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Increasing efficiency of a 33 MW OTEC in Indonesia using flat-plate solar collector for the seawater heater

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Abstract

This paper presents a design concept of Ocean Thermal Energy Conversion (OTEC) plant built in Mamuju, West Sulawesi, with 33 MWe and 7.1% of the power capacity and efficiency, respectively. The generated electrical power and the efficiency of OTEC plant are enhanced by a simulation of a number of derived formulas. Enhancement of efficiency is performed by increasing the temperature of the warm seawater toward the evaporator from 26˚C up to 33.5˚C using a flat-plate solar collector. The simulation results show that by increasing the seawater temperature up to 33.5˚C, the generated power will increase up to 144.155 MWe with the OTEC efficiency up to 9.54%, respectively. The required area of flat-plate solar collector to achieve the results is around 6.023 x 10^6 m^2.

Keywords: enhanced efficiency; OTEC plant; flat-plate solar collector; Mamuju West Sulawesi

I. Introduction

An Ocean Thermal Energy Conversion (OTEC) power generation utilizes the temperature differences between surface layer and deeper layers (800–1000 m) of the sea where the operation temperature difference is generally around 20°C or more. Considering the temperature levels at one kilometer depth, the temperature difference will be relatively constant at 4°C so that OTEC is particularly suitable for mean surface temperatures around 25°C. This small temperature difference is converted into usable electrical power through the heat exchangers and turbines [1, 2]. Moreover, OTEC plant can also produce another output such as fresh water, refrigeration, hot water, and hydrogen [2, 3, 4, 5].

OTEC plant is principally designed for tropical waters such as in Indonesia, which has a high temperature difference between the temperature of the seawater at the surface and at a depth of 1000 meters [1, 2, 6, 7]. Figure 1 shows the temperature differences in the tropical ocean ranges from 22^0C to 24^0C. Potential ocean thermal power plant in Indonesia is ranked number three after the United States and Australia. Indonesia has a coastline length of 95.181 km with approximately 70% of the potential OTEC. Therefore, the OTEC power generation of 222 GW can be estimated from the coastline length of 66.627 km with the generated capacity of 100 MW. Thus, the potential electrical estimation of OTEC in Indonesia is amounted to 15.500 TWh [8].

The feasibility of OTEC power plant was studied for Mamuju, West Sulawesi. Mamuju is located close to the sea that has a depth of 1000 meters. The system design of OTEC is island based which has some advantages such as the integration of the cooling system, water desalination, aquaculture, and agriculture [9]. Figure 2 shows the studied construction site for OTEC in Mamuju and Figure 3 presents an OTEC island based systems.

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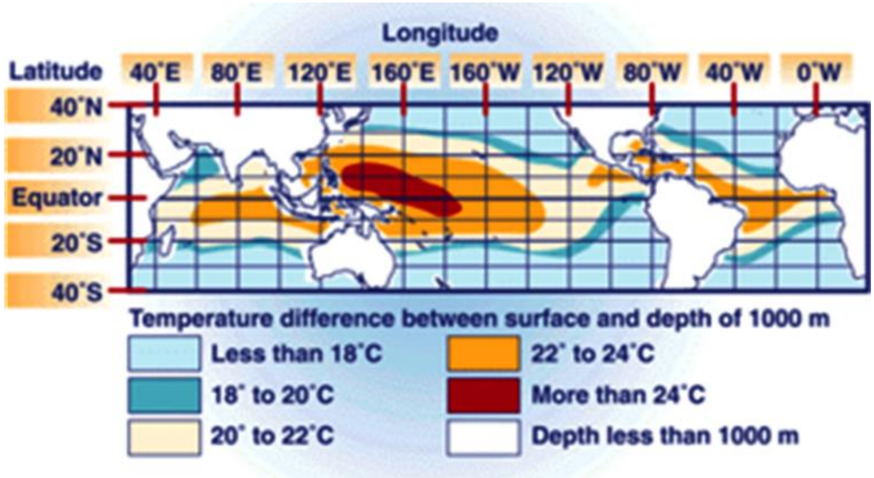

Figure 1. Potential OTEC in the world [6]

The cycle OTEC in Mamuju uses closed-cycle, as shown in Figure 4, where the generated electrical power (gross) and Carnot efficiency is designed for 33 MW and 7.283%, respectively [3, 7, 9]. Carnot efficiency of OTEC is determined by the temperature difference between the warm seawater and the cold seawater, so that OTEC has the maximum efficiency ranged from 7.5% to 8% [10]. There is another way to improve the efficiency of OTEC such as by increasing the surface temperature of the seawater using a solar collector, technique that was introduced by Ahmadi *et al.* [4]. A solar collector on warm seawater pipe that enters the evaporator was added into OTEC 72.49 kW (net) [4]. Aydin added a heat exchanger with the solar collector on warm seawater pipe that enters the evaporator or evaporator exit through the turbine on OTEC 100 kW [11]. Yamada *et al*. analyzed two configurations of a solar collector installation on an ordinary closed-cycle OTEC. The solar collector heats the warm seawater entering the evaporator for the first configuration, while for the second configuration, the solar collector heats the working fluid after exiting the evaporator [12]. Husada *et al*. improved the efficiency of OTEC by the technique of double-stage Rankine cycle flow [13].

This paper presents analysis of OTEC to increase the power capacity of 33 MW which is designed based on the calculation by Yeh *et al.* [7, 14] In this study, a flat-plate solar collector in warm seawater pipe that enters the evaporator without a heat exchanger is added to the OTEC plant in Mamuju, West Sulawesi.

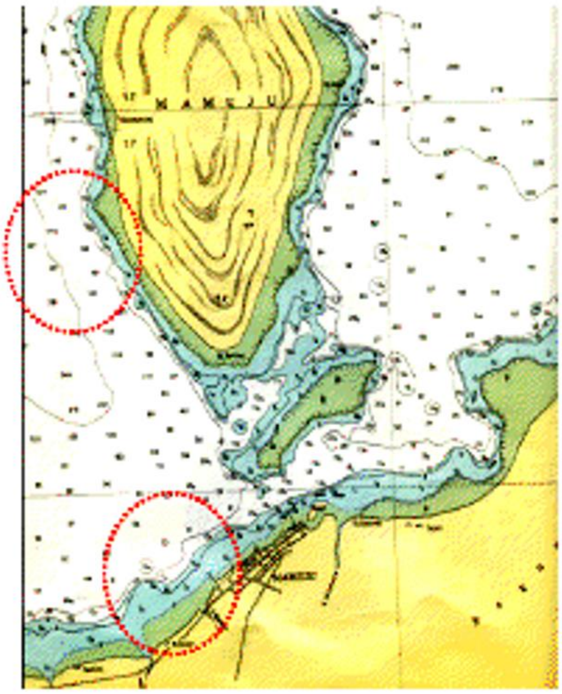

Figure 2. Location study of OTEC plant in Mamuju [9]

II. Methodology

A. Kalina cycle

The designed OTEC that is studied to be implemented in West Sulawesi is a type of Kalina closed-cycle as shown in Figure 4. A closed-cycle OTEC with a higher temperature of surface water is used to provide heat to a working fluid with a low boiling temperature hence a higher vapor pressure is provided.

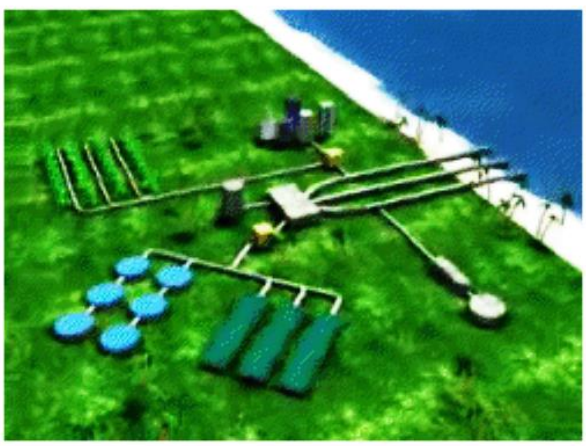

Figure 3. Illustration of OTEC island based system at Honolulu, Hawaii [9]

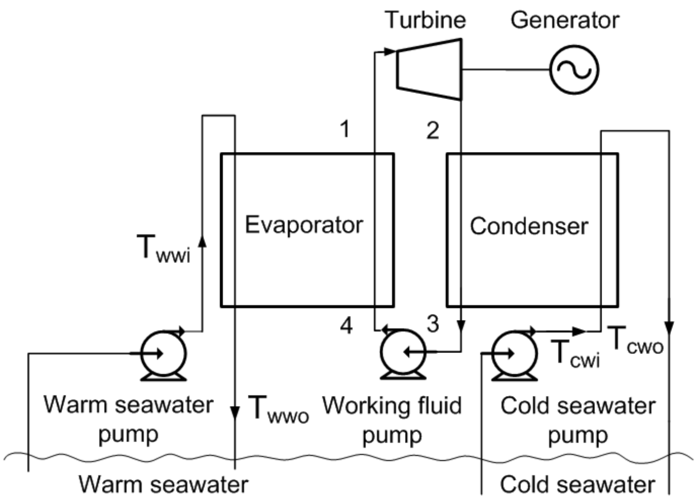

Figure 4. OTEC plant closed-cycle [12]

Ammonia is commonly used as a working fluid. Its vapor drives a generator that produces electrical power. After driving a generator, the working fluid vapor is then condensed by the cold water from the deep ocean and pumped back in a closed system. The Kalina cycle is a variation of a closed-cycle OTEC, where by instead of pure ammonia, a mixture of water and ammonia is used as the working fluid. Such a mixture lacks of a boiling point but it has a boiling point trajectory [2, 9]. Furthermore, Matsudah *et al.* had used an ammonia-water mixture as the working fluid. This working fluid is flow to the evaporator to be partially evaporated through heat transfer process between warm seawater and working fluid. Thus, wet vapor is generated. The wet vapor is flowed to the separator to separates liquid from the wet vapor. The liquid is stored in the separator tank, and the rest of vapor (dry vapor) is finally flow to turbine to generate electrical power so that the liquid level in the separator controlled [14].

The equation for OTEC plant as shown in Figure 4 is written as follows [3, 7, 9, 15]:

$$\dot{m}_w = \left(\frac{\pi D^2}{4}\right)\rho v \quad (1)$$

where m_w is mass flow rate of warm seawater or cold seawater in the pipe (kg/s), ρ is seawater density = 1025 kg/m^3, D is pipe diameter (m), and v is the velocity of seawater flowing in the pipe (m/s). Based on OTEC designs for real implementation in Mamuju, pipe diameter for warm seawater and for cold water are 8.9 m and 7.9 m, respectively and v is 2.03 m/s. Furthermore, the heat transfer rate for the warm seawater in the evaporator can be calculated using the following equation:

$$Q_e = \dot{m}_{ww} C_{pw} (T_{wwi} - T_{wwo}) \quad (2)$$

where Q_e is heat transfer rate in evaporator (J/s), C_{pw} is specific heat of seawater as much as 4000 J/kg.°C, T_{wwi} is input temperature of warm seawater (assumed to be constant at 26°C), T_{wwo} is output temperature of warm seawater approximately of 23.8°C, m_{ww} is mass flow rate of warm seawater (calculated using equation (1)) as much as 129380.723 kg/s. Mass flow rate of working fluid in the evaporator is calculated by the following equation:

$$\dot{m}_{wf} = \frac{Q_e}{(H_1 - H_4)} \quad (3)$$

where $\dot{m}_{wf}$ is mass flow rate of working fluid (ammonia) (kg/s), H_1 is output enthalpy of ammonia and H_4 is input enthalpy of ammonia. The ammonia exiting the evaporator has a higher temperature, is then used to rotate turbines. The ammonia vapor quality is calculated by the following equation:

$$x = \frac{(S_2 - S_2\_L)}{(S_2\_V - S_2\_L)} \quad (4)$$

where x is ammonia vapor quality, S_2 is ammonia entropy out of the turbine (J/Kg.K), S_2_L is the entropy of saturated liquid ammonia at condensation temperature (J/Kg.K), and S_2_V is the entropy of saturated ammonia vapor at the condensation temperature (J/Kg.K). Furthermore, the enthalpy of ammonia vapor exiting the turbine, H_2, (J/Kg), is obtained using the following equation:

$$H_2 = (1 - x)H_2\_L + xH_2\_V \quad (5)$$

where H_2_L is enthalpy saturated liquid ammonia out of the turbine (J/Kg), H_2_V is enthalpy saturated vapor ammonia exiting the turbine (J/Kg). The electrical power is generated by connecting the turbine to an electric generator. The power generated by the turbine, W_T (W), is calculated by the following equation:

$$W_T = \dot{m}_{wf}(H_1 - H_2)\eta \quad (6)$$

where η is a turbine efficiency which is assumed about 0.896 and H_2 is enthalpy of ammonia vapor exiting the turbine. Ammonia vapor exit the turbine is then cooled by the cold seawater in the condenser to become liquid. The value of the heat transfer rate in condensers, Q_C (J/s), is obtained from the following equation:

$$Q_c = \dot{m}_{wf}(H_2 - H_3) \quad (7)$$

where H_3 is the enthalpy of output ammonia liquid from condenser (J/kg).

Equation (7) can also be written as follows:

$$Q_c = \dot{m}_{wc} C_{pw} (T_{cwo} - T_{cwi}) \tag{8}$$

where $\dot{m}_{wc}$ is mass flow rate of input cold seawater into condenser (kg/s), T_{cwi} is input cold seawater temperature into condenser (4.22°C) and T_{cwo} is output cold seawater temperature from condenser (6.89°C).

B. Seawater heater using flat-plate solar collector

As shown in Figure 5, to increase the efficiency of OTEC, the warm seawater temperature is increased before entering the evaporator using a flat-plate solar collector. The maximum possible useful energy gain (heat transfer) in a solar collector occurs when the whole collectors are at the inlet fluid temperature. Therefore, heat losses to the surroundings are then at a minimum. The collector heat removal factor times this maximum possible useful energy gain is equal to the actual useful energy gain, Qu [16].

The value of Qu (W), is obtained by the following equation:

$$Q_u = A_c F_R [S - U_L (T_{wwi} - T_a)] \tag{9}$$

where A_C is the area of flat-plate solar collector (m^2), S is the solar irradiance (W/m^2), and F_R is the heat removal factor (dimensionless), obtained by the following equation:

$$F_R = \frac{\dot{m}_{ww} C_p}{A_C U_L} \left[1 - \exp\left(-\frac{A_C U_L F'}{\dot{m}_{ww} C_p}\right)\right] \tag{10}$$

where U_L is the overall heat loss coefficient for collector which is assumed by 0.8 W/m^2°C, and F' is the collector efficiency factor which is assumed by 0.841.

The magnitude of the seawater temperature that comes out of the flat-plate solar collector, T_{SO}, (°C), is obtained based on the following equation:

$$Q_U = \dot{m}_{ww} C_{pw} (T_{SO} - T_{wwi}) \tag{11}$$

By modifying equation (11), the following equation is obtained:

$$T_{SO} = T_{wwi} + \frac{Q_U}{\dot{m}_{ww} C_{pw}} \tag{12}$$

The value of OTEC Carnot efficiency is calculated using the following equation:

$$\eta = \frac{T_{wwi} - T_{cwi}}{T_{wwi}} \tag{13}$$

where η is Carnot efficiency, T_{wwi} and T_{cwi} are in Kelvin.

III. Result and discussion

Simulations are performed by raising the temperature of the warm seawater flowing in the pipe toward the evaporator, started from temperature 26°C. The increasing of the warm seawater temperature is caused by the irradiation of sunlight received by the flat-plate solar collector. The maximum temperature of the water is limited to 33.5°C, because the higher temperature can result in instability when OTEC system is connected to a single machine infinite bus [7].

A. Determining area of flat-plate solar collector

Using equation (11), heat transfer rate to raise the temperature of warm seawater from 26°C to 33.5°C, Qu, is calculated as much as 3.881 x 10^9 J/s. The heat removal factor should be calculated to determine the area of the flat-plate solar collector. By modifying equation (10), the heat removal factor can be calculated as follows:

$$\ln F_R = \ln \frac{\dot{m}_{ww} C_p}{A_C U_L} \left[1 - \exp\left(-\frac{A_C U_L F'}{\dot{m}_{ww} C_p}\right)\right] \tag{14}$$

Then, equation (14) can be simplified as follows:

$$\ln F_R = -\frac{A_C U_L F'}{\dot{m}_{ww} C_p} \tag{15}$$

And, now F_R can be written as follows:

$$F_R = \exp\left(-\frac{A_C U_L F'}{\dot{m}_{ww} C_p}\right) \tag{16}$$

By substituting equation (16) to equation (9), the formula of Qu is obtained as follow:

$$Q_u = A_c \exp\left(-\frac{A_C U_L F'}{\dot{m}_{ww} C_p}\right) [S - U_L (T_{wwi} - T_a)] \tag{17}$$

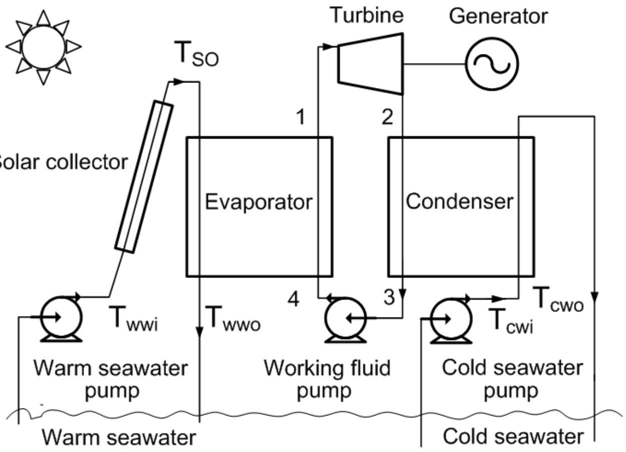

Figure 5. The temperature of the warm seawater on OTEC plant raised using a flat-plate solar collector [12]

By assuming the peak sun irradiation (S) as much as 1000 W/m^2 and substituting this value to equation (17), it is obtained the flat-plate solar collector area, Ac, as much as 6.023 x 10^6 m^2.

B. The increase of warm seawater temperatures

The irradiation of sunlight is absorbed by a flat-plate solar collector throughout the day to increase warm seawater temperature. By assuming the data of solar irradiation [17] that is collected from Mamuju using Matlab, the obtained curve S sunlight irradiation in W/m^2 versus time for the entire day as shown in Figure 6 is substituted into equation (17). The obtained value of Ac is then substituted into equation (9) and equation (10). Therefore, the increase of seawater temperature from the flat-plate solar collector is obtained by using equation (12), as shown in Figure 7.

Figure 6 shows that the irradiation of sunlight is approximately between 6 a.m. until 6 p.m. and the peak hour is about at 12 p.m. with approximately irradiation of 1000 W/m^2 to increase the seawater temperature from 26°C to 33.5˚C at the peak hour, as shown in Figure 7.

C. Output power of turbine

As a result of changes in warm seawater temperatures, power is generated by the turbine generator, the value of T_{so} is substituted into equation (2) where T_{wwi} is equal to T_{so}. By assuming the values of T_{wwo}, H_1, H_2, and H_4 are constant, and using equation (6), the changes of turbine power generator due to changes in warm seawater temperatures are obtained as shown in Figure 8.

Figure 8 shows that due to the increasing of warm seawater temperatures from 26°C up to 33.5°C, the output power of turbine is increase from 33 MW up to 144 MW. OTEC efficiency also increases from 7.1% up to 9.54% as shown in Figure 9.

The increasing of warm seawater temperatures resulting in an increasing of power output of the turbine, based on equation (3) and equation (6), it requires the increasing of working fluid mass flow rate that is proportional to changes in the seawater temperatures as shown in Figure 10. The simulation results are also shown in Table 1.

The simulation results in Figure 10 are obtained by assuming that heat losses from piping and other auxiliary components are negligible, and enthalpy of input ammonia into evaporator, output ammonia from evaporator, and output ammonia from turbine are constant for every change of seawater temperature.

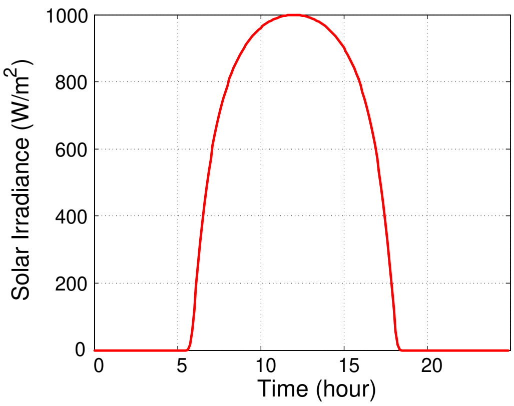

Figure 6. Irradiation of sunlight throughout the day [12]

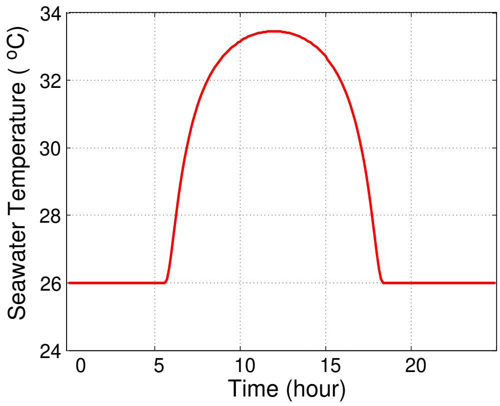

Figure 7. Correlation between seawater temperatures and time.

Table 1.
Simulation results in enhancing OTEC efficiency

Parameter	Unit
Flat-plate solar collector area, A_c	6.023×10^6 (m^2)
Warm seawater temperature, T_{SO}	26 – 33.5 (°C)
Turbine output power, W_T	33 –144.155 (MW)
Working fluid mass flow rate, $\dot{m}_{wf}$	883-3885 (kg/s)
Warm seawater mass flow rate, $\dot{m}_{ww}$	129380.723 (kg/s)
Output enthalpy of ammonia from evaporator , H_1	1462.6 (kJ/kg)
Output enthalpy of ammonia vapor from turbine, H_2	1425.5 (kJ/kg)
Input enthalpy of ammonia into evaporator, H_4	225.196 (kJ/kg)
Efficiency, η	7. 1 – 9. 54 (%)

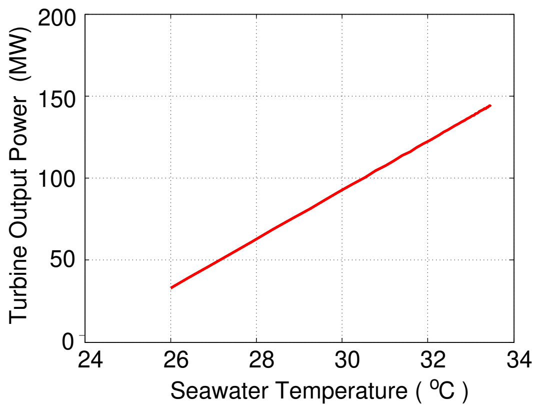

Figure 8. Correlation between output power of turbine and warm seawater temperatures

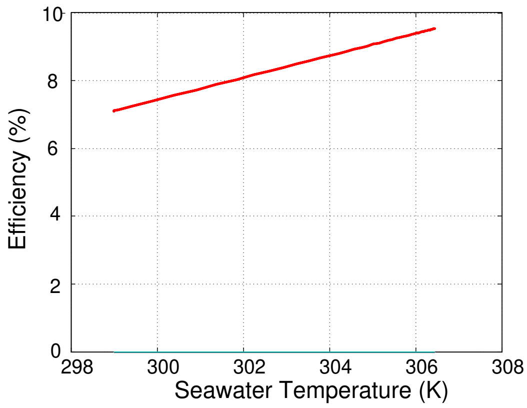

Figure 9. Effect the increasing of seawater temperatures on OTEC efficiency

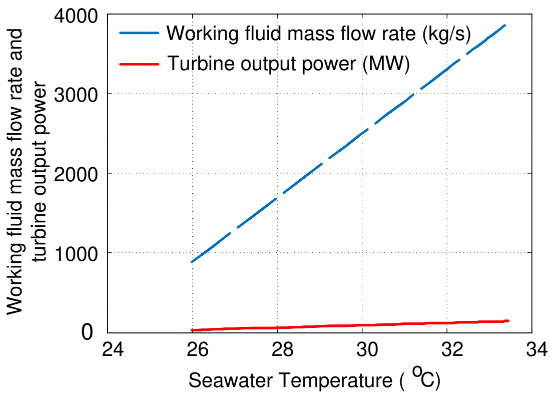

Figure 10. The effect of the increasing of warm seawater temperatures on the working fluid mass flow rate and turbine output power

IV. Conclusion

As the effect of the increasing of input temperature of warm seawater into evaporator from 26°C to 33.5°C using a flat-plate solar collector with an area of 6.023 x 10^6 m^2, the power generated by the turbines increase from 33 MWe to 144.155 Mwe and the OTEC efficiency also increase from 7.1% to 9.54%. The increase and decrease output power of turbine, as well as the efficiency of OTEC, is a function of the mass flow rate of the working fluid which is proportional to the increase and decrease of seawater temperature that comes out of the flat-plate solar collector.

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