

# **Heat Exchangers of 2 MW OTEC in 3T Region “Siberut Island, Sumatra Barat, Indonesia”**

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## **ABSTRACT**

Indonesia is an equatorial country located at latitudes less than 20 degrees covered by 77 % ocean with thousand islands, strain and many difference of topography. Most of areas are in the deep sea, OTEC is very compatible build in Indonesian. As thermal efficiency of the OTEC is low, it is necessary to reduce energy loss in heat exchangers by reducing the temperature difference between sea water and working fluid. This paper discussed on heat exchanger of 2 MW OTEC in Siberut Island Sumatra Barat, Indonesia. The required area of heat transfer of evaporators and condensers is 5381 m<sup>2</sup> and 4141 m<sup>2</sup>, respectively.

**KEY WORDS:** *Siberut Island, Sumatera Barat, Indonesia, 2MW Ocean Thermal Conversion Energy, Heat Exchangers.*

## **NOMENCLATURE**

|      |                                  |
|------|----------------------------------|
| TTT  | Terluar, Terdepan & Terbelakang  |
| LMTD | Long Mean Temperature Difference |
| OTEC | Ocean Thermal Energy Conversion  |
| SST  | Sea Surface Temperature          |

## **1.0 INTRODUCTION**

Indonesia is a tropical archipelago consisting of 17,000 islands with coastline of 95,185 kilometers, approximately located at latitudes less than 20 degrees may be defined as enormous passive solar collectors. Indonesia has 77% of the total area covered by the ocean, most area in the deep sea as shown in Figure 1. Ocean Thermal Energy Conversion (OTEC) can be effectively applied within a large scale to provide a source of renewable energy that is needed to cover a wide range of energy issues. As an OTEC system operates in conditions of small temperature differences within 20 degrees, an appropriate working fluid must have a low boiling point if it is to be used in a closed-cycle OTEC. The OTEC system requires surface seawater, deep seawater, and a working fluid pump power; the ratio of the surface and deep water pump power to output power is comparatively higher than that of conventional fossil power plants.

Many studies on OTEC conventional closed cycles to improve efficiency by exploiting low boiling point work fluids such as ammonia. The results show that the thermal efficiency of the OTEC cycle can be improved in two ways, namely: first by reducing irreversible losses in the cycle and second by increasing the effective temperature difference, specifically the difference between evaporation temperature and working fluid condensation. Efficiency can be increased by reducing energy loss in heat exchangers which can be done by reducing the temperature difference between sea water and working fluid. This technique is done by increasing the area of heat transfer or the overall heat transfer coefficient.

Koto et.al has applied closed cycle OTEC in several locations in Indonesia such as Mentawai, Sumatera Barat (A), North of Sulawesi Utara (B), North of Maluku Utara (C) and Banda (D), Maluku, Makasar Strait (E), East Kalimantan (F), North of Bali (G), Nusa Tenggara Barat (H), Papua Barat (I), Sulawesi Tenggara (J) [3-13]. This paper discusses on heat exchanger of 2 MW OTEC in Siberut, West Sumatra, Indonesia.

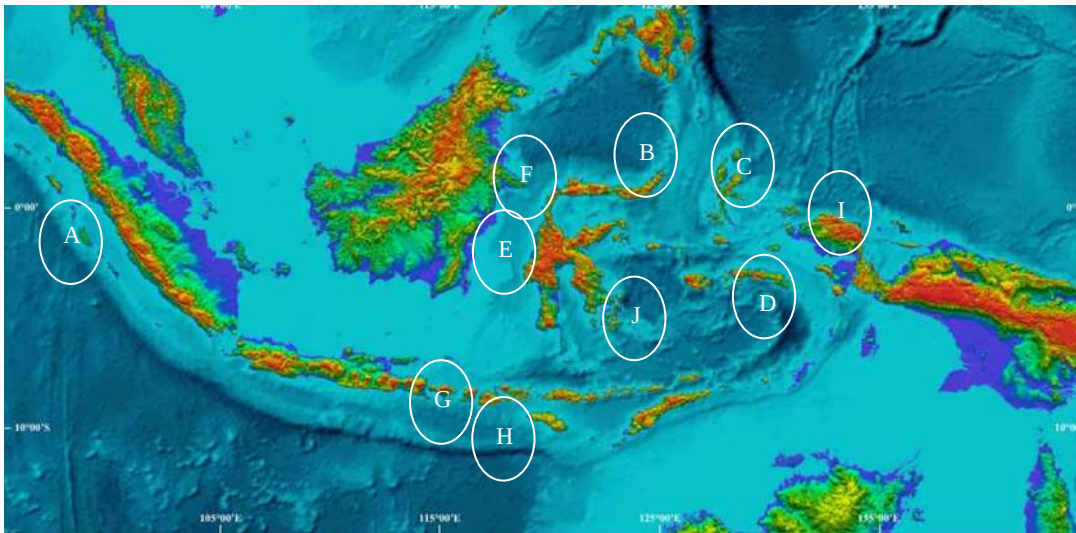


Figure 1: Bathymetry map of Indonesia [1-11]

## 2.0 HEAT EXCHANGER ON OTEC

### 2.1 Types and Flow Arrangement of Heat Exchanger

A heat exchanger is a heat transfer device for cooling and heating processes of two or more fluids. The fluids are separated by a solid wall to prevent mixing or they may be in direct contact. An example heat exchanger is found in an internal combustion engine. A circulating fluid known as engine coolant flows through radiator coils and air flows past the coils which cools the coolant and heats the incoming air. There are many types of heat exchangers as follows:

1. shell and tube heat exchanger,
2. plate heat exchangers,
3. plate and shell heat exchanger,
4. adiabatic wheel heat exchanger,
5. plate fin heat exchanger,
6. pillow plate heat exchanger,
7. fluid heat exchangers,
8. waste heat recovery units,
9. dynamic scraped surface heat exchanger,
10. phase-change heat exchangers,
11. direct contact heat exchangers and
12. micro-channel heat exchangers

There are three primary classifications of heat exchangers according to their flow arrangement.

- a. In *parallel-flow heat exchangers*: the two fluids enter the exchanger at the same end, and travel in parallel to one another to the other side as shown in Figure 2.
- b. In *counter-flow heat exchangers*: the fluids enter the exchanger from opposite ends. The counter current design is the most efficient, in that it can transfer the most heat from the heat (transfer) medium per unit mass due to the fact that the average temperature difference along any unit length is higher.
- c. In a *cross-flow heat exchanger*: the fluids travel roughly perpendicular to one another through the exchanger. For

efficiency, heat exchangers are designed to maximize the surface area of the wall between the two fluids, while minimizing resistance to fluid flow through the exchanger.

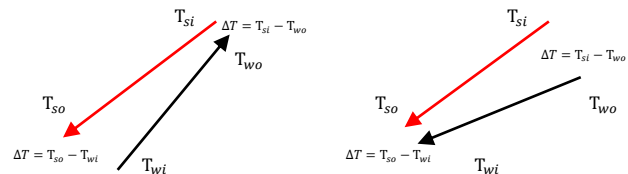


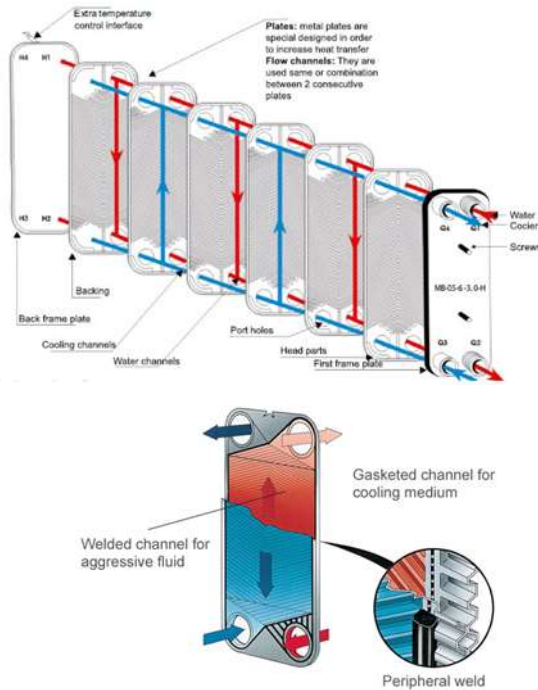
Figure 2: Countercurrent (left) and parallel (right) flows.

### 2.1 Plate Heat Exchanger

A Plate heat exchanger (PHE) is an apparatus for exchanging heat between seawater and a medium to be heated or cooled by the seawater and comprises a plurality of plates, wherein seawater is made to flow in the opposite directions on both the side of each plate. PHE is manufactured by many thin with arrangement slightly separated plates with very large surface areas and small fluid flow passages for heat transfer. The arrangement of PHE typically has lower volume and cost. The PHE serves low to medium pressure fluids. The PHE employ more counter current flow rather than cross current flow, which allows lower approach temperature differences, high temperature changes, and increased efficiencies.

Plate and shell heat exchanger offers high heat transfer, high pressure, high operating temperature and close approach temperature. The heat transfer area of a gasket plate-and-frame heat exchanger consists of a series of corrugated plates, assembled between the frame and pressure plates, which retain the design pressure as shown in Figure 3. For the highest thermal performance and to enable a very close temperature approach, fluids normally run counter-currently through the heat exchanger.

The sealing between the plates on the Industrial semi-welded line alternates between laser welds and gaskets. The laser welded channel allows use of fluids that are not compatible with normal gaskets and also allows for higher design pressure than fully gasket plate-and-frame heat exchangers



**Figure 3:** Fluid temperatures

There are three types of heat transfer that using PHE technology responsible for heat exchange: namely,

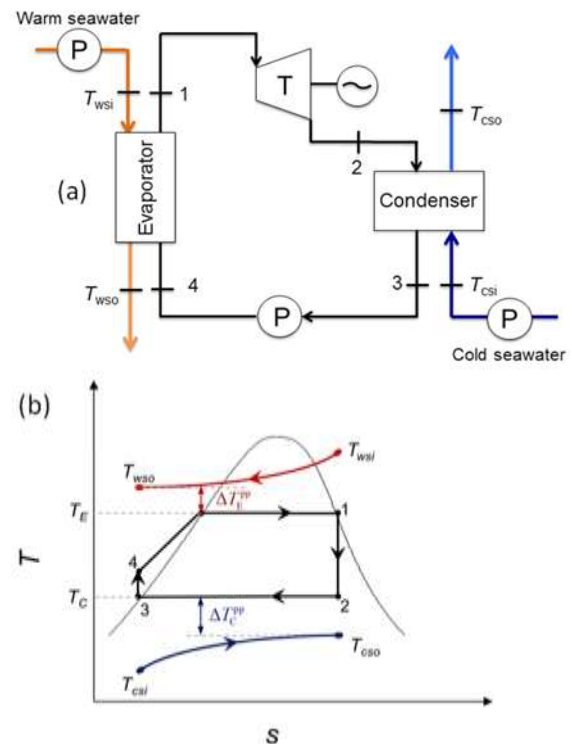
1. liquid-single-phase forced-convection heat transfer which is hot water discharged cooled by cold seawater;
2. evaporation heat transfer which is working fluid converted into gas by warm seawater as in the case of ocean thermal energy conversion
3. Condensation heat transfer which is working gas is converted into liquid.

Improving the performance of each type of heat transfer improves the efficiency of heat exchangers. There are two critical parameters in the design-point analysis of the heat exchanger which is the overall heat transfer coefficient and surface area. Various research and development have so far been carried out to improve the efficiency of heat exchangers. There are several methods of improving the heat transfer from the plate material, particularly in the case of evaporation heat transfer.

1. Thermally spraying stainless steel particles on a plate surface to make it porous.
2. Utilization of the electro deposition of copper to form a coating film with fine asperities on the surface. The fine asperities on a surface act as boiling nuclei to promote nucleate boiling and thus improve evaporation heat transfer.

## 2.2 Rate of Heat Transfer

The single stage ideal cycle provides an idea of the scale of the operating conditions of an OTEC plant. Figure.4 shows closed cycle Ocean Thermal Energy Conversion Schematic. The evaporator and pumps can be generated using solar or wind energies due to cheaper that OTEC system. The waste surface seawater can be distilled to produce fresh water and the deep seawater can be used to produce cooling system for distillation fresh water and cold agriculture.



**Figure 4:** (a) Closed Cycle of Ocean Thermal Energy Conversion Schematic and (b) Temperature versus entropy diagram [Hakan].

The simple ideal Rankine cycle model calculates the work output from the power cycle and cycle efficiency based on the specified design parameters. There are four principal states in a Rankine cycle, and four principal processes.

- The first process is from state 3 to state 4 which pressurize the saturated liquid working fluid from the condenser temperature and pressure to the saturation pressure of the evaporator.
- Next process is from state 4 to state 1. The working fluid is evaporated to change phase from a liquid to a saturated vapor.
- Third process is from state 1 to state 2 in which the vapor is then expanded through a turbine to generate work.
- Finally, from state 2 to state 3, the saturated liquid-vapor mix is condensed back down to saturated liquid.

### 2.2.1. Evaporator

In the OTEC system, a working fluid is evaporated to saturated vapor by receiving heat from the warm seawater. Under the assumption that seawater is an ideal incompressible fluid, the rate of heat transfer from the continuous phase to the dispersed phase ( $\dot{Q}_e$ ) in (W), given by:

$$\dot{Q}_e = \dot{m}_f (h_1 - h_4) = \dot{m}_w \cdot c_p \cdot (T_{wi} - T_{wo}) \quad (3.2)$$

Where;  $\dot{m}_f$  is mass flow rate of working fluid (kg/s),  $h_{1-4}$  is enthalpy working fluid at inlet and outlet (J/kg),  $\dot{m}_w$  is mass flow rate of warm seawater (kg/s),  $T_{wi}$  is inlet temperature of warm seawater and  $T_{wo}$  is outlet temperature of warm seawater (K) and  $c_p$  is the specific heat capacity of the seawater (J/kg · K).

Overall heat transfer coefficient and effective surface area of the evaporator is correlated with the heat addition rate as shown in the following equation:

$$\dot{Q}_e = U_e A_e \Delta T_{LMTD,e}$$

Where;  $\Delta T_{LMTD,e}$  is the logarithmic mean temperature difference across the evaporator.

### Condenser

The energy balance equation at the condenser is basically the same as the evaporator and can be written as

$$\dot{Q}_c = \dot{m}_f (h_2 - h_3) = \dot{m}_c \cdot c_p \cdot (T_{cso} - T_{csi}) \quad (3.2)$$

The effective thermal conductance of the condenser is correlated with the heat transfer rate as

$$\dot{Q}_c = U_c A_c \Delta T_{LMTD,c}$$

Where;  $\Delta T_{LMTD,c}$  is the logarithmic mean temperature difference across the condenser.

### 2.3. Logarithmic Average Temperature Difference

The LMTD method has traditionally been used to evaluate the temperature difference between the heat source and the working fluid in a heat exchanger. The LMTD method is used only when the thermo-physical properties of the local fluid in the heat exchanger and the overall heat transfer coefficient are constant. Hence, the fluid in the heat exchanger undergoes temperature changes as shown in Figure 5 with the horizontal axis conceptually representing the length.

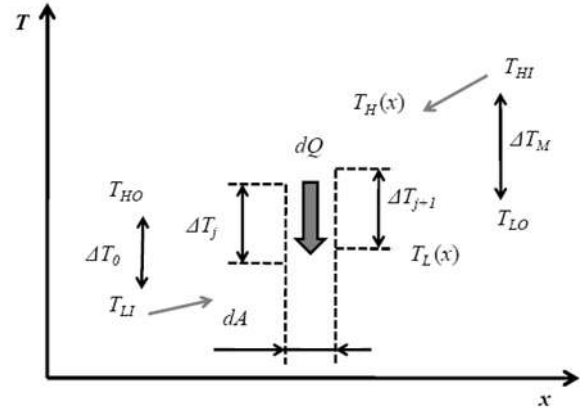


Figure 5: Fluid temperatures in the counter-flow heat

Using Figure 3, the heat flow rate for the heat exchanger,  $d\dot{Q}$  from  $x$  to  $x + dx$ , is calculated using:

$$d\dot{Q} = U_i dA_i \Delta T_{LMTD} \quad (3.4)$$

Where;  $U_i$  represents the overall heat transfer coefficient for the  $i$  –  $th$  segment, mass flow rate of the warm or cold source,  $dA_i$  is the heat transfer surface area, and  $\Delta T_{LMTD}$  is the temperature difference between high- and low-temperature fluids. Integrating equation over all segments of the exchanger yields

$$\int_0^{Q_0} d\dot{Q} / \Delta T_{LMTD} = \int_0^{A_i} U_i dA_i \quad (3.5)$$

Integration 3.5, the overall evaporative heat-transfer coefficient ( $U$ ), was calculated using Equation.

$$U = \frac{\dot{Q}}{A \Delta T_{LMTD}} \quad (3.6)$$

The Logarithmic Average Temperature Difference ( $\Delta T_{LMTD}$ ) is the logarithmic mean temperature difference, which is defined as:

$$\Delta T_{LMTD} = \frac{(T_{ci} - T_{do}) - (T_{co} - T_{di})}{\ln \frac{(T_{ci} - T_{do})}{(T_{co} - T_{di})}} \quad (3.3)$$

Where;  $T$  is temperature in Kelvin, the subscript  $c$  refers to the continuous phase (warm/cold seawater),  $d$  refers to the dispersed phase (evaporator/condenser) of ammonia,  $i$  refers to the inlet, and  $o$  refers to the outlet.

### 2.3.1. Evaporator

The logarithmic mean temperature difference across the evaporator which can be expressed as

$$\Delta T_{LMTD,e} = \frac{(T_{wsi} - T_e) - (T_{wso} - T_e)}{\ln \frac{(T_{wsi} - T_e)}{(T_{wso} - T_e)}} \quad (3.3)$$

### 2.3.2. Condenser

The logarithmic mean temperature difference across the condenser which can be expressed as

$$\Delta T_{LMTD,c} = \frac{(T_c - T_{csi}) - (T_c - T_{cso})}{\ln \frac{(T_c - T_{csi})}{(T_c - T_{cso})}} \quad (3.3)$$

## 2.4. Heat Transfer Coefficient

### 2.4.1. Evaporator

The effective thermal conductance  $U_e$  of the evaporator can be approximated as

$$U_e = \frac{1}{1/\alpha_e + 1/\alpha_f + t/\delta_e + R_f}$$

Where;  $\alpha_e$  is the forced convection heat transfer coefficient of warm seawater ( $W/m^2K$ ),  $\alpha_f$  is the heat transfer coefficient of the working fluid ( $W/m^2K$ ),  $t$  is the plate thickness ( $m$ ),  $\delta_e$  is the coefficient of thermal conductivity of evaporator ( $W/mK$ ), and  $R_f$  is the thermal resistance due to fouling ( $m^2K/W$ ).

### 2.4.2. Condenser

The effective thermal conductance  $U_c$  of the condenser can be approximated as

$$U_c = \frac{1}{1/\alpha_c + 1/\alpha_f + t/\delta_c + R_f}$$

Where;  $\alpha_c$  is the forced convection heat transfer coefficient of deep seawater ( $W/m^2K$ ),  $\alpha_f$  is the heat transfer coefficient of the working fluid ( $W/m^2K$ ),  $t$  is the plate thickness ( $m$ ),  $\delta_c$  is the coefficient of thermal conductivity of condenser ( $W/mK$ ), and  $R_f$  is the thermal resistance due to fouling ( $m^2K/W$ ).

## 3.0 OTEC IN SIBERUT ISLAND, SUMATERA BARAT, INDONESIA

### 3.1 Overview of Siberut Island

Siberut is located in the Mentawai Islands which is a chain of about seventy islands and islets off the western coast of Sumatra in Indonesia. The Mentawai islands with population 76,421 people are approximately 150 km from shoreline of Sumatera Barat as shown in Figure 6. The indigenous inhabitants of the islands are known as the Mentawai people. Mentawai Island has a hot and humid tropical rainforest climate, with an annual rainfall of 4,000 mm with temperatures range 22-31 °C and humidity averages 81-85%. Siberut is the largest and northernmost of the Mentawai Islands, lying 150 km west of Sumatra in the Indian Ocean. A part of Indonesia, the island is the most important home for the Mentawai people. Siberut Island has area 4,030 km<sup>2</sup> with population 35,091 people. Other major islands are Sipura, North Pagai and South Pagai.



**Figure 6:** Schematic of the OTEC potential in Siberut Island, Sumatera Barat-Indonesia.

### 3.2 Electricity and Clean Water Crisis at Siberut

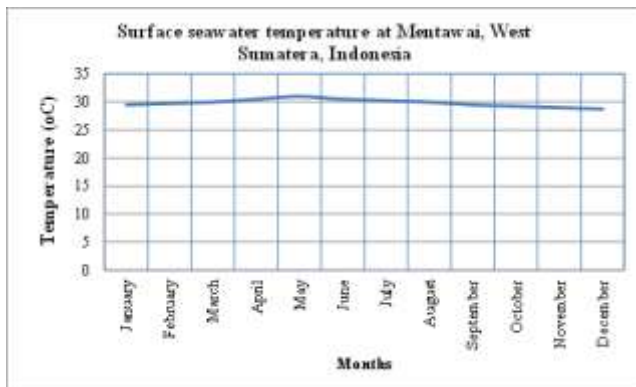
Siberut was selected as 3T (Frontiers, Remotest & Outermost). The 3T islands usually have a variety of specific natural resources, limited, as well as the environmental carrying capacity is limited. In small or outermost islands, both in the West and the East, Indonesia, supplying fresh water in the dry or rainy season and supply of electricity is still a problem difficult and must be addressed by the government. The problem is more complex if the supply of water and electricity associated with integrated regional development plan that includes residential areas, industry, trade, transportation, Hankamnas, and others as shown in Figure 7. Strategic management of remote islands and outermost should be sought so that the water and electricity resources available will not be used beyond the limits of carrying capacity.



**Figure 7:** Scarcity of clean water (top) and electricity (bottom) in remote islands or outermost in Indonesia.

### 3.3 Surface Seawater Temperature

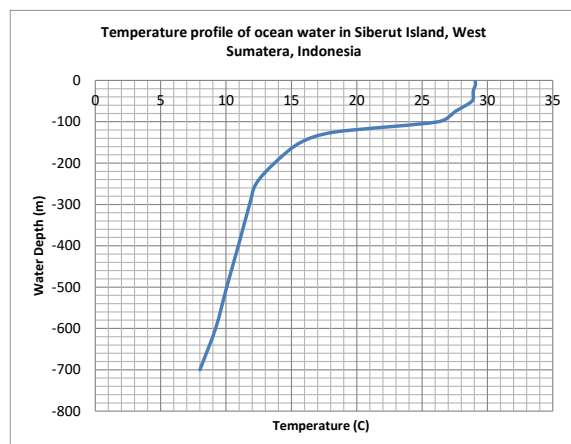
The Sea Surface Temperature (SST) patterns over the Mentawai region clearly demonstrate the effect of the monsoons cycle as shown in Figure 8. The surface temperatures are influenced by the Southwest and Northeast monsoons. The SST increase from January to reach the maximum on May with 31 °C before down to the minimum at 28 °C. The average SST is at 29.8 °C.



**Figure 8:** Mean monthly surface seawater temperature in Mentawai Islands, Sumatera Barat-Indonesia.

### 3.4 Seawater Profile Temperature

Figure 9 shows profile temperatures at different water depths in Sumatera Barat. The temperature profiles show a pronounced thermocline between 100 and 125 m with an almost homogeneous upper layer. At some stations off the west coast, temperatures below 10 °C were measured deeper than 400 meters.



**Figure 9:** Temperature profile of ocean water in Siberut Island in Sumatera Barat-Indonesia.

### 3.5 OTEC Closed System in Siberut Island

In the study, the performance was simulated using Ocean Thermal Energy Conversion Pro Simulation as shown in Figure 10. The software was developed by Ocean and Aerospace Research Institute, Indonesia. The simulation was based on following assumptions:

- Surface temperature inlet was assumed 28 °C and the temperature outlet was setup 26.5 °C.
- The evaporation and condensation ammonia temperatures were set up 26 and 8 °C
- The outlet surface and deep sea water temperatures were set up 26.5 and 9 °C
- Turbine and generator efficiencies were assumed 75 and 85 %, respectively

- Working fluid was using pure ammonia
- Depth of inlet sea water was 700 meter.
- The inlet surface and deep sea water temperatures are 28 and 6.2 °C, respective.
- Specification of heat exchangers is shown in Table 1.



**Figure 10:** Ocean Thermal Energy Conversion Pro Simulation

**Table 1:** Heat exchanger specifications

| Specification                                   | Values |
|-------------------------------------------------|--------|
| Length (mm)                                     | 960    |
| Width (mm)                                      | 576    |
| Plate thickness (mm)                            | 0.7    |
| Clearance of plates (mm)                        | 4      |
| Equivalent diameter (mm)                        | 8      |
| Heat-transfer coefficient (W/m <sup>2</sup> K ) | 4000   |

Figure 11 shows a simplified schematic diagram of a 2 MW plant closed cycle OTEC system. The principal components are the heat evaporator, condenser, turbine and generator, and seawater supply system. The figure did not included ancillary devices such as separators to remove residual liquid downstream of the evaporator and subsystems to hold and supply working fluid lost through leaks or contamination.

Simulation results of 2 MW OTEC plant of electrical power in Siberut island Sumatera Barat, Indonesia shows that the suitable mass flow rate of the working fluid is 19 kg/sec. The surface and deep seawater flow rates were founded 3775 and 8090 kg/sec. The simulation shows several founding as follow:

- Long Mean Temperature Difference (LMTD) of evaporator and condenser is 1.08 and 1.32 respectively.
- The Carnot efficiency of ammonia saturation is 7.21 percent
- The cycle efficiency of ammonia saturation is 6.26 percent

Heat transfer from high temperatures occurs in the evaporator can produce saturated ammonia. The area of heat transfer required for evaporators and condensers is 5381 m<sup>2</sup> and 4141 m<sup>2</sup>, respectively. Meanwhile, the length of the evaporator and condenser required for heat transfer are 123587 mm<sup>2</sup> and 95108 mm<sup>2</sup>, respectively. To make the evaporator and condenser, required raw material of titanium is \$ M 0.339 and \$ M 0.261, respectively.



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