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OCEAN THERMAL ENERGY CONVERSION (OTEC) POWER PLANT AND IT'S BY PRODUCTS YIELD FOR SMALL ISLANDS IN INDONESIA SEA WATER

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ABSTRACT

Small islands in Indonesia sea water are current heavily dependent of fossil fuels. Environmental concerns at global, regional and local levels, past and recent price hikes in the price of oil among others, have been drives behind a regional wide interest in renewable energy technologies. One of the renewable energy resources is the he temperature difference between the upper layer of warm sea water and the bottom layer of cold sea water. As long as the temperature between the warm sea water and cold deep sea water differ by about 18 to 24 ^{O}C, an Ocean Thermal Energy (OTEC) system can produce a significant amount of electricity.

The sea area in Indonesia region is ideal for OEC power plant to generate electricity for small islands, because the sea area in Indonesia have average monthly temperature difference between 20 to 22 ^{O}C of warm sea water surface and colder sea water in the bottom layer. Therefore OTEC is very promoting as an alternative energy source for small islands.

OTEC has important benefit other than power production, as by product of OTEC, support chilled soil agriculture, aquaculture, fresh water, mariculture and OTEC power plant is not source of environmental pollution.

In this study, we presently propose an OTEC system that utilizes not only thermal energy but also mariculture, chilled soil agriculture, aquaculture, fresh water as by product of OTEC power plant.

Keyword: ***energy, power plant, by product of OTEC***

1. INTRODUCTION

Indonesia, which has the largest population of all ASEAN countries, will became a net oil import in the early 21st century. The Indonesia government has set up a long term energy plan aiming at energy diversification to reduce the country's dependence in oil.

One of the renewable energy resources is the temperature gradient to exit in the sea, solar energy which creates this gradient and in particular OCEAN THERMAL ENERGY CONVERSION (OTEC). OTEC uses the temperature difference that exists between deep and swallow water to run a heat engine. The chart of Figure 1 [1], demonstrate that this is area which excellent thermal potential of OTEC.

The temperature difference between the warm sea water layer in the surface range of 24 ^{O}C to 28 ^{O}C and a 1000 m deep ocean water (cold water) temperature ranging from 4 ^{O}C to 5 ^{O}C. the potential thermal resources of the equatorial Pacific Ocean and the sea surrounding Indonesia have been estimate by Hiroshi Komogawa [2]. The thermal resource in the equatorial sea is estimated at about 5 x 10^5 GWh/yr/mesh, Komogawa [2]. OTEC power plants are also capable of producing multiple products including electricity, fresh water and the discharged cold water is rich in nutrients and thus growth in the phytoplankton population caused by the presence of the plant is to be expected.

The sea area in Indonesia is ideal for OTEC power plant because the surface of sea water temperature is high and almost constant throughout the year. Some se area in East Indonesia, West Sumatera and South Java have average monthly temperature difference between 22 ^{O}C up to 24 ^{O}C of warm sea water and cold sea water is shown in Figure 2, Arismunandar [3].

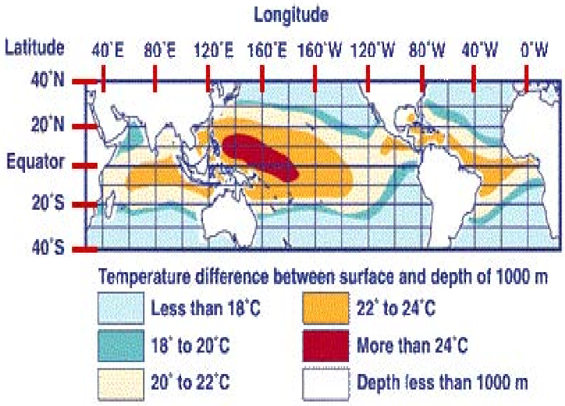

Figure 1: Large scale distribution of OTEC thermal resource of the equatorial area.

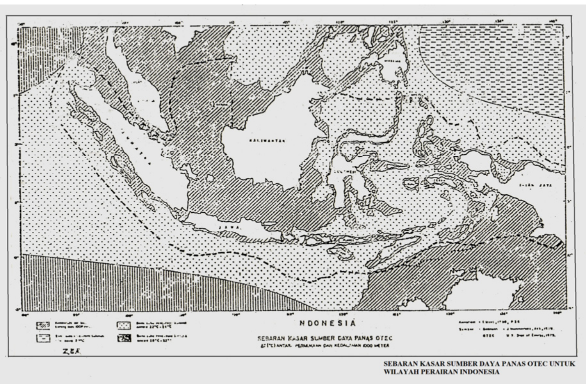

Figure 2: Large scale distribution of OTEC thermal resource of the Indonesia area.

2. OTEC POWER PLANT

Figure 3 show a schematic of the closed-cycle OTEC power plant and the general arrangement of the evaporator, condenser, warm sea water pump, cold sea water pump, working fluid pump and turbine generator. The corresponding T – s diagram is shown in Figure 4, where T_{EV} is the evaporating temperature, T_{CON} is the condensing temperature, T_{WSWI} is the warm sea water inlet, T_{WSWO} is the warm sea water outlet, T_{CSWI} is the cold sea water inlet temperature, T_{CSWO} is the cold sea water outlet temperature, Q_{EV} is the heat flow rate at the evaporator and Q_{CON} the heat flow rate at the condenser. P_{WF} is the working fluid pumping power and P_G is the turbine generator power.

2.1 Principles of Thermodynamics Design for OTEC

Figure 3 is a schematic of the closed-cycle OTEC plant and Figure 4 is a schematic T-s diagram of the closed system. The working fluid is selecting of the OTEC is ammonia. According to the result investigating by Hiroshi Kamogawa [2] the best working fluid of OTEC are ammonia and R-22. As a result, ammonia is used to the best working fluid for this analysis because this evaluation took into account the reducing of heat exchanger size and piping cost.

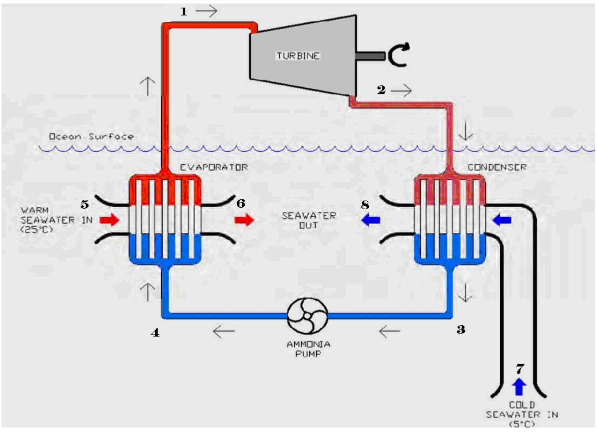

Figure 3: Flow diagram and schematic of Anderson Closed-Cycle.

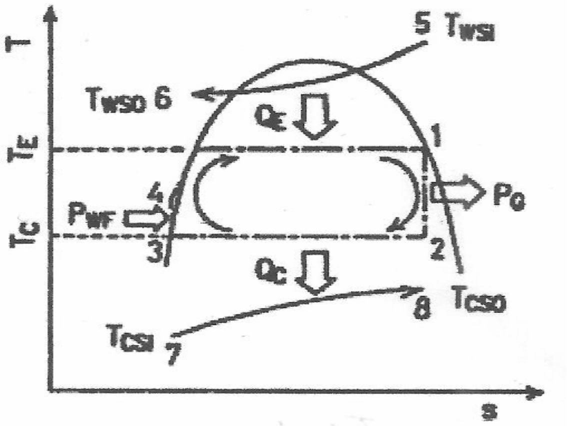

Figure 4: T-s diagram of the closed Rankine Cycle. Source Noburu Yamada et al [4].

2.2 General equation of closed-cycle OTEC plant

As referred to the T-s diagram in Fig. 4, pressure is assumed to be constant during heat addition to the evaporator, ($p_1 = p_4$) and heat extraction from the condenser ($p_2 = p_3$).

2.2.1 Net Power

The net power, P_{NET}, is given by:

$$P_{NET} = P_{TG} - \left(P_{WSW} + P_{CSW} + P_{WF}\right) \tag{1}$$

where P_{TG} is the turbine generator power, P_{WSW} is the warm sea water pumping power, P_{CSW} is the cold sea water pumping power and P_{WF} is the working fluid pumping power.

2.2.1.1 Turbine Generator Power

The turbine generator power P_{TG} is given by:

$$P_{TG} = \dot{m}_{WF} \cdot \eta_T \cdot \eta_G \cdot \left(h_1 - h_2\right) \tag{2}$$

where $\dot{m}_{WF}$ is mass flow rated of working fluid, η_T is the turbine efficiency, η_G is the generator efficiency. Efficiency of turbine is given as:

$$\eta_T = \eta_m \cdot \eta_e \tag{3}$$

where η_m is the mechanical efficiency and η_e is the theoretical efficiency, defined in reference [5] as:

$$\eta_e = \frac{H_{ad} - \left(\Delta h_N + \Delta h_R + \Delta h_{Ex} + \Delta h_D + \Delta h_{WET}\right)}{H_{ad}} \tag{4}$$

where h_{AD} is the adiabatic heat drop, Δh_N is the kinetic energy loss in nozzle, Δh_R is the rotor loss, Δh_{Ex} is the exhaust loss, Δh_D is the rotary disc loss due to disc friction and windage, and Δ_{WET} is the losses due to wetness of steam.

2.2.1.2 Cold Sea Water Pumping Power

The equation of cold sea water pumping power is given by:

$$P_{CSW} = \dot{m}_{CSW} \cdot v_{CSW} \cdot \Delta P_{CSW} / \eta_{CSP} \tag{5}$$

where $\dot{m}_{CSW}$ is mass flow rate of cold sea water, v_{CSW} is the specific volume of cold sea water, Δp_{CSW} is the total pressure difference of the cold sea water piping, and η_{CSP} is the cold sea water pump efficiency.

2.2.1.3 Warm Sea Water Pumping Power

The warm sea water pumping power, P_{WSW} is given by:

$$P_{WSW} = \dot{m}_{WSW} \cdot v_{WSW} \cdot \Delta p_{WSW} / \eta_{WSP} \tag{6}$$

where $\dot{m}_{WSW}$ is the mass flow rate of warm sea water, v_{WSW} is the specific volume of the warm sea water, Δp_{WSW} is the total difference of the warm sea water piping and η_{WSP} is the warm sea water pump efficiency.

2.2.1.4 Working Fluid Pumping Power

The working fluid pumping power P_{WF} is given by:

$$P_{WF} = m_{WF} \cdot v_{WF} \cdot \Delta p_{WF} / \eta_{WF} \tag{7}$$

where $\dot{m}_{WF}$ is the mass flow rate of the working fluid, v_{WF} is the specific volume of the working fluid, Δp_{WF} is the total pressure difference of the working fluid, and η_{WF} is the working fluid pump efficiency.

2.2.2 Heat Transfer Surface Area

Evaporator and condenser (Heat exchanger) are the most important component of an OTEC power plant. In 1975, the shell-and-tube type heat exchanger (evaporator, condenser) were selected. The overall heat transfer coefficient is 3300 kcal/m^2.h.^{O}C. evaporator tube is the titanium and also condenser tube is the titanium. It was found by the cost estimation of the 1975 design that the total heat exchanger cost amounted to 45,7 % of the plant construction cost. Improvement of the heat exchanger should be the most important item OTEC plant development. T. Uehara of Saga University was proposed use of new plate-type heat exchanger, based advanced technology.

The total heat transfer surface area, A_T, is gives by:

$$A_T = A_{EV} + A_{CON} \tag{8}$$

where A_{EV} and A_{CON} are the heat transfer areas of the evaporator and condenser.

In this paper, the shell and plate-type heat exchanger is used as the evaporator and condenser. The heat transfer surface area of evaporator, AEV, is given as:

$$\begin{aligned} A_{EV} &= Q_{AE} / \left[U_{EV} \cdot (LMTD)_{EV} \right] \\ &= \dot{m}_{WSW} \cdot cp_{WSW} \cdot \left(T_{WSW_i} - T_{WSW_o} \right) / \left[U_{EV} (LMTD)_{EV} \right] \end{aligned} \tag{9}$$

Where Q_{EV} is the heat transfer rate of the evaporator, $LMTD_{EV}$ is the logarithmic mean temperature difference of the evaporator, U_{EV} is the overall heat transfer coefficient.

The heat transfer surface area of condenser is gives as:

$$\begin{aligned} A_{CON} &= Q_{CON} / \left[U_{CON} \cdot (LMTD)_{CON} \right] \\ &= \dot{m}_{CSW} \cdot c_{p_{CSW}} \cdot \left(T_{CSW_o} - T_{CSW_i} \right) / \left[U_{CON} (LMTD)_{CON} \right] \end{aligned} \tag{10}$$

where Q_{CON} is the heat transfer rate of the condenser; $LMTD_{CON}$ is the logarithmic mean temperature difference of the condenser.

Q_{EV} and Q_{CON} is the heat transfer rate of the evaporator and condenser, respectively, defined as:

$$Q_{EV} = \dot{m}_{WSW} \cdot (h_1 - h_4) \tag{11}$$

$$Q_{CON} = \dot{m}_{CSW} \cdot (h_2 - h_3) \tag{12}$$

h_1, h_4, h_2 and h_3 are the enthalpy indicated by the four point in Figure 4.

$\dot{m}_{WF}$ is the working fluid (ammonia) flow rate is given by:

$$\dot{m}_{WF} = P_G / \left[\eta_T \cdot \eta_G (h_1 - h_2) \right] \tag{13}$$

Rankine cycle efficiency η_R and the net Rankine cycle efficiency η_{net} are given by:

$$\eta_R = P_G / Q_E \tag{14}$$

$$\eta_{net} = P_{NET} / Q_E \tag{15}$$

Table 1 Condition of Calculation Data of OTEC Plant Proposed.

Generator Power	P_G	kW	120
Turbine efficiency	η_T	-	0.82
Generator efficiency	η_G	-	0.95
Warm sea water pump efficiency	η_{WSP}	-	0.80
Cold sea water pump efficiency	η_{CSP}	-	0.80
Working fluid pump efficiency	η_{WF}	-	0.75
Evaporator (plate-type heat exchanger) overall heat transfer coefficient (obtained by Uehara and Nakaoka, [6])	U_{EV}	$W / m^2 \cdot K$	4000
$T_{WSW_i} - T_{EV}$		K	4.0
Condenser (plate-type heat exchanger) overall heat transfer coefficient (obtained by Uehara and Nakaoka, [6])	U_{CON}	$W / m^2 \cdot K$	3500
$T_C - T_{WSW_i}$		K	4.0
Sea water temperature from Figure 2 (Annual mean value in Indonesia)			
- Warm sea water temperature at depth 0 m		^oC	26
- Cold sea water temperature at depth 1000 m		^oC	5

Table 2 Calculation results of 125 kWe OTEC

Warm sea water inlet temperature	T_{WSNI}	(^oC)	26.5
Warm sea water outlet temperature	T_{WSNO}	(^oC)	23.0
Cold sea water inlet temperature	T_{CSWI}	(^oC)	6.0
Cold sea water outlet temperature	T_{CSWO}	(^oC)	8.0
Evaporation temperature	T_{EV}	(^oC)	22.0
Condenser temperature	T_{CON}	(^oC)	10.0
Net power	P_{NET}	(kW)	69.4
Warm sea water pumping power	P_{WSW}	(kW)	20.4
Cold sea water pumping power	P_{CSW}	(kW)	30.75
Working fluid pumping power	P_{WF}	(kW)	4.41
Warm sea water flow rate	$\dot{m}_{WSW}$	kg/s	325.25
Cold sea water flow rate	$\dot{m}_{CSW}$	kg/s	4920
Working fluid flow rate	$\dot{m}_{WF}$	kg/s	3467
Heat flow rate of evaporator	Q_{EV}	kW	4085.3
Heat flow rate of condenser	Q_{CON}	kW	4119.3
Logarithmic mean temperature differences	$LMTD_{EV}$	^oC	4.37
Logarithmic mean temperature differences	$LMTD_{CON}$	^oC	2.89
Heat transfer area of evaporator	A_{EV}	m^2	236.0
Heat transfer area of condenser	A_{CON}	m^2	407.0
Rankine cycle efficiency	η_R	%	3.1
Net Rankine cycle efficiency	η_{net}	%	2.0

3. ECONOMIC ANALYSIS

3.1 Estimation of Capital Investment

In the evaluation and cost optimization of an energy conversion system, we need to compare the annual values of capital-related charges (carrying charges), ammonia cost, and operating and maintenance cost.

In typical cost-estimating chart, when available cost data are plotted versus the equipment size on a double logarithmic plot, the data correlation results in a straight line within a given capacity range. The slope of the line α represents an important cost estimating parameter (scaling exponent) as shown by the relation:

$$C_{P.Y} = C_{P,W}\left(\frac{x_Y}{x_W}\right)^{\alpha} \tag{16}$$

where $C_{P,Y}$ is the purchase cost of the equipment in question, which has a size or capacity x_Y. $c_{P,W}$ is the purchase cost of the same type of equipment in the same year but of capacity or size x_W. In the absence of other cost information, an exponent value of 0,6 may be used (six-tenths rules).

3.2 Calculation of Revenue Requirement

Figure 5 shows the major cost categories considered in the calculation of the total revenue requirement.

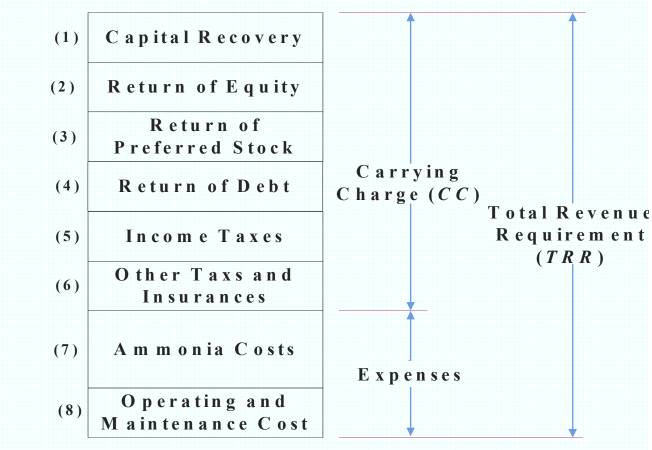

Figure 5 Revenue requirement method of economic analysis.

The total revenue requirement (*TRR*) is expressed as:

$$TRR = CC + AC + OMC \tag{17}$$

where *TRR* is the carrying charges, include the following: total capital recovery, return on investment for debt, preferred stock, and common equity, income taxes, and other taxes and insurance. *AC* is ammonia cost, and *OMC* is operating and maintenance cost, Bejan et al [7].

A levelized value ***TRR$_L$*** for the total annual revenue requirement is given by:

$$TRR_L = CRF\sum_{1}^{n}\frac{TRR_j}{\left(1+i_{eff}\right)^j} \tag{17}$$

where *CRF* is the capital recovery factor, i_{eff} is the interest rate of money.
The capital recovery factor (*CRF*) is given by:

$$CRF = \frac{\left(1+i_{eff}\right)^n \cdot i_{eff}}{\left(1+i_{eff}\right)-1} \tag{18}$$

The levelized cost of ammonia AC_L is given by:

$$\begin{aligned} AMC_L &= FC_O \cdot CELF \\ &= FC_O \frac{k_{AC}\left(1-k_{ac}^{n}\right)}{1-k_{AC}} CRF \end{aligned} \tag{19}$$

where $CELF$ is the constant escalating levelized factor

with $k_{AC} = \dfrac{1+r_{AC}}{1+i_{eff}}$.

The term r_{AC} denotes the annual escalating rate of the ammonia cost.

Accordingly, the levelized annual operating and maintenance cost, OMC_L are given by:

$$\begin{aligned} OMC_L &= OMC_O \times CELF \\ &= OMC_O \frac{k_{OMC}\left(1-k_{OMC}^{n}\right)}{1-k_{OMC}} CRF \end{aligned} \tag{20}$$

with $k_{OMC} = \dfrac{1+r_{OMC}}{1+i_{eff}}$

The term r_{OMC} is the nominal escalating rate for the operating and maintenance cost.

The levelized carrying charges CC_L are obtained from:

$$CC_L = TRR_L - AMC_L - OMC_L \tag{21}$$

Table 3 Parameter and assumption used in the calculation of total revenue requirement.

	Parameter (units)		value
1. a.	Average general inflation rate (2011 – 2034) (%)		5.0
b.	Average nominal escalation rate of all (except ammonia) cost (2011 – 2034) (%)		5.0
c.	Average nominal escalation rate of ammonia cost (2011 – 2034) (%)		5.0
2. a.	Plant economic life (year)		20
b.	Plant life for tax purposes (year)		15
3.	Plant financing fraction and required return on capital		
	Type of financing	debt	
	Financing fraction (%)	100	
	Required annual return (%)	10	
4. a.	Average combine income tax rate (%)		35
b.	Average insurance rate (%)		0.50
5.	Average capacity factor (%)		85.0
6.	Annual fixed operating and maintenance cost (10^6 \$)		1.8
7.	Annual variable operating and maintenance cost (10^3 \$)		200

3.3 Cost of The Main Product

The main product of OTEC (electricity) can be calculated directly from the annual total revenue requirement (*TRR*). Therefore the main product unit cost (*MPUC*) is given by:

$$MPUC = \frac{TRR}{MPQ} \tag{22}$$

where *MPQ* is the electricity energy developed by the OTEC plant per year.

$$MPQ = \left(Net\ Power\ OTEC \times average\ capacity\ factor\right) \tag{23}$$

The economics analysis of OTEC plant are given respectively in table 4.

Table 4 Economic analysis of OTEC Plant

1. Total Revenue Requirement (TRR) = $\$131 \times 10^3$/yr
2. Electricity energy developed (MPQ) = 513774 kWh/yr
3. Main product unit cost (MPUC) = $0.55cent/kWh

Estimated kWh price of OTEC is 17 $cent/kWh, Paul J. T. Straatman et al [9].

Table 5 Summary of kWh price estimations of 120 kWh OTEC Power Plant.

Investment (Million $)	14.8×10^6
Production (million kWh/year)	513×10^3
$C_{O\&M}$ (million $/year)	0.248
Theoretical thermal efficiency (%)	2.5
Estimated kWh price ($cent/kWh)	0.55

4. BYPRODUCT OF THE OTEC POWER PLANT

According to the US Department of ENERGY, OTEC has important benefits other than power production.

1. Aquaculture is perhaps the most well-known by product of OTEC. It is widely considered to be one of the most important way to reduce the financial and energy costs of pumping large volume of water from the deep ocean. Deep ocean water contains high concentration of essential nutrient that are depleted in surface waters due to biological consumption. This artificial upwelling mimics the natural upwellings that are responsible for fertilizing and supporting the world's large marine ecosystems, and the largest densities of life on the planet. Cold water delicacies, such as salmon and lobster, thrive in then nutrient –rich, deep seawater from the OTEC plant.
2. OTEC also may one day provide a means to mine ocean water for 57 trace elements.
3. Hydrogen can be produced via electrolysis using electricity generated by the OTEC process.
4. Potential mariculture yield of OTEC power plant in a combine OTEC/ Mariculture system, in which the discharged deep water – unchanged except for its temperature and rich in inorganic nutrients.

Nutrient – rich deep water is pumped to the surface through three polyethylene pipeline. Maricultue is not only compatible with electrical power production in sea thermal power plants, but it is a highly desirable and economically sensible approach to the energy and food situation currently facing the world.

5. RESULTS AND DISSCUSSION

Optimized net power output at the busbar of the OTEC plant 69,4 kW for the design, the heat transfer area of the evaporator and condenser are 236 m^2 and 407 m^2 respectively. The value of main production cost of OTEC, this value represent the levelized cost for 20 year period assuming average annual nominal escalating rates for the ammonia costs and the operating and maintenance expenses of 5 and 5 % respectively is 25.5 $cent/kWh. Unit power cost in 1980 is $0.098/kWh, Hiroshi, Komogawa [2].

An economic analysis indicated that, OTEC power plant may be competitive in four markets. The first market is the small island nation in South Pacific. In this islands the relatively high cost of diesel – generator electricity and desalinated water may make small 1 MWe, land based, open–cycle OTEC, plant coupled with a second–stage desalinated water production system cost effective. A second market can be found in American territories such as Guam and American Samoa, where land – based, open cycle OTEC plant rate 10 MWe with a second–stage water production system would be cost effective. A third market is Hawaii, where a large land based, closed – cycle OTEC plant produce electricity with second-stage desalinated water production system. The fourth market is for floating closed-cycle OTEC plant rated at 40 MWe, transmit electricity to shore via a submarine power cable.

In planning OTEC plants, the heat transfer coefficient of evaporator and condenser are 3500 N/m^2K and 4000 W/m^2K respectively, Y. Nakamoto et al [8] and Uehara et al [5].

In the OTEC plants a low boiling point medium is used for working fluid. The proposed working fluid for OTEC is ammonia (boiling point: 240 K). The turbine heat drop for ammonia is around five times greater than that for R-22 t the same temperature difference and the ammonia heat transfer characteristic are superior to those R-22, Yasumobu Nakomoto [8].

Potential mariculture yield of OTEC plant, in which the discharge deep water is rich in inorganic nutrients.

CONCLUSION

1. The sea area in Indonesia is ideal for OTEC power plant to generate electricity for small islands, because the sea areas in Indonesia have average monthly temperature difference between 20 – 23 ^{O}C.
2. The discharge cold water is rich in nutrients and thus a growth in the phytoplankton population caused by the presence of the plant is to be expected.

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