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Modeling, Designing and Fabrication of a Mini-Ocean Thermal Energy Conversion Plant for Power Generation

Igoma, E.N.[a], *Tamunodukobipi, D.*[b], *Theophillus- Johnson, K.*[c], *Nitonye, S* [d]

[a] *Marine Engineering Department, Faculty of Engineering, Nigeria Maritime University Okerenkoko, Delta State, Nigheria.*
[b,c,d] *Marine Engineering Department, Faculty of Engineering, Rivers State University, Nkpolu – Oruworukwo, Port Harcourt, Rivers State, Nigeria.*

ABSTRACT

This study focus on the modeling, designing and fabrication of a mini closed-cycle ocean thermal energy conversion (OTEC) power plant for electrical power generation and it has been conducted. The Mini OTEC Plant was fabricated utilizing the designed models. The objective is to synergistically harness both ocean thermal energy and concentrated solar thermal energy as complementary heat sources to elevate the temperature of the surface seawater that is going to the heat exchanger. The plant is ready for experimentation testing of the performance parameters of the OTEC. It is recommended that before the experimentation, the water at the condenser should be below 100C in order to have the required operational differential temperature and this is achievable by using ice blocks.

Keywords: Modeling; Design; Fabrication; OTEC; Generation

1. INTRODUCTION

Nigeria undisputedly is a country endowed with energy resources, yet the energy industry of the country cannot meet the energy requirements of its citizen (Dioha *et al.*, 2018; Osueke and Ezugwu, 2011). Precisely, there is supposed to be an optimistic expectation for stable energy production in Nigeria as a result of the enormous oil and gas reservation, but unstable energy generation makes industrial and economic development unattainable (Bimbola *et al*., 2016). The Ocean Thermal Energy Conversion (OTEC) is an innovative clean energy technology that harnesses the temperature differential between warm surface seawater and colder water found at ocean depths to generate electricity. The OTEC has gained increasing interest globally due to its potential as a renewable, sustainable electricity source with minimal environmental impact (Carlson *et al.*, 2014; Del Rio and Mir-Artigues, 2014). While large-scale OTEC plants over 100 MW capacity has proven technologically feasible (Vega and Michealis, 2010). Further work is still needed to improve efficiencies and cost-effectiveness, especially for smaller modular platforms that could provide distributed power generation more locally (Rajagopalan and Nihous, 2013). Several studies have highlighted the promise of OTEC in island communities and developing nations near the tropics, where sea surface temperatures tend to be the warmest (Nihous, 2005; Robert *et al.*, 2009). In particular, implementing and testing modular mini-OTEC systems may hold unique advantages for bringing clean electricity to isolated rural regions and islands currently off national power grids in countries like Nigeria (Okoro *et al.*, 2013). With Nigeria possessing a long coastline in the Gulf of Guinea and an abundance of shallow offshore oil platforms no longer in use, the ocean space and infrastructure for innovative mini-OTEC projects is immense (Nnaomah and Arisukwu, 2012).

2. LITERATURE REVIEW

A variety of efforts creating small to medium scale OTEC models for concept validation, component testing, and thermodynamic assessment provide context for this study focused on a mini plant tailored to Nigerian waters. Early numerical models used steady state mass and energy conservation equations applied to control volumes representing each component to predict overall OTEC performance metrics like power generated based on desired operating conditions and seawater temperatures (Avery & Wu, 1994). Subsequent dynamic simulations offered more temporal fidelity (Yasunaga *et al.*, 2011). Leveraging modern software packages supports quickly evaluating multiple configurations. For example, ASPEN Plus and HYSYS have been deployed to simulate 10-100 kW modular OTEC systems in recent years and provide good initial sizing estimates before building hardware prototypes (Vega, 1992; Xu and YaLing, 2011). Physical test facilities have ranged from miniature bench top units to offshore platforms with up to 105 kW capacity (Rajagopalan and Nihous, 2013). A small-scale ammonia-water system built at the Solar Energy Research Institute in the early 1980s helped verify component sizing and control principles (Bharathan *et al.*, 1988). In Japan, a 100-kW closed cycle OTEC was connected to land grid supply via undersea cable, demonstrating stable power supply over three years and yielding insightful temperature/pressure data (Ikegami and Uehara, 1990). The world's largest 0.25 MW experimental open cycle plant operated for months offshore Hawaii in 2015, overcoming corrosion and vapour formation challenges that had stymied earlier attempts (Cohen, 2009). These pioneering setups have provided empirical validation of OTEC systems at different scales and boundaries. The modular nature also points to a potential pathway for incremental capacity growth from small units to central plants. This background helps inform design decisions for the mini OTEC project in Nigeria using simulation-driven development complemented by hands-on testing. Hence, this study will look at modeling, designing and fabrication of a mini-ocean thermal energy conversion plant for power generation in Nigeria.

3. MATERIALS AND METHOD

3.1 Materials Used

The materials used during the fabrication process were locally source and they are:

i. $1\frac{1}{2}$ inches Stainless Sheet Plate
ii. 316 L $\frac{1}{2}$ inches Stainless tube round Pipes
iii. 25 Pieces of Stainless Coupling Plugs
iv. 12 Kg Gas Cylinder for the storage of the Refrigerant
v. Heat Exchanger Accessories: Stainless Sheet and Stainless tubes
vi. Condenser Accessories: Stainless Sheet and Stainless tubes
vii. Turbine Accessories: Impeller made of Stainless Steel and cylindrical compartment.
viii. Five (5) Digital Temperature Control Gauge
ix. Five Analog Pressure Control Gauge
x. 0.5KW pump
xi. Stop/control Valves
xii. 1.5KVA Alternator
xiii. Temperature Control Dashboard
xiv. 10 packets of Electrodes
xv. 6 lengths of 1.5 inches Angle Steel Iron
xvi. lengths of 1.5inches Square Pipe Steel Iron
xvii. Ammonia Refrigerant
xviii. Small 0.5KVA Generator for Initial Start-up
xix. Ice Block
xx. Water
xxi. ASPEN HYSYS Software
xxii. MATLAB Software
xxiii. PFD Software
xxiv. EXCEL Software

3.2 Conceptualization and Modelling of the Mini-OTEC System

3.2.1 Process Flow Diagram of the Mini -OTEC Plant

The mini-scale OC-OTEC prototype is constructed according to the schematic outlined in **Figure 1**, adhering to appropriate engineering specifications for components like pipes, pumps, turbines, and concave glass reflectors serving as integrated solar collectors and condensers. During operation, instrumented readings will be taken, and experimental results meticulously recorded. Systematic validation studies will assess the agreement between experimental measurements and simulated model predictions (Aydin, 2013; Adesanya *et al.*, 2020; Aldale, 2017). The plant encompasses the pipes with specifications at each section used, pump, turbine, water heater, solar water heater and solar boiler respectively.

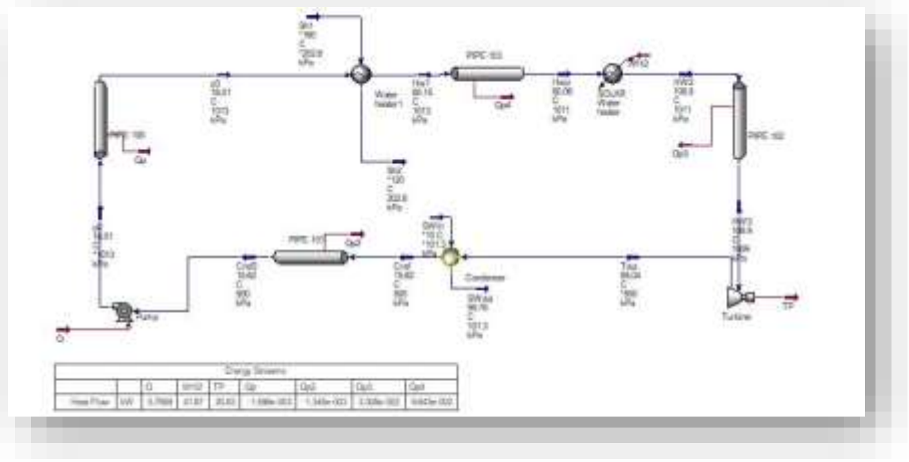

Figure 1 Mini Close Cycle OTEC Sketch HysysASPEN Interface Diagram

3.3 Design and Fabrication of the Mini- OTEC System Components

3.3.1 Volume of the Heat Exchanger Tank

Figure 2 illustrates the rectangular tank that was used to construct the heat exchanger for the mini-OTEC plant. While the heat exchanger and condenser share similarities in their design, they serve different purposes in the system. The heat exchanger is employed to transfer heat to the working fluid, whereas the condenser's role is to remove heat from the working fluid, facilitating the cooling process (Yunus & Afshin, 2015).

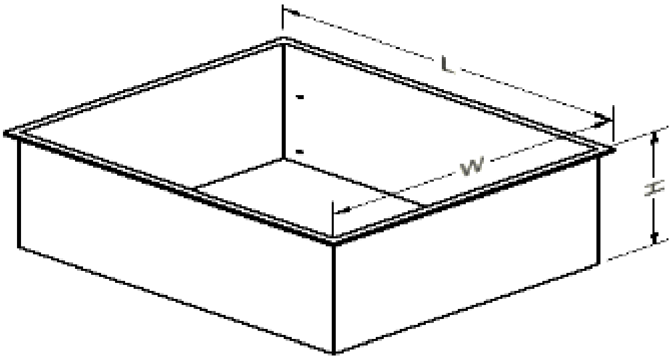

Figure 2 Heat Exchanger/Condenser Tank

From **Figure 2**, the volume of the heating tank is expressed as follows

$$V = AH \quad (1)$$

$$A = LW \quad (2)$$

$$V = LWH \quad (3)$$

where :

$V =$ Volume, $A =$ Area, $L =$ Length, $W =$ Width and $H =$ Height.

3.3.2 Coil Surface Area

The surface area of the coil utilized by the heat exchanger/Condenser as shown in **Figure 4** is expressed as (Yunus & Afshin, 2015).

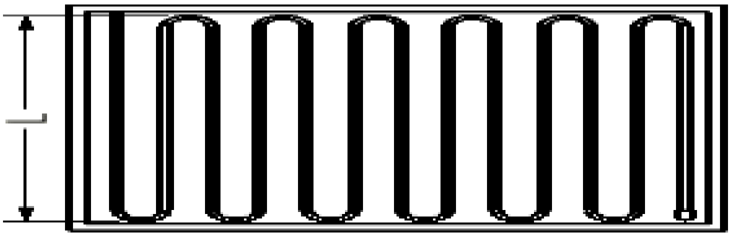

Figure 3 Multi-phased Coils of the Heat Exchanger and Condenser

$$A_{coil} = \pi D N L_{coil} \quad (4)$$

where : D = Coil diameter, N = Number of turns, and L_{coil} = Length of coil.

3.3.3 Tank Surface Area

The surface area of the tank is expressed as

$$A_{tank} = 2[(LW) + (LH) + (WH)] \quad (5)$$

This accounts for the surface area of all sides of the tank

3.3.4 Insulation thickness

Insulation is added around the tank to minimize heat loss. This is crucial for maintaining a consistent temperature of the fluid. It is expressed as

$$t_{ins} = \frac{T_{tank} - T_{ambient}}{K_{ins}} \quad (6)$$

3.3.5 Overall Heat Transfer Coefficient (U)

The overall heat transfer coefficient for the system is determined by the combined effects of the several resistances such as conduction through the tank material and convection at the fluid interface. The equation for calculating the overall heat transfer coefficient is (Yunus & Afshin, 2015).

$$\frac{1}{U_o} = \frac{1}{h_{in}} + \frac{L_{tank}}{K_{tank}} + \frac{1}{h_{out}} \quad (7)$$

where

L_{tank} = thickness of the tank wall,

K_{tank} = thermal conductivity of the wall material,

h_{in} and h_{in} = convective heat transfer coefficient on the inside and outside of the tank.

Considering the overall heat transfer coefficient for the tank equation (3.35) becomes:

$$\frac{1}{U_{tank}} = \frac{1}{h_{in}} + \frac{L_{tank}}{K_{tank}} + \frac{1}{h_{out}} \quad (8)$$

Also, considering the overall heat transfer coefficient for the tank equation (3.35) becomes:

$$\frac{1}{U_{coil}} = \frac{1}{h_{in}} + \frac{L_{coil}}{K_{coil}} + \frac{1}{h_{out}} \quad (9)$$

$$\frac{1}{U_{total}} = \frac{1}{U_{tank}} + \frac{1}{U_{coil}} \quad (10)$$

Therefore,

$$U_{total} = \frac{1}{\frac{1}{U_{tank}} + \frac{1}{U_{coil}}} \quad (11)$$

3.3.6 Pulley and Belt System Design

In this study, a pulley and belt system is used in the turbine (driver) and the alternator (driven) assembly as illustrated in **Figure 5** (Scribd, 2023; Lingyuan & Robert, 2005).

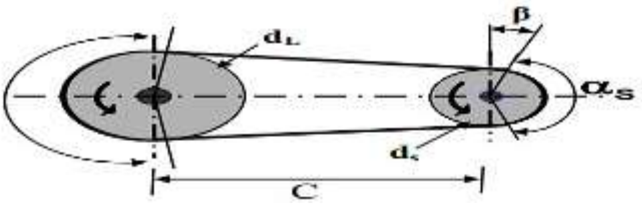

Figure 4 Pulley and Belt System (Scribd, 2023)

The design equations help determine various parameters such as the speed ratio, belt length and pulley sizes.

3.3.7 Speed Ratio

The speed ratio is the ratio of the speed of the driven pulley to the driver pulley as expressed:

$$N_s = \frac{N_2}{N_1} \quad (12)$$

3.3.8 Belt Length

The length of the belt coupling the driver and the driven pulley is expressed as:

$$L_B = \pi(r_1 + r_2) + 2C + \frac{(r_1 - r_2)^2}{C} \quad (13)$$

where

r_1 and r_1 = radius of the driver and driven pulleys,

C = center distance between the pulley centers.

3.3.9 Tangential Velocity

The tangential velocity is given as

$$V_t = \frac{\pi D_1 N_s}{60} \quad (14)$$

3.3.10 Tension in Belt

The belt tension is the force that keeps the belt in contact with the pulleys and prevents it from slipping or sagging. It is expressed as follows:

The power that the belt can transmit is calculated as

$$P = (T_1 - T_2)V \quad (15)$$

$$\frac{T_1}{T_2} = e^{\mu\theta} \quad (16)$$

$$T_1 = T_2 e^{\mu\theta} \quad (17)$$

where T_1 and T_2 are the tension in the tight and slack sides of the pulley-belt assembly

3.3.11 Refrigerant Storage Tank Sizing

The ammonia storage tank serves as a reservoir for storing the ammonia refrigerant, which is utilized as the working fluid in this study. The dimensions and sizing of the ammonia storage tank, as depicted in **Figure 6**, are provided as follows:

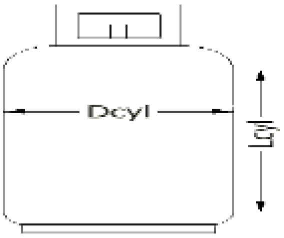

Figure 5 Refrigerant Storage Tank

$$V_{st} = V_{cyl} + 2(V_{ellipse}) \quad (18)$$

$V_{cyl} = \pi r_{cyl}^2 h_{cyl}$ (19)

$V_{ellipse} = \frac{\pi}{24} D_h^3$ (20)

Therefore equation (3.45) becomes,

$V_{st} = \pi r_{cyl}^2 h_{cyl} + 2(\frac{\pi}{6} D_h^3)$ (21)

where

r_{cyl} = radius of the cylindrical body, h_{cyl} = height of the cylindrical body and

D_h = diameter of the elliptical head.

3.3.12 Fabrication Process

The fabrication process commenced after modeling the dimensions of the various components that make up the mini-OTEC plant. The ASPEN HYSYS Software was used to verify the accuracy of the modeling and dimensions before proceeding with the fabrication. The modeling and ASPEN HYSYS Software also guided the selection of the specific pipes to be used in the piping system. This was achievable utilizing the specifications given in the **Figure 1** in the material selection. The heat exchanger and condenser were fabricated using materials such as stainless-steel sheet plates, and the tubing was made using 316 L $\frac{1}{2}$ inches stainless steel round pipes. The impellers of the turbine and the cylindrical body, known as the turbine housing, were manufactured from stainless steel plates. The fabrication of these three components was carried out with a focus on air and water tightness, ensuring that there were no leaks. Angle steel and square pipe steel were used to construct the housing for all the components of the Mini-OTEC, including the heat exchanger, condenser, turbine with impeller, coupling plugs, valve, pump, gas cylinder, alternator, and temperature dashboard. The diagrams of the modeling are shown in **Figure 7 - 11.**

Figure 6 3D Model of the Mini-OTEC Plant

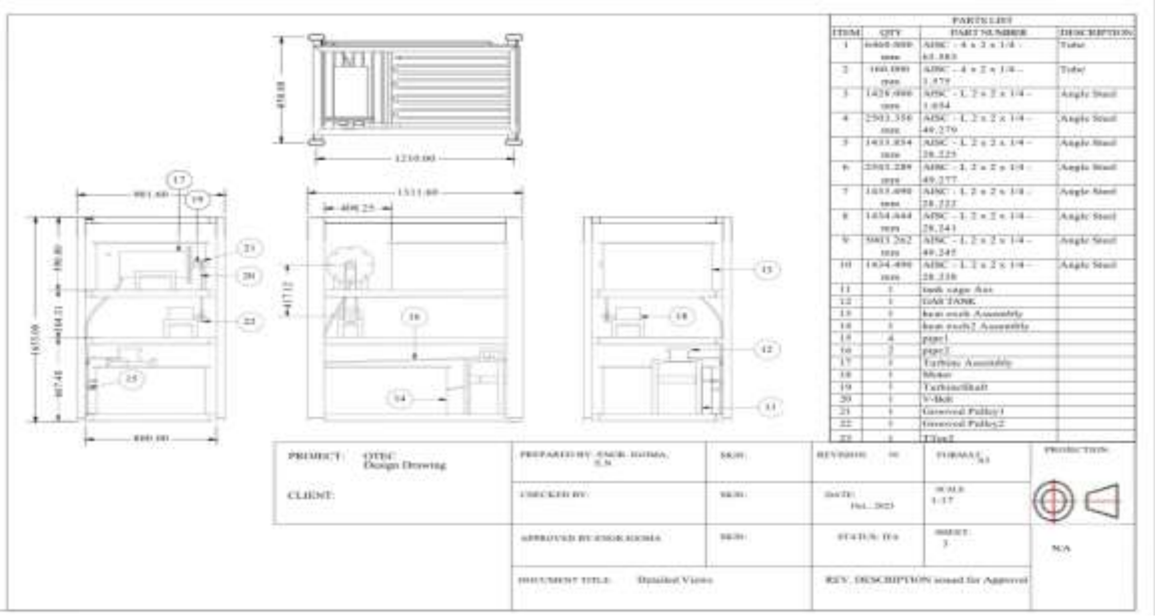

Figure 7 Sectioning/ Dimension of the Model of the Mini-OTEC Plant

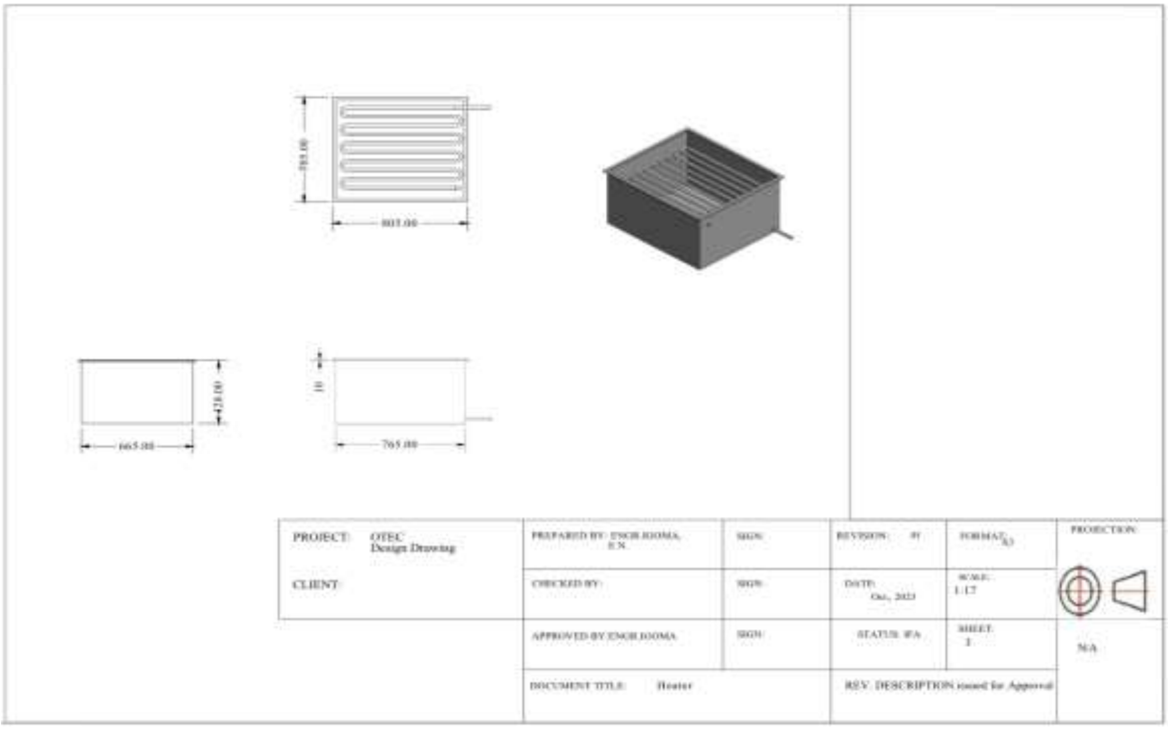

Figure 8 3D Model of the Heat Exchanger

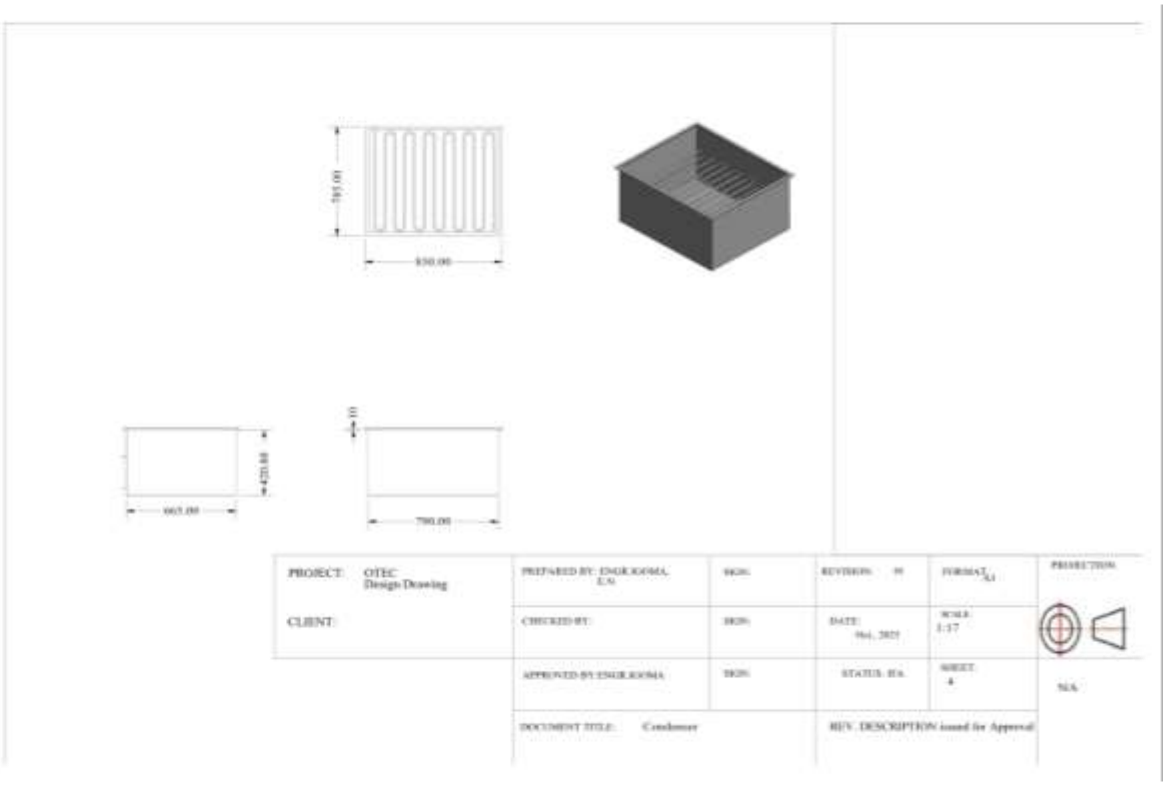

Figure 9 3D Model of the Condenser

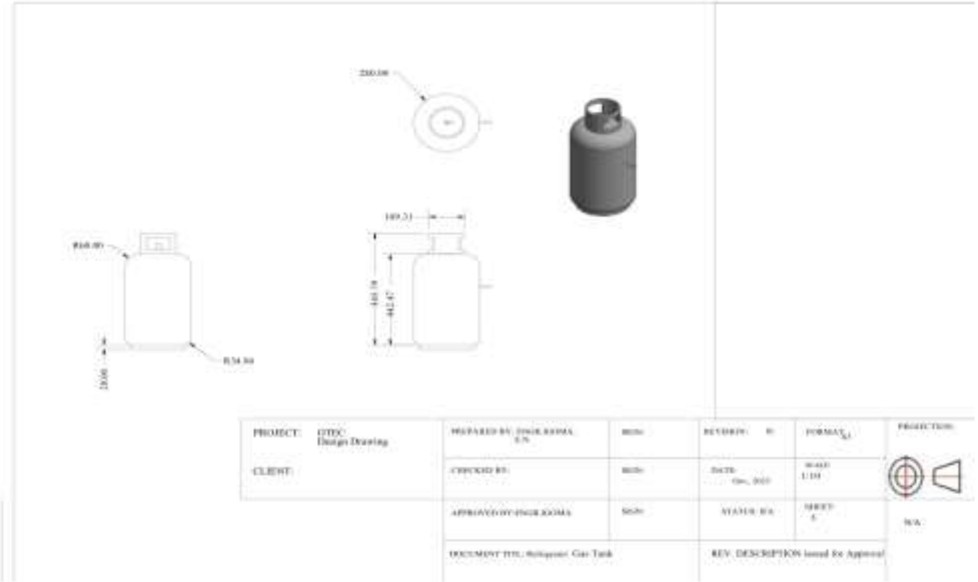

Figure 10 3D Model of the Refrigerant Gas Tank

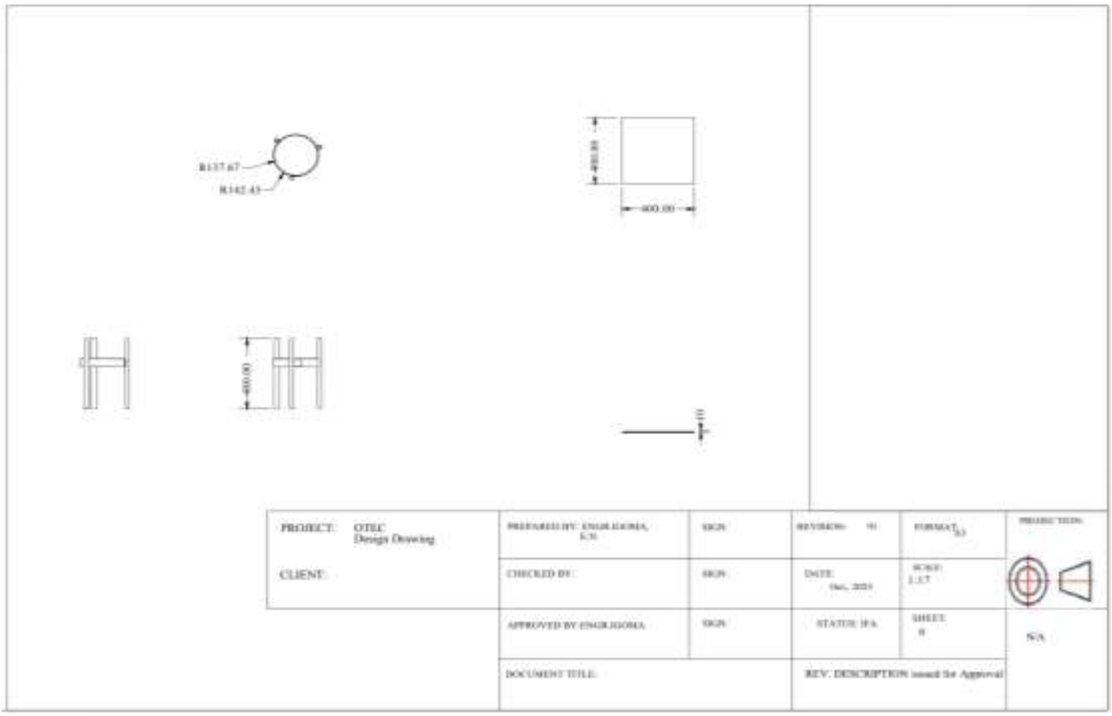

Figure 11 3D Model of the Refrigerant Gas Tank Holder

4. RESULTS AND DISCUSSION

Plate 1 is the product of the design and fabrication work done. It is a pictorial view depicting the fabricated Mini-OTEC plant with all the components incorporated.

Plate 1 Pictorial View of the Mini –OTEC Plant

5. CONCLUSION

This study focus on the modeling, designing and fabrication of a mini closed-cycle ocean thermal energy conversion (OTEC) power plant for electrical power generation and it has been conducted. The Mini OTEC Plant was fabricated utilizing the designed models and it is depicted in **Plate 1**. The objective is to synergistically harness both ocean thermal energy and concentrated solar thermal energy as complementary heat sources to elevate the temperature of the surface seawater that is going to the heat exchanger. The plant will be utilized for experimental test characterization of the performance parameters of the OTEC.

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