable energy sources encompasses integrating difference sources of energy into hybrid systems like solar or wind energies which in turn gives ameliorated optimized power doubled with its management, operation and control plans (Shivarama and Sathish, 2015; Chamandoust *et al.*, 2020).

The Ocean is the world biggest solar receiver and storage of energy system and in a day, sixty million kilometres per squares (60MKm^2) of equatorial seas absorbed the total ratio of solar radiation that is equitable to heat proportion of approximately two hundred and fifty billion barrels of oil (Alkhalidi *et al.*, 2014). Ocean thermal energy conversion (OTEC) is a plant which utilizes the temperature gradient between hot surface seawater and cold deep seawater to propel a working fluid in a Rankin cycle to produce electric power. Notwithstanding, surface seawater differs with a range of 24 to 30°C depending on season, while deep seawater often does not change meaningfully by season and remains moderately steady in the range of 5 to 9°C. The sea surface temperature of the Atlantic Ocean ranges from 27.1 - 29.4°C and the temperature at depths of 1000m and is below 5°C for all oceans globally as shown in Figure 1 (Bruce, 2008).

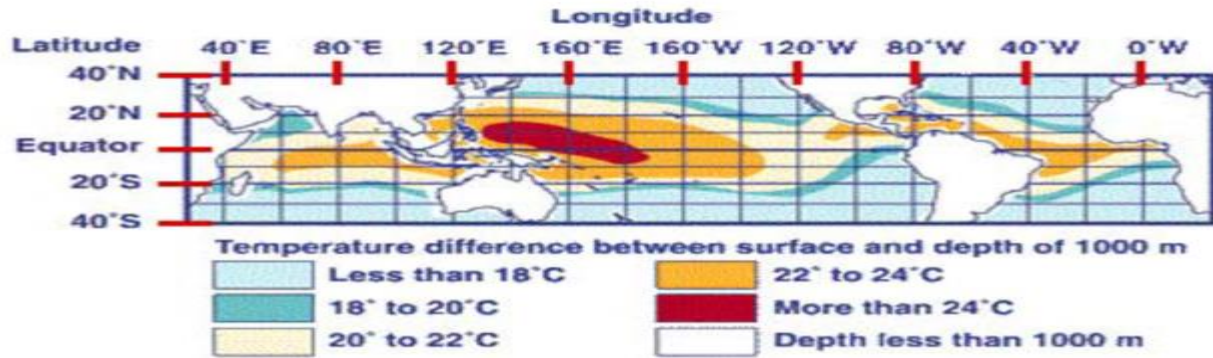


Figure 1: Worldwide Ocean Surface Temperatures (Yusuf and Lydia 2010)

Notwithstanding, the Ocean Thermal Energy Conversion is a solar energy likened renewable energy due to the conspicuous fact that the Ocean absorbs the sunlight daily and this is equitable to different thousand times the elementary energy need of the earth planet we are living (Avery and Wu, 1994). Precisely, this energy is reserved as heat in the upper surface of the Oceans and the equatorial coastal part of the surface of the earth has a mean temperature of between 27°C and 29°C and the deep temperature decreases from 4°C to 5°C as the depth rises to 1000m and above the depth of 1000m; the temperature decreases to another degrees even at a mean ocean of depth of 3650m as depicted in Figure 2 (Othermer and Roels, 1973).

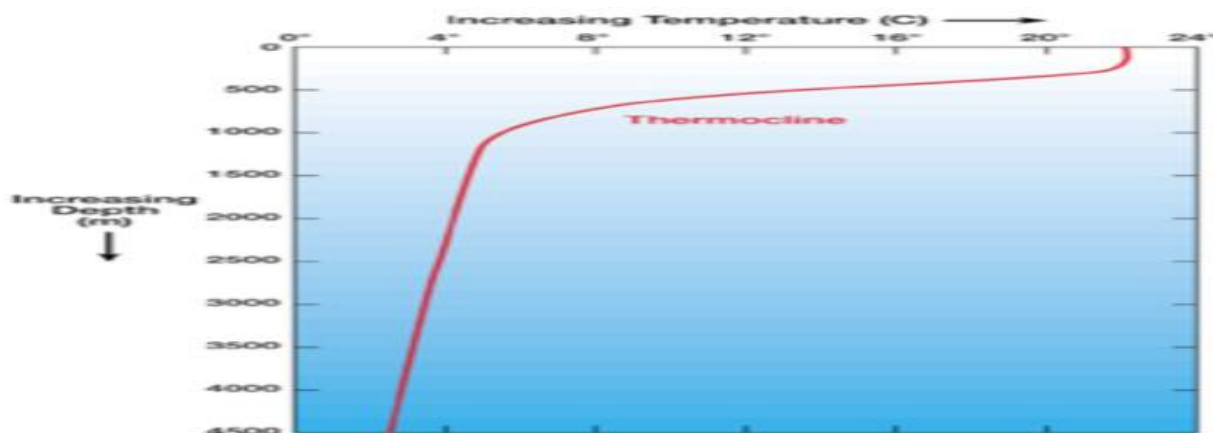


Figure 2: The temperature profile of ocean water (Walter and Farshid, 2014)

The Ocean Thermal Energy Conversion system produces electric power endlessly and it can be utilized as a base load power generating plant which is a considerable benefit comparable to other renewable powers like solar and wind (Ruud and Frank, 2014). Also, the potential energy conserves of the ocean temperature difference are relatively four thousands multiplied by that of the energy consumed per year worldwide. Precisely, pulling out potential energy obtainable inside the ocean is pendent on the efficacy of the thermal system engaged like pumps, condensers together with heat exchangers. The ocean thermal energy conversion uses



different kind of power generation cycles like the closed cycle, open cycle coupled with the hybrid cycle respectively (Aftring and Taylor, 1979).

Precisely, Nigeria as the largest black nation in the world that is in dire need of sustainable energy rather than the epileptic power supply that is solely dependent on fossil fuels. The fossil fuel produces carbon-dioxide and other harmful emissions that adversely affects negatively on our ozone layer. Nigeria needs constant power generation but its epileptic nature has made many industries to move out of the country and this need solution via provision of the secure power, power inefficiency handling together with other climate change mitigation. Notwithstanding, considering this mindful challenges, augmenting the renewable energy distribution within total primary energy supply of Nigeria is important. This can aid by assuring the power supply, allowing decentralization of electric power generation together with lesser vestige of carbon left comparable to fossil fuels power generation systems (Aida, 2018).

Shylesh, 1998 appraised the OTEC and how bright this type of renewable energy technique in the generation of electrical energy coupled with the generation of fresh water, sea water air-conditioning, marine culture together with chilly soil agriculture. The investigation accompanying with wide summary of the technique, marketable regions, technological together with economical appraisal of the technique, effect of environment of the technique double with comparable levelization expenditures of power of this technique with ones that already being completed. The study revealed that the present technique subsists to design ocean thermal energy conversion systems exception of some constituents like Coldwater pipe that represents an engineering question when high energy supply is required and the technique is very expensive.

Ahaotu *et al.*, 2018 conducted thermodynamic development coupled with economic appraisal of OTEC in coastal Nigeria: Bonga Offshore. The work proffers a 50MW ocean thermal energy conversion system that will be located in latitude: $4^{\circ} 30' 01.5''$ together with longitude $4^{\circ} 29' 58.1''$ doubled with the seawater upper surface temperature grading $26 - 29^{\circ}\text{C}$ of twenty meters (20m) deepness together with the grading of 3.5 to 4.0°C of one thousand and twenty one meters (550 - 1021m) deepness which utilizes the temperature gradient to generate electrical power.

Jannis *et al.*, 2020 conducted a reviewable of present development in the economics of ocean thermal conversion. Precisely, in this research work seven cognition voids were fingered and they includes present economic appraisal cynosure on separate systems rather than combine economic possibility within spatial boundaries; the omission of nature's position on the precise



effects of the actual net power output and the incertitude of the capital cost on both plant together with constituent level coupled with costs of operation.

Adesanya et al., 2020 looked at perspectives together with economic effect appraisal of an ocean in Nigeria on the basis of renewable energy. The study reveals that acclimatizing ocean energy in Nigeria can meaningfully generate the required energy irrespective of the large amount it required at the initial stage.

Charles, 2012 performed the thermodynamically economic capability investigation of a 20MW OTEC system. The work looked at the design of a thermal fluids plants modeled closed cycle ocean thermal energy conversion for the aim of appraising the influence of cardinal development parameters of the system performance. Precisely, the appraisal from the various models hint that ocean thermal energy conversion is unquestionably achievable from the angle of engineering but the economical attainability for 20MW system will probably be restricted to remote areas.

Safaa et al., 2022 conducted reviewable improvement of the OTEC plant. The work appraised different models of the ocean thermal energy conversion plants together with the provision of the summary of the principal impediments in the technology of the ocean thermal energy conversion. The study reveals that to ameliorate the efficiency of the ocean thermal energy conversion plants, the optimization of the steam turbine must be carried out coupled with the improvement of the accessible temperature gradient which some diversity kind of energy could be utilized like solar power which can improve plant temperature gradient. Hence, the problem of clean sustainable energy supply via ocean renewable energy via Ocean Thermal Energy Conversion (OTEC) necessitated this project work and the study will design and carryout a performance analysis of OTEC plant for power generation.

2. Material and Methods

The approach adopted in this study encompasses the design and modeling together with performance appraisal of close cycle ocean thermal energy conversion plant for power generation. Since it is known that the ocean thermal energy conversion is a technological renewable energy which utilizes temperature difference between the surface and the depth ocean to generate electrical power as a result of the operation of a low pressure turbine (Vega, 1995; Vega, 2002). There are temperature variations with the depth of Atlantic Ocean water. About 5m to 50m depth, it is relatively warm with about 25 to 30⁰C. This temperature drops rapidly to about 4⁰C at 560m. This made the average temperature difference about 26⁰C. This variation in temperature has made the coastal regions in Nigeria a viable location for the

installation of an OTEC plant. Practically, the design encompasses development of a dependable model via utilization of pertinent data such as surface sea water temperature, sea water temperature at a given depth, mass flow rate of the refrigerant, pressure of the refrigerant etc., and these data will be obtained from the Burutu Offshore Sea and from standard tables and graphs. Also, appropriate thermodynamic principle will also be applied in developing the model equations coupled with ASPEN HYSYS and Microsoft Excel software programs that will also be used to carry out the analysis.

2.1 Modeling of the OTEC Plant

The close cycle OTEC plant being propounded operates similar to the conventional Rankin cycle power plant. It comprises of a turbine, a condenser, the working fluid (Ammonia), ammonia feed pump, an evaporator, and two auxiliary pumps for warm sea surface water and cold sea water.

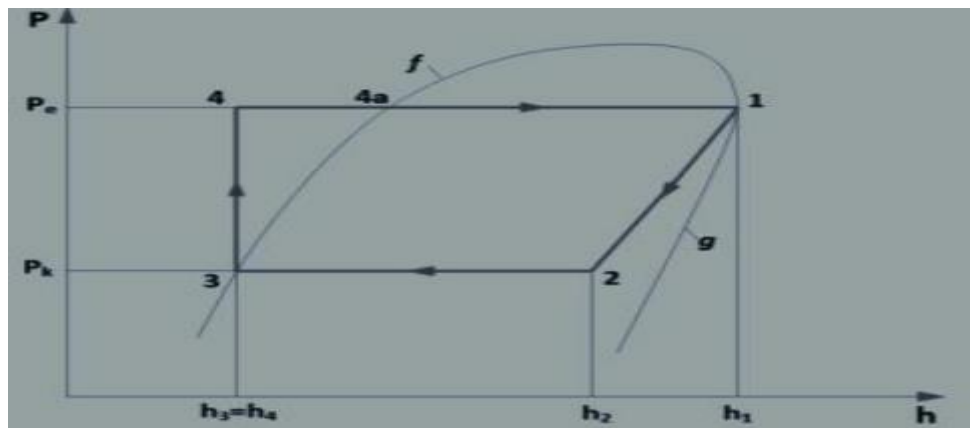


Figure 3: Pressure and Enthalpy (P-H) Diagram of the Proposed OTEC Plant

Meanwhile, the thermodynamic processes of a closed cycle ocean thermal energy conversion system utilizing Ammonia as working fluid are modeled as the saturated Rankine cycle and the appraisal is on the basis of the Figure 3 depicted (Ahoatu *et al.*, 2018):

2.2 Modeling of the Heat

Heat Added to the System (Process 4-1)

$$\text{Heat Added} = Q_{\text{added}} = h_1 - h_4 \quad 1$$

Heat Rejected from the System (Process 2-3)

$$\text{Heat Rejected} = Q_{\text{Rejected}} = h_2 - h_3 \quad 2$$

However for Heat Exchanger that is satisfied with its operations, the heat transfer rate in the Evaporator is expressed as:

$$Q_a = \dot{m}_{\text{hw}} C_{\text{pw}} \Delta T_h = \dot{m}_a (h_1 - h_4) \quad 3$$

Where $\Delta T_h = T_{hi} - T_{ho}$

Also, the rate of Heat Rejected in the main Condenser is expressed as:

$$Q_c = \dot{m}_{hw} C_{pw} \Delta T_c = \dot{m}_a (h_2 - h_3) \quad 4$$

Where $\Delta T_c = T_{ci} - T_{co}$

2.3 Modeling of the Work

Process (1-2) is the Turbine Work while Process (3-4) is the pump work which is expressed as follows:

$$\text{Turbine Work} = W_T = h_1 - h_2 \quad 5$$

$$\text{Pump Work} = |W_p| = h_4 - h_3 \approx \theta_3 (P_4 - P_3) \quad 6$$

$$\text{Net Work} = W_{net} = W_T - |W_p| = h_1 - h_2 - h_3 + h_4 \quad 7$$

The power output of the Ranking power plant is expressed as:

$$\dot{W}_{net} = \dot{m} W_{net} = \dot{m} (h_1 - h_2 - h_3 + h_4) \quad 8$$

The actual mechanical Net Work after putting into consideration the cycle efficiency is expressed as:

$$\dot{W}_{net} = \dot{m}_a W_{net} \eta_{c\ eff} \quad 9$$

2.4 Modeling of the Head Loss and Power Loss

Work is required to move large quantity of warm water (WW) and cold water (CW) around the plant against friction.

The Head Loss due to friction at different section of the pipe is expressed as:

$$h_{fi} = \frac{2f l_i U_i^2}{d_i g} \quad 10$$

The power loss due to at the different sections is expressed as:

$$P_{iw} = h_{fi} m_{iw} g \quad 11$$

The Net Power generated by the ocean thermal energy conversion system after due consideration of the suction pumps is expressed as:

$$\dot{W} = \dot{W}_{net} - P_{iw} \quad 12$$

Where, $P_{iw} = P_{hw} - P_{cw}$

i = signifies for both warm-water and cold-water respectively.

2.5 Modeling of the Efficiency of the System

The Cycle Efficiency of the system is expressed as:

$$\eta_{c\ eff} = \frac{W_{net}}{Q_{added}} = 1 - \frac{h_2 - h_3}{h_1 - h_4} \quad 13$$

The Thermal Efficiency of the System is expressed as:

$$\eta_{thermal} = \frac{T_1 - T_3}{T_3} = 1 - \frac{T_3}{T_1} \quad 14$$

2.6 Modeling of the Speed

The mean speed of the sea water for cold and warm water is expressed as:

$$U_i = \frac{V_i}{A_i} \quad 15$$

2.7 Ocean Thermal Energy Conversion Flow-Chart of Simulation

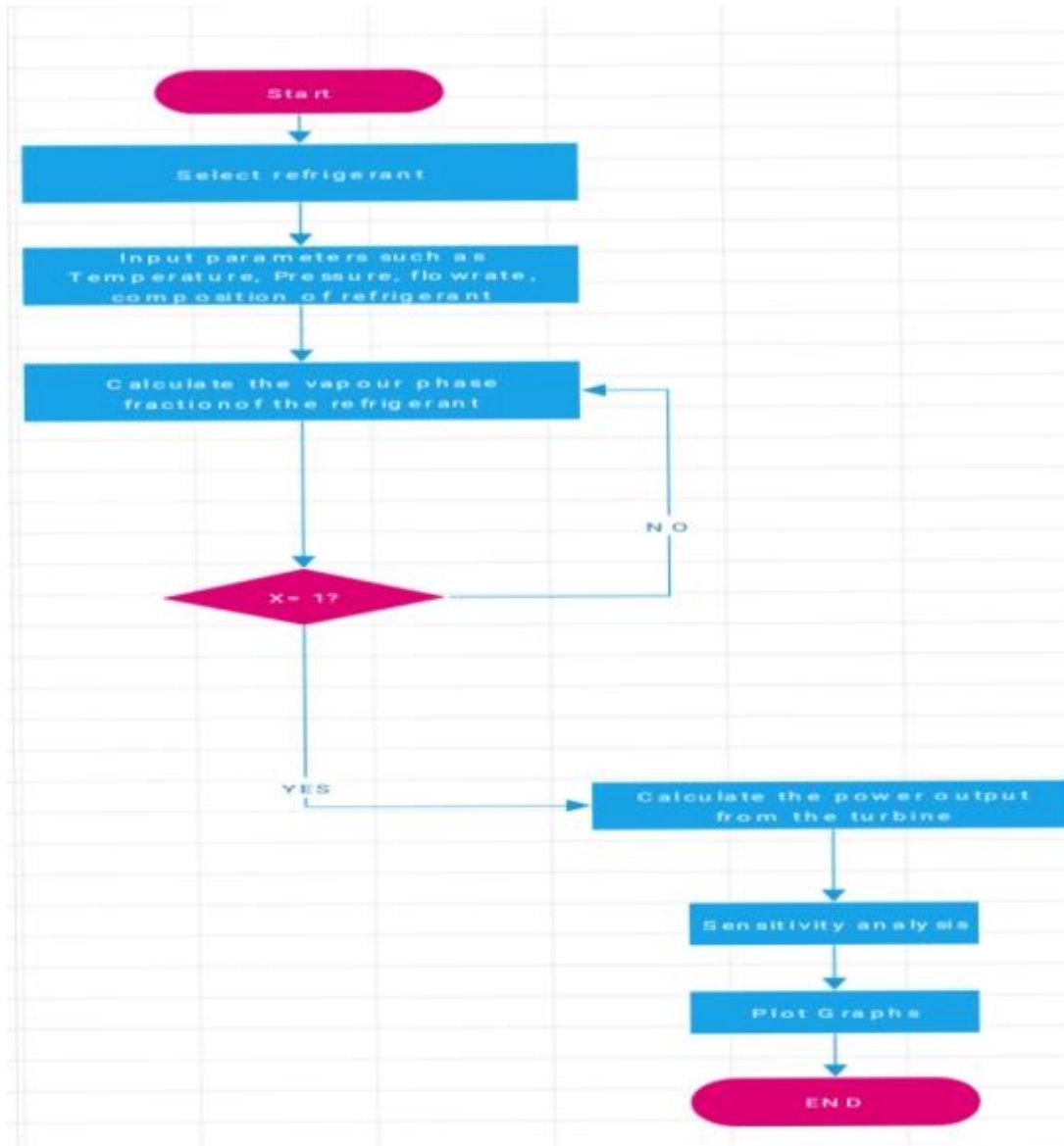
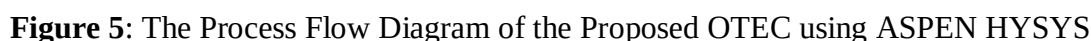


Figure 4: Depicts the Flow Chart simulation of the OTEC using ASPEN HYSYS Software.

2.8 Proposed Ocean Thermal Energy Conversion Process Flow Diagram



3.1 Results

Table 1 shows the initial proposed working design data for the 50MW OTEC plant, Table 2 is the monthly average sea surface temperature of Burutu River, Delta State and Table 3 which is Ammonia utilized enthalpies. The maximum average surface (hot) sea water temperature was utilized and the deep cold seawater temperature was taken as 4–6°C. Precisely, the ASPENHYSYS Software was utilized via the process flow diagram (PFD) putting the atmospheric conditions into considerations and all other thermodynamic data couple with principles: Equations 1-15 was used to generate the following parameters in Tables 4–10 respectively. While the Microsoft Excel software program was utilized to get the characteristics features of the performance of the OTEC plant and it is depicted in Figures 6–16 respectively.

Table 1: Initial Proposed Working Design Data for the 50MW 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	50	MW
Generator Efficiency	0.946	%
Pumps Efficiency	0.895	%
Warm seawater inlet temperature	25.2 and 29.9	°C
Cold seawater inlet temperature	4 and 6	°C
Pipe length of warm seawater	100	m
Pipe diameter of warm seawater	103	m
Pipe length of cold seawater	550	m
Pipe diameter of cold seawater	101	m
Heat exchangers conductivity	14	W/m K
Surface sea water temperature	29.9	°C
Deep cold water temperature	4	°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 Burutu River, Delta State.

Months	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Mini-Temp. (°C)	26.2	26.6	27.6	27.5	27.8	26.1	25.7	25.2	25.4	26.6	27.5	26.9
Max. Temp. (°C)	28.6	29.7	29.3	29.9	29.8	28.8	27.6	26.2	27.5	28.3	29.3	29.3

Table 3: Enthalpies of Ammonia

h1 (KJ/Kg)	h2 (KJ/Kg)	h3 (KJ/Kg)	h4 (KJ/Kg)
1624.7	1564.8	378.03	378.59

Table 4: Generated Turbine Power via Simulation

State	Tout - Pressure	TP - Power
Case 1	300	95.67
Case 2	400	75.13
Case 3	500	57.85
Case 4	600	43.87
Case 5	700	30.76

Table 5: Generated Vapour Phase Fraction via Simulation

State	Sh1 - Temperature	Hw1 - Vapour Fraction
Case 1	20	0.2975
Case 2	22	0.4398
Case 3	24	0.582
Case 4	26	0.7242
Case 5	28	0.8664
Case 6	30	1

Table 6: Generated Turbine Power and Net Work via Simulation

State	Sh1 - Temperature	TP - Power	Pump - Power	Wnet
Case 1	20	14.41	0.2037	14.2063
Case 2	25	29.13	0.3565	28.7735
Case 3	30	44.21	0.5092	43.7008
Case 4	35	73.92	0.662	73.258
Case 5	40	99.49	0.8148	98.6752

Table 3.7: Generated Pump Power via Simulation

State	p2 - Pressure	Pump - Power
Case 1	700	0.2037
Case 2	775	0.3565
Case 3	850	0.5092
Case 4	925	0.662
Case 5	1000	0.8148

Table 3.8: Generated Evaporator Heat Duty via Simulation

Water heater1 - Performance Table			
State	p2 - Pressure	(Tube) (Heat Flow-Heat Flow_2)	Water heater1 - UA
Case 1	800	38	6.57E+05
Case 2	850	46.44	7.01E+05
Case 3	900	54.54	7.53E+05
Case 4	950	62.36	8.16E+05
Case 5	1000	69.89	8.96E+05

Table 3.9: Generated Net Work and Cycle Efficiency via Simulation

p2 - Pressure	Water heater	Turbine Power	Pump - Power	Wnet	neff
800	38	15.08	0.2037	14.8763	39.14816
850	46.44	18.5	0.3565	18.1435	39.06869
900	54.54	21.92	0.5092	21.4108	39.25706
950	62.36	25.34	0.662	24.678	39.57344
1000	69.89	28.76	0.8148	27.9452	39.98455

Table 3.10: Generated Condenser Heat Duty via Simulation

State	Tout - Pressur e	Condenser - Performance Table (Tube) (Heat Flow-Heat Flow_2)
Case 1	400	1133
Case 2	500	1150
Case 3	600	1163
Case 4	700	1173
Case 5	800	1183

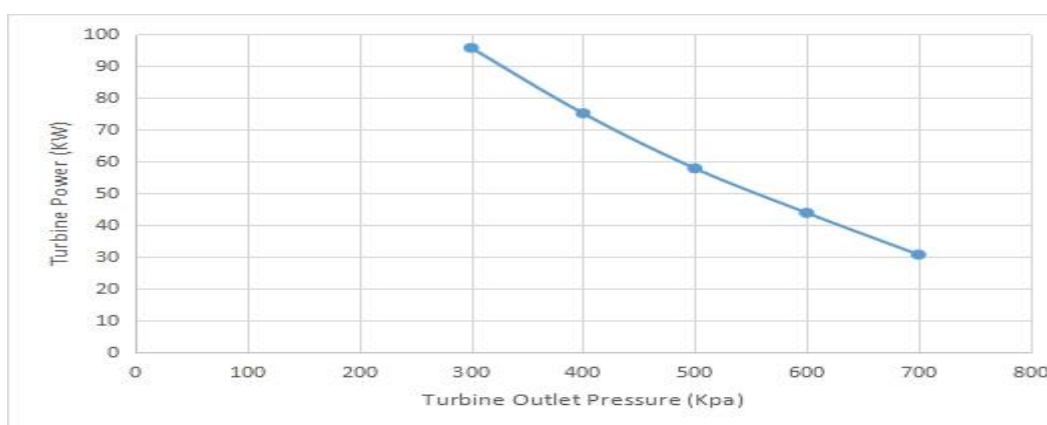


Figure 6: Turbine Power against Turbine Outlet Pressure

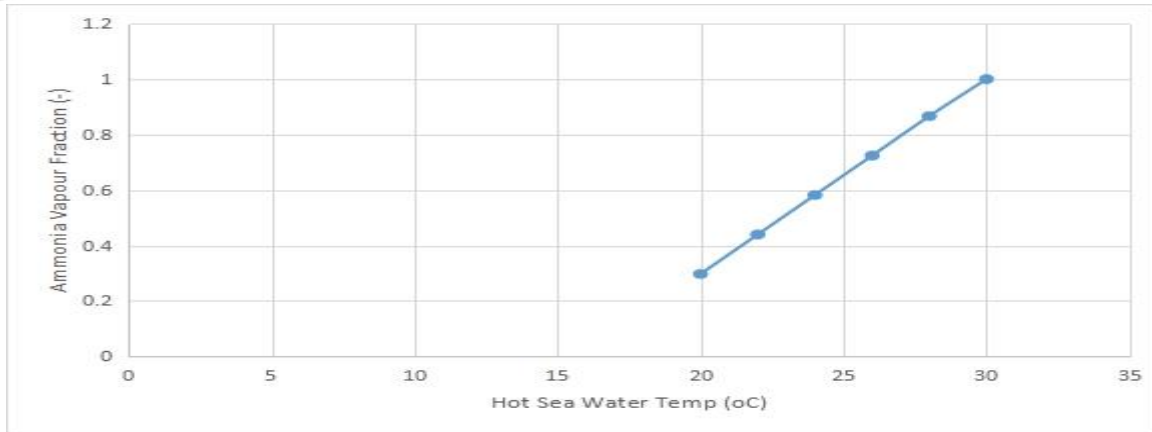


Figure 7: Ammonia Vapour Fraction against the Hot Sea Temperature

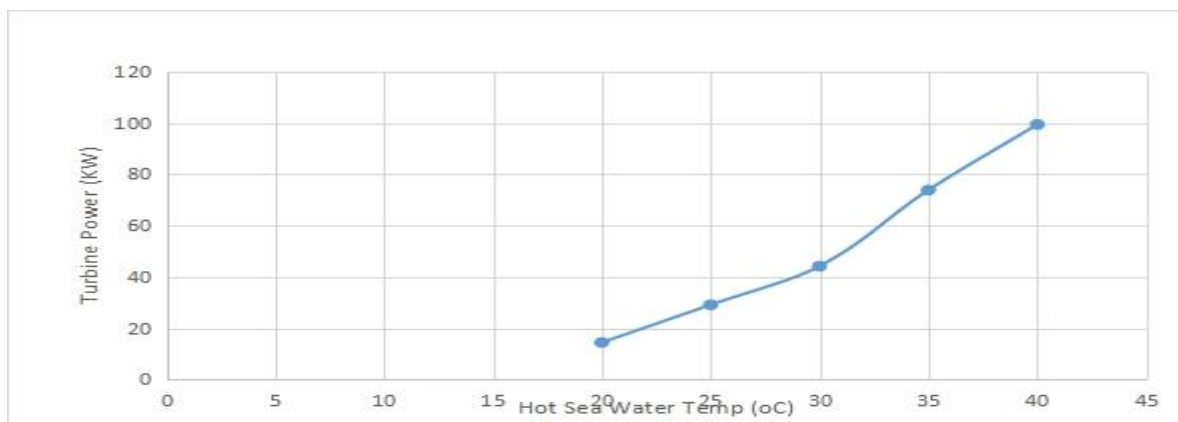


Figure 8: Turbine Power against the Hot Sea Temperature

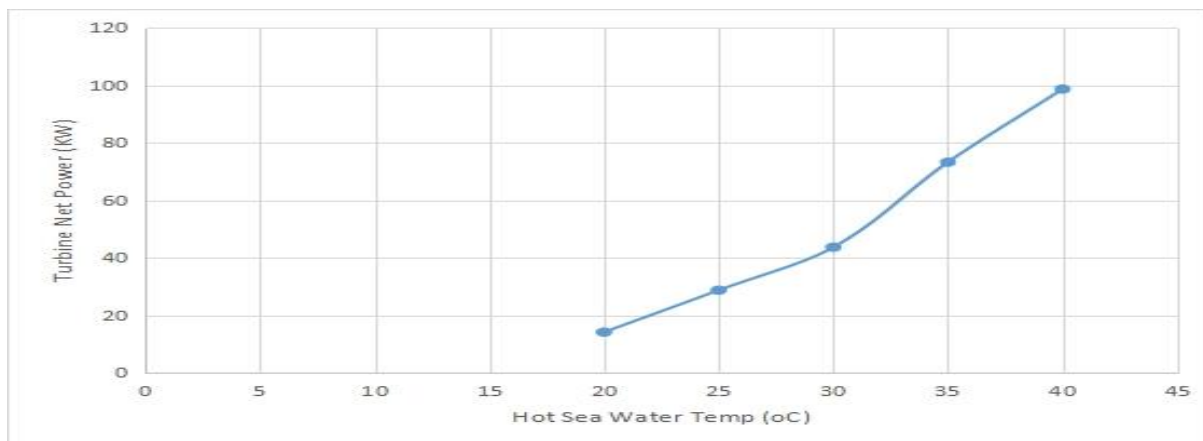


Figure 9: Turbine Net Power against Hot Sea Water Temperature

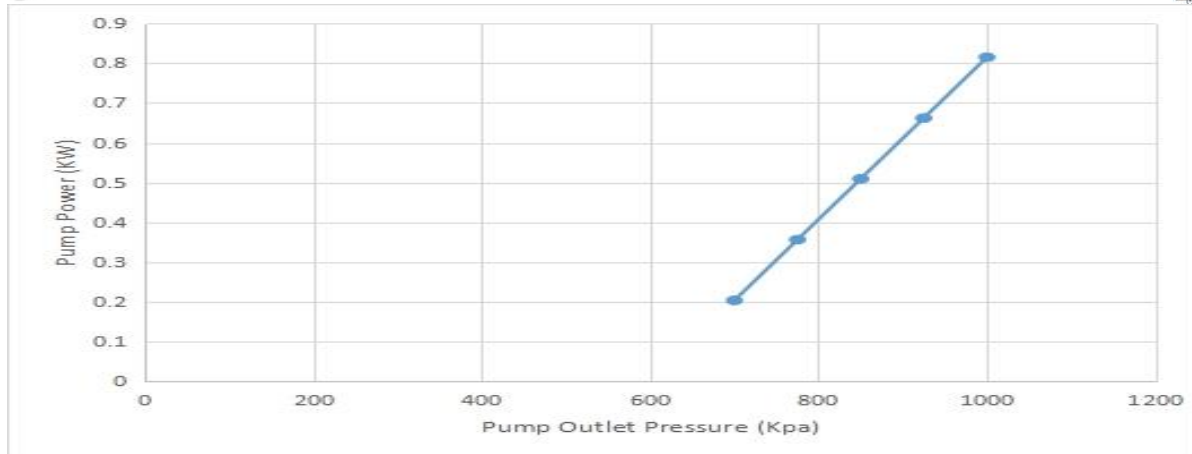


Figure 10: Pump Power against Pump Outlet Pressure

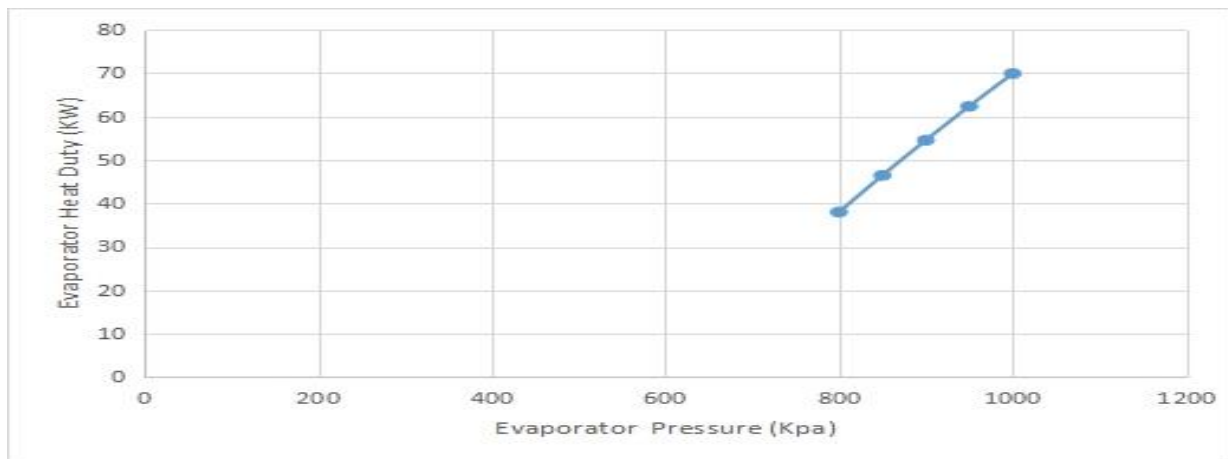


Figure 11: Evaporator Heat Duty against Evaporator Pressure

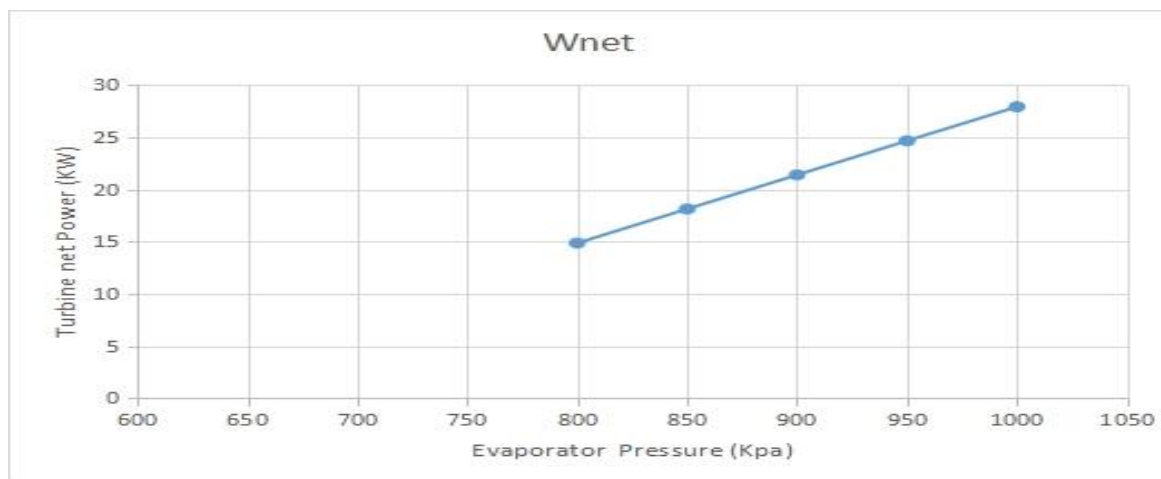


Figure 12: Turbine Net Power against Evaporator Pressure

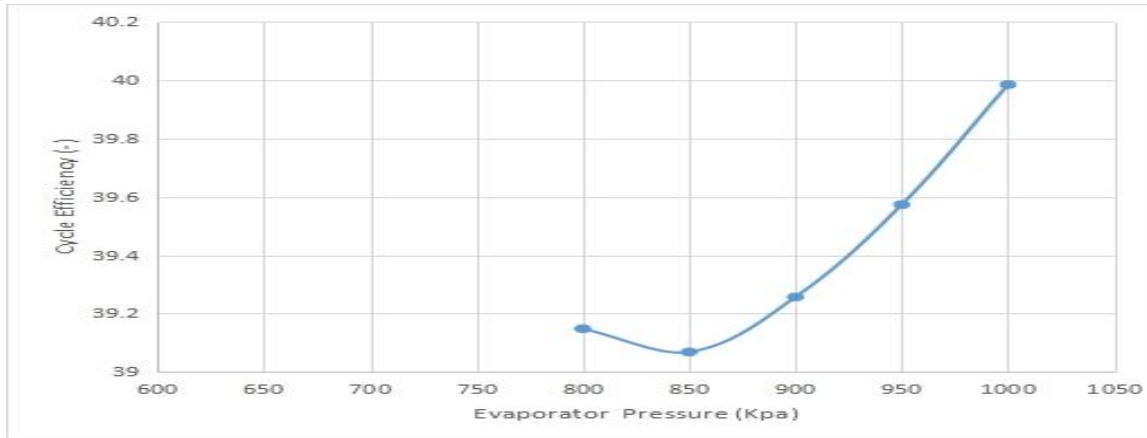


Figure 13: Cycle Efficiency against Evaporator Pressure

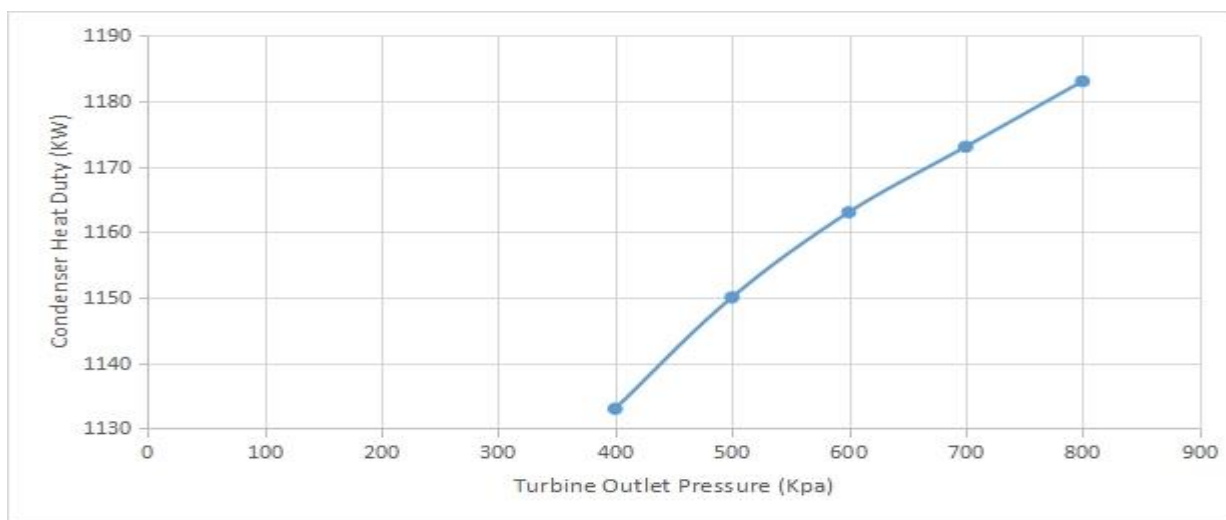


Figure 14: Condenser Heat Duty against Turbine Outlet Pressure

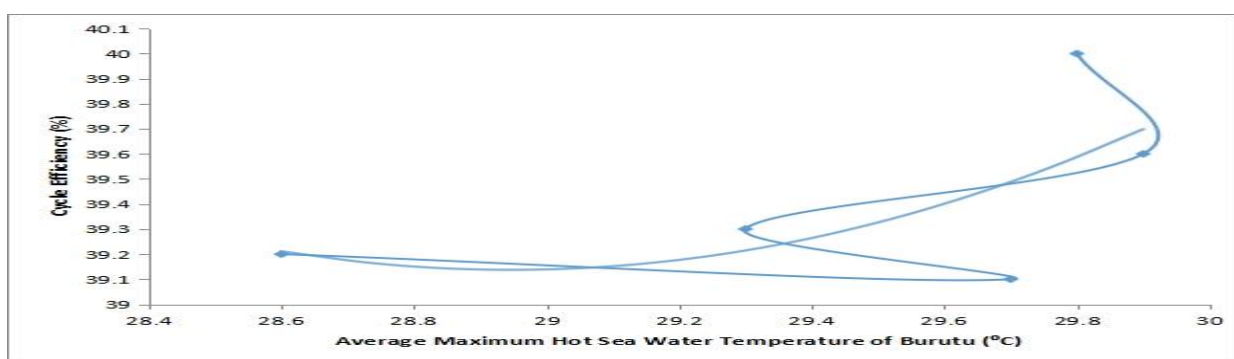


Figure 15: Cycle Efficiency against Average Maximum Hot Sea Water Temperature of Burutu

3.2 Discussion

Figure 6 represents turbine power against turbine outlet pressure showing that the higher the turbine power gives a decrease in the turbine outlet pressure and this means that the OTEC perform normal at a decrease turbine outlet pressure. Figure 7 is ammonia vapour fraction

against the hot sea temperature depicts that as the hot sea water temperatures increases via the aid of the heat exchanger, the concentration of ammonia vapour rises thereby exhibiting enough energy to propel the turbine to turn the alternator for power generation. Figure 8 is turbine power against the hot sea temperature and Figure 9 is turbine net power against hot sea water temperature. The two diagrams represent that as the hot sea water temperature increases via the heat exchanger, the turbine power and the turbine net power increases thereby depicting that the OTEC operation is normal since there is enough temperature difference. Figure 10 is pump power against pump outlet pressure. It shows that as the pump outlet pressure increases, the power to pump the OTEC pump in order for the circulation of the refrigerant in the OTEC system increases. Figure 11 is evaporator heat duty against evaporator pressure. The graph represents that the heat at the evaporator rises correspondingly with respect to the pressure. Figure 12 is turbine net power against evaporator pressure figure and Figure 13 is the Cycle Efficiency against Evaporator Pressure respectively. These diagrams depict that as the evaporator pressure increases, the turbine net power increases with a corresponding increase in the cycle efficiency. It also indicates that the cycle efficiency of the OTEC plant increases with appropriate increase in the evaporator temperature. Figure 14 is condenser heat duty against turbine outlet pressure. The figure illustrates that as the turbine outlet pressure increases, the condenser assumption of heat increases in a parabolic proportion and stops at 1183KW. Furthermore, Figure 15 is cycle efficiency against average maximum hot sea water temperature of Burutu. This is the climax of all depicted that there is potentiality in the citing of the proposed OTEC plant because the mean maximum hot sea water temperature and the cycle efficiency increases proportionally. Also, the cycle efficiency is at normal operational performance in the twelve months of the year.

4. Conclusion

The design and the performance appraisal of proposed ocean thermal energy conversion that will be used for clean power supply in the Niger Delta, Burutu River, Delta State, Nigeria has been conducted. The study indicates that there is potentiality of citing the proposed OTEC because there is enough temperature difference to give rise to a workable cycle efficiency which also indicates normal operational performance. Precisely, Figures 6–15 depict that the OTEC will perform well. Also, the temperature difference is 26.5°C and this is above the recommended 22°C for OTEC plant citing. The cycle efficiency is at normal operational performance in the twelve months of the year considering Figure 15 and Table 2 respectively.



It is recommended a solar booster should be incorporated in the heat exchanger so that it can increase the heat generated and thereby increasing the efficiency of the OTEC plant.

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