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DESIGN OPTIMIZATION OF POWER GENERATION AND DESALINATION APPLICATION IN MALAYSIA UTILIZING OCEAN THERMAL ENERGY

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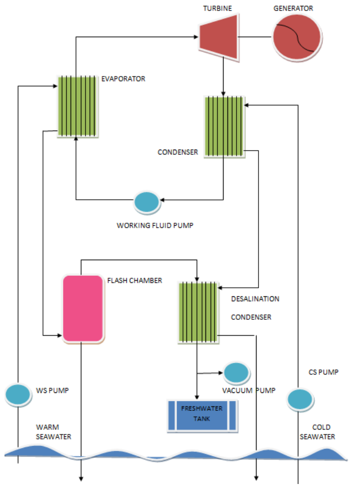
Graphical abstract



Abstract

Sources of electricity in Malaysia are highly depending on fuel, natural gas and coal and desalination plant as for brackish water consume high electricity to produce freshwater. Ocean Thermal Energy Conversion (OTEC) and the Low Temperature Thermal Desalination (LTTD) plant is one of the mediums that will reduce these problems. This paper presents a simulation of the OTEC plant, LTTD plant and the Integrated OTEC plant using temperature and topographic characteristic information in Malaysia. The design optimization was also preferable in this study which affected and influenced the maximum output of power generation and freshwater production at maximum net power generation based on tropical data in Malaysia. A model for calculation and optimization is presented in this paper.

Keywords: Ocean Thermal Energy Conversion, OTEC, LTTD, power generation, Integrated OTEC, I-OTEC

Abstrak

Sumber tenaga elektrik di Malaysia amat bergantung kepada bahan api, gas asli dan arang batu dan loji penyahgaraman air payau menggunakan tenaga elektrik yang tinggi untuk menghasilkan air bersih. 'Ocean Thermal Energy Conversion' (OTEC) dan 'Low Temperature Thermal Desalination' (LTTD) adalah salah satu medium yang akan mengurangkan masalah ini. Kertas kerja ini akan menunjukkan simulasi bagi loji OTEC, loji LTTD dan loji Hibrid-OTEC dengan menggunakan suhu dan maklumat topografi di Malaysia. Pengoptimuman reka bentuk juga ditunjukkan dalam kajian ini yang menyebabkan serta mempengaruhi kuasa maksimum penjanaan kuasa elektrik dan pengeluaran air tawar pada kuasa penjanaan elektrik paling maksimum berdasarkan data tropika di Malaysia. Model bagi pengiraan dan pengoptimuman berdasarkan formula ditunjukkan dalam kertas ini.

Kata kunci: *Ocean Thermal Energy Conversion*, OTEC, LTTD, penjanaan kuasa, Hibrid-OTEC, I-OTEC

1.0 INTRODUCTION

Ocean Thermal Energy Conversion is one of the methods or materials in green technology that uses seawater as a solar agent. It also uses difference in seawater temperature to generate electricity. The technology makes use of the difference in temperature from warm and cold seawater. It is estimated that the surface seawater temperature in tropical region is about 28°C. The difference in temperature of at least 20°C which take from the several depth of seawater is necessary to sustain and maintain the performance of OTEC [1]. A Close-Cycle OTEC, seawater was used as an agent to vaporize the working fluid which has low boiling point elevation such as Ammonia and Freon to drive the turbine that coupled with a generator for the electricity production. A study has been conducted by Rong-Hua Yeh et al. [2] to find the maximum output of an OTEC power plant by investigating the effects of temperature and flow rate of cold seawater which considered the variable parameters that are based on the specific conditions in Taiwan such as pipe length and diameter, seawater depth and flow rate. The optimization based on a fixed pipe diameter and flow velocities condition in the results showed that the maximum power output can be achieved with a larger pipe diameter for the fixed inlet and outlet seawater temperature and the fixed velocity of cold seawater and warm seawater temperatures. Sun, Ikegami *et al.* [3] conducted a research entitled 'Optimi - zation design and exergy analysis of organic Rankine cycle in OTEC' and came out with derivation and optimization of a performance analytical function and exergy efficiency of (ORC) in the OTEC system. The paper showed the optimization design with a theoretical approached to find the maximum net output of the turbine. Other parameters such as the pipe diameter, pipe length, pumping power, and thermal conductance of the heat exchanger optimization are very important in order to figure out the maximum output of an OTEC system [4].

Low Thermal Temperature Distillation (LTTD) makes use of the flash evaporation concept. Flash or partial evaporation is a boiling of a liquid that occurs when a saturated liquid encountering sudden reduction of its pressure which generates vapor and non evaporating liquid. For desalination, many studies of low pressure evaporation have been developed by many researchers, such as Kumar et al. [5] who conducted a pilot study and designed a desalination system utilizing ocean thermal gradient and the system performance evaluated by varying the condenser and evaporator temperature and the vacuum chamber pressure . J. H. Tay et al. [6] investigated the vacuum desalination application using the waste heat from a steam turbine that received by the superheated vapor heater at corresponding low pressure is possible and have several advantages. Zhijiang and Wang [7] were did an experiment on Ocean Thermal Energy for Desalination (OTED) by modeling the integrated device for the evaporation and condensation process using a Siphon principle to get more freshwater production with less energy consumption and found out that the temperature difference will affect to the yield production. Muthunayagam et al. [8] conducted both theoretical and experimental studies with their own device through the droplet of the flash evaporation model at temperature between 26°C to 32°C. The experiment meets the theoretical prediction and showed the height change in vaporizer do not have much influenced for yield production. The simulation and experimental studies were carried out by Kudish et al. [9] , their work on desalination system consist of a solar collector coupled on the evaporator and condenser. The performance was evaluated by utilizing the parametric sensitivity studies by the design optimization and operation condition. Experimental study on spray flash desalination was demonstrated by Ikegami et al. [10] by investigating the direction of injection of seawater and came out with the spray flash desalination process is more efficient with using upward jet method based on the experimental result. A simulation model for the spray flash desalination system was studied by Satoru Goto et al. [11] by using energy conservation law and mass conservation law and the results compared with the experimental study under constant conditions and the properties of fluid was derived by PROPATH.

There are many researches conducted about OTEC and desalination plant. Among the recent works, the OTEC implementation in a Chilean thermal power plant was evaluated and an Ocean Thermal Energy Conversion hybrid plant was designed which optimized the effect of the size and the operating conditions based on the plant efficiency by Rodrigo [12]. The optimization of OTEC and desalination plant have been carried out by Ikegami *et al.* for the optimum output power based on the temperature different of the evaporator, condenser, the working fluid flow rate and the heat exchanger performance which produced a maximum turbine power and desalinated water. Sami et al. [13] conducted a simulation studies based on the Kumejima Island condition for power generation and freshwater production using renewable thermal energy. All these researches and data were very useful and important for the power generation and desalination utilizing ocean thermal energy development. Malaysia is a country with equator season year-round. The mean sea temperature around the Malaysia calculated more than 28˚C up to 31˚C. Unfortunately, the depth of the Malaysian ocean is not too deep to achieve the OTEC potential of cold seawater temperature except at Sabah trough which the temperatures exceed 3˚C for range from 1.0 to 1.2 km depth and the mean temperature for warm seawater are about 28˚C as shown in Figure 1.

In this paper, the simulation of OTEC and desalination plant will be done based on the Malaysia condition using FORTRAN and showed the feasibility of the integrated OTEC (I-OTEC) plant using a Close Cycle OTEC plant and LTTD plant which can boost the OTEC plant in term of energy consumption as well of the desalinated water produced by OTEC-LTTD plant.

2.0 INTEGRATED-OTEC WORKING PRINCIPLE

From Figure 2, the surface layer of warm seawater act as a solar agent that will absorb the sunlight from the sun and distributed by the mixing effects induced by surface currents that will give the relative uniform temperature for up to 20m-40m depth. After a certain depth, the temperature of seawater decline gradually with depth due to thermocline effect which is a layer within a water body as shown in Figure 1 [14]. Besides of rapid changes in the temperature, the density, pressure and salinity of seawater also changed. Despite having a relatively small value of change, it must be taken into the calculation which affects the loss in the seawater pipe and pump. In Close Cycle OTEC, the working fluid (ammonia) turns to vapor and drive the turbine based on the evaporation concept using the warm seawater in the evaporator heat exchanger. The remaining low wet vapor discharging from the turbine will be condensed by the cold seawater in the condenser. The working fluid pump will complete the cycle by compressed the working fluid to the evaporator.

Desalination plant act as the integrated OTEC plant which the warm seawater exits from the evaporator heat exchanger flow to the flash chamber by a nozzle or spouts which is maintain the pressure lower than its saturation pressure. The warm seawater will undergo process of "flash evaporation" or rapid boiling .The vapor generated in the flash chamber then is cooled and condensed by the deep cold seawater in the condenser which the freshwater is obtained from the condensation process occur in the condenser.

3.0 SIMULATION MODEL CALCULATION

The thermal temperature, topographic and site information based on AB Jaafar [14, 15].The calculation model for all pumping power, Organic Rankine Cycle will be shown below and LTTD as integrated to power generation followed the Sotoru *et al*. [11] calculation model and the input parameters as in Table 1.

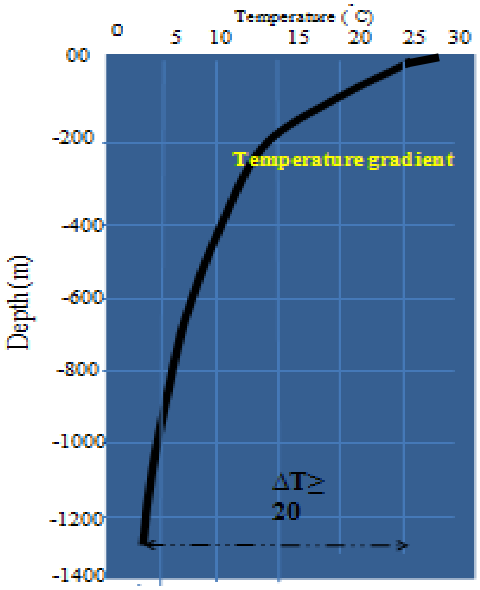


Figure 1 The graph temperature vs depth of Sabah Trough

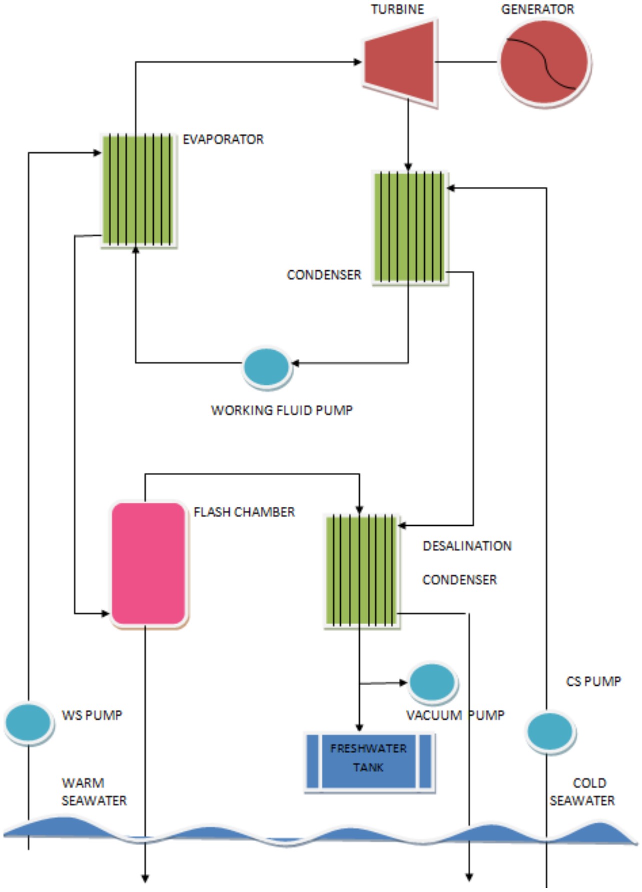


Figure 2 Schematic diagram of OTEC-LTTD plant

3.1 Pumping Power

For power generation cycle, the pumping power for the warm seawater intake and cold seawater intake is [16]

$$W_{p,w} = \frac{m_w \Delta H_w g}{\eta_{wp}} \quad (1)$$

Where m_w is mass flow rate of seawater for cold and warm side, g is gravitational acceleration,9.18ms^{-2} ,η_{wp} is the efficiency of the seawater pump and $\Delta H_{ws}$is the total head difference of the seawater piping as for warm and cold seawater calculated as:

$$\Delta H_{ws} = \Delta H_{w,f} + \Delta H_{w,d} + \Delta H_{w,PH} \quad (2)$$

Where from Darcy Weichbach equation, frictional head loss due to pipe, ΔH_{ws} is

$$\Delta H_{ws} = \frac{L}{D}\frac{v^2}{2g}, \quad (3)$$

$$\frac{1}{\sqrt{F}} = -2\log_{10}\left(\frac{\epsilon/D_h}{3.72} + \frac{2.51}{Re\sqrt{F}}\right) \quad (4)$$

Where F is the friction factor as obtained in Colebrook equation [17] , L is pipe length, D is pipe diameter and v is the flow velocity of seawater, ϵ is the surface roughness of the used pipe. The losses on the plate heat exchanger side, $\Delta H_{w,PH}$ is

$$\Delta H_{w,PH} = F\,\frac{Lp}{D_{eq}}\frac{{V_{w,PHE}}^2}{2g}, \quad (5)$$

Where Lp is plate length, $V_{w,PHE}$ is seawater velocity in heat exchanger and D_{eq} is the equivalent diameter which 2 times the clearance between the plate. $\Delta H_{w,d}$ is head loss due to density different which is assumed to be same to the equivalent head to the seawater pipe as

$$\Delta H_{w,d} = \frac{V_w g H(\rho_{w-}\rho_{avg})}{m_{cs}} \quad (6)$$

Where V_w is the velocity of seawater inside the pipe , ρ is the seawater density and H is the depth of the intake seawater. Vacuum pump work can calculated as

$$W_{vp} = \frac{W_{Comp}\, nRC_a m_{ws}}{2(n-1)}\{(T_{wsi} + 273.15)\left(\left(\frac{P_{atm}}{P_{stv}}\right)^{\frac{n-1}{n}} - 1\right) \quad (7)$$

Where n is the specific heat ratio of air,R is the gas constant of air,C_a is the mass concentration of air taken as 19.36 mg/kg based on Hawaii data [18],P_{atm} is pressure at atmospheric ,P_{stv} is pressure at saturated vapor , T_{wsi} is inlet temperature of seawater and m_{ws} is mass flow rate of warm seawater inlet in flash evaporator .

3.2 Power Generation

In the evaporator, a working fluid is evaporated to saturated vapor by receiving heat from the warm seawater. The energy balance equation at each side of the evaporator can be written as:

$$Q_E = m_{ws}Cp_{ws}(T_{wsi} - T_{so}) = m_{wf}(h_1 - h_4) \quad (8)$$

Seawater is an ideal incompressible fluid. Enthalpy and entropy of the working fluid, which are in general a function of pressure and vapor quality during phase change, were determined from PROPATH. Overall heat transfer coefficient and effective surface area of the evaporator correlates with the heat addition rate as shown in the following equation:

$$Q_E = U_E A_E \Delta T_{lm,E} \quad (9)$$

Where $\Delta T_{lm,E}$ is the logarithmic mean temperature difference across the evaporator, and the effective thermal conductance $U_E A_E$ can be approximately as

$$\frac{1}{U_E A_E} = \frac{1}{h_{wf} A_E} + \frac{1}{h_{ws} A_E} \quad (10)$$

Basically the energy balance equation for the condenser is same like evaporator and written as:

$$Q_C = m_{cs}cp_{cs}(T_{cso} - T_{csi}) = m_{wf}(h_2 - h_3) \quad (11)$$

The heat transfer area of the condenser can be defined as below:

$$Q_C = U_C A_C \Delta T_{lm,c} \quad (12)$$

The logarithmic mean temperature difference across the evaporator and condenser is correlated as below :
For condenser,

$$\Delta T l_m, C = \frac{T_{cso} - T_{csi}}{\ln\frac{T_c - T_{csi}}{T_c - T_{cso}}} \quad (13)$$

For evaporator,

$$\Delta T_{lm,E} = \frac{T_{wsi} - T_{wso}}{\ln\frac{T_{wsi} - T_E}{T_{wso} - T_E}} \quad (14)$$

In Organic Rankine Cycle, all the point properties are derived by PROPATH.

3.3 Turbine Generator Power

The turbine generator can be calculated from the product of mass working fluid flow rate,m_{wf} and the adiabatic heat loss across the turbine. The equation is as follows:

$$W_{T-G} = m_{wf}\,\eta_T\,\eta_G(h_2 - h_1) \quad (15)$$

Where, η_T and η_G are the turbine isentropic efficiency and generator mechanical efficiency which assumed as 0.9 and 0.95 respectively. Power generation and desalination calculation will measure by the net power output which calculated as:

$$W_N = W_{T-G} - W_{P,wf} - W_{P,ws} - W_{P,cs} \quad (16)$$

Where the net power is equal to the generator power minus all the pumping power.

Table 1 Initial condition for the simulation

Turbine generator power, P_G	1000	kW
Generator efficiency, η_G	0.96	-
Turbine efficiency, η_T	0.85	-
Efficiency of all pumps,	0.85	-
Evaporator (plate-type heat exchanger)		
Thermal Conductance	8.0	MW/m^2K
Condenser (plate-type heat exchanger)		
Thermal Conductance	8.0	MW/m^2K
Diameter of warm and cold seawater pipe		
Weather condition (Malaysia)		
Temperature of sea water		
Warm sea water surface temperature (0 m)	28.0	°C
Cold deep sea water temperature (1000 m)	4.0	°C
Diameter of warm and cold seawater pipe	1.2	m

4.0 RESULTS AND DISCUSSION

For standalone LTTD plant utilizing the renewable thermal energy from the ocean could gave more freshwater production than the desalination coupled with power generation plant as shown in Table 2. This is because the temperature difference of the desalination plant received from the OTEC plant is lowered than standalone LTTD plant. But, for the standalone desalination and LTTD plant, it needs specific energy consumption to operate which is the main disadvantage for the plant. This is the reason why there are many desalination plants combined with the power generation plant to minimize the energy consumption cost. Interestingly, the 1MW power generation plant will give more than 1000 tons per day as in this and Sami *et al.* [13] which integrated with the LTTD plant. The specific pumping power for the LTTD plant in I-OTEC can be neglected as the requirement only for the OTEC power plant. The different in pumping power of all pumps for both cases is because the tropical condition to deliver a warm seawater and cold seawater from the several depths and length .For the output power generation and freshwater production, tropical data give different output which the main parameters in utilizing the performance of LTTD and OTEC plant are the temperature of the warm and cold seawater. 1°C increase and decrease in temperature will give much effect on the output and performance of the system. Figure 3 shows the effects of warm seawater temperature on the amount of desalinate water production. The higher the temperature of warm seawater will give more freshwater production. This is because, when temperature of seawater higher, the specific heat of seawater increase but the latent heat of seawater decrease. Therefore, the desalinate water production can be calculated by applying the desalination of effectiveness equation as the results shown in Figure 3. The temperature of cold seawater taken as 4°C which ~~is~~ relatively remains constant under certain depth. The amount of heat stored at the surface layer of ocean from the sunlight is depends on the weather conditions. The same concept applied to the power generation plant. Utilizing ocean thermal energy, larger temperature gradient will give better performance in power generation as well in freshwater production. Working principle of the OTEC plant is based on the Rankine Cycle. For a Closed-Cycle OTEC, ammonia working fluid will be used which is has low boiling point to generate vapor to drive the turbine. Figure 4 shows the T-s diagram of ammonia working fluid that was used in this study. The Rankine cycle in the T-s diagram is for the OTEC cycle which is to produce 1MW of electricity generation. In order to achieve 1MW of work turbine, the simulation used same mass flow rate of warm and cold seawater that's 1751.4 kg/s with overall heat transfer coefficient area of evaporator and condenser of 8.0×10^6 W/K and the others parameters are kept constant. The evaporator temperature is 21.76 °C and the condenser temperature is 9.90 °C that calculated using a log mean temperature difference method. Point 1 is the saturated vapor that will be an inlet and drive the turbine which is coupled with generator to generate electricity. Point 2 will be the outlet of the turbine and the inlet of the condenser which the $s1=s2$ and point 3 is the outlet of the condenser which is in saturated liquid condition. Warm surface seawater is pumped through the evaporator heat exchanger to vaporize the working fluid. The Ph diagram showed as in Figure 5.

Table 2 Simulation results of 1MW I-OTEC and LTTD

			This study (LTTD)	Sami (I-OTEC)	This study (I-OTEC)
Warm sea water					
Inlet temperature	T_{wsi}	°C	28.0	26.0	28.0
Outlet temperature	T_{wso}	°C	25.1	21.6	23.7
Cold sea water					
Inlet temperature	T_{csi}	°C	4.0	6.0	4.0
Outlet temperature	T_{cso}	°C	6.8	10.21	8.04
Evaporation temperature	T_E	°C	16.26	20.78	21.77
Condensation temperature	T_C	°C	15.88	10.99	9.90
Flow rate					
Warm sea water	m_{ws}	kg/s	1751	2040	1751
Cold sea water	m_{cs}	kg/s	1751	2040	1751
Working fluid	m_{wf}	kg/s	-	24	24
Net power	P_N	kW	-	675.88	821.95
Warm sea water pumping power	P_{ws}	kW	34 .0	94.3	58.26
Cold sea water pumping power	P_{cs}	kW	111.26	221.31	111.26
Working fluid pumping power	P_{wf}	kW	-	9.58	9.57
Vacuum pump pumping power	P_{vp}	kW	25.64	15.92	24.89
Freshwater production	m_{dw}	kg/s	33.57	15.04	17.58

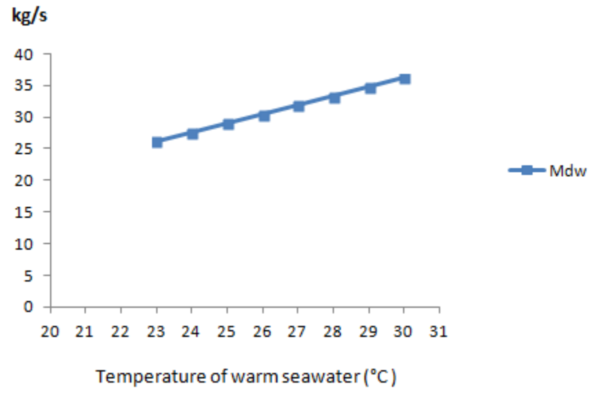


Figure 3 Desalinate freshwater production by different temperature of warm seawater

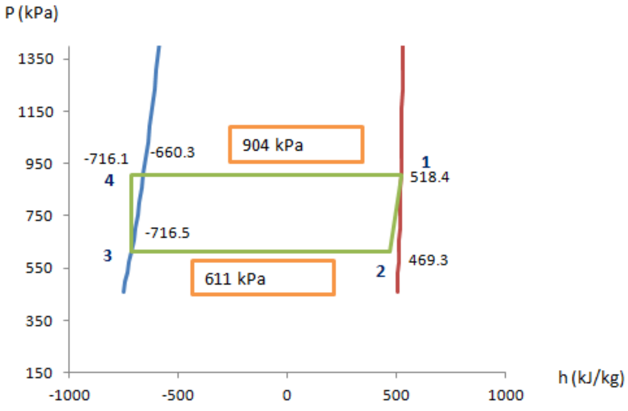


Figure 5 P-h diagram for ammonia working fluid produce a 1MW turbine power generation (emphasized)

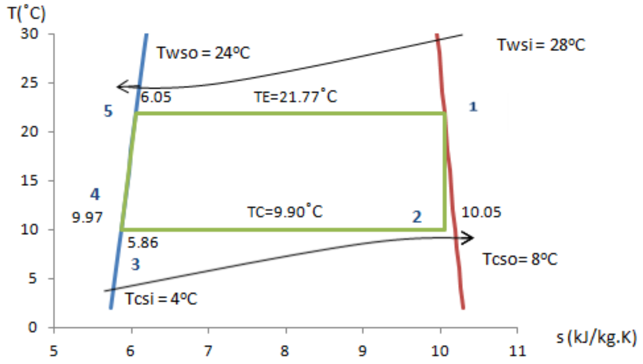


Figure 4 T-s diagram for ammonia working fluid produce a 1MW turbine power generation (emphasized)

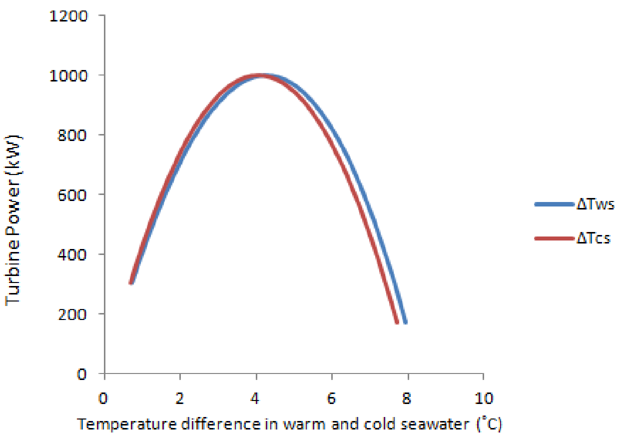


Figure 6 Turbine power output with temperature difference of seawater

Figure 6 shows the variation of turbine power with temperature changes in the warm and cold sources, Twsi-Twso and Tcso-Tcsi while other parameters are kept constant. From the graph, the idea that larger difference of temperature changes ~~of~~ the warm and cold sources at certain condition is not right. The graph shows that the turbine power keeps increasing until at certain peak at temperature changes, then the turbine power will starts to keep decreasing with a larger temperature difference. This is because the value of Qe will further increase with larger difference of the warm and cold seawater and the efficiency of OTEC system will gradually decrease with the larger temperature difference. So, the turbine power output/net output is equal to the multiplication of the Qe and the efficiency. The changes in temperature of warm and cold sources do not have a big difference but almost identically to each others as shown in the Figure 6. The result in Figure 7 shows the effect of the temperature difference with the turbine power and the net power output with the freshwater production. The result shows that at the same condition, with a turbine power generation of 1MW, the freshwater production generated is 17.58 kg/s which are more than 1500t/d with net power output of 821.95 kW. The rate of freshwater production is decline linearly by further increasing of the warm and cold seawater temperature difference. In order to generate more power generation and freshwater generation, its need the larger OTEC-LTTD plant capacity.

Figure 8 shows the mass of seawater and the net power output from the turbine by the different thermal conductance of the evaporator and condenser (UAe =UAc).The figure shows the variation of the warm seawater flow rate to produce turbine power of 1MW and the net output gained by variation of the warm and cold seawater mass flow rate and the thermal conductance of the heat exchanger. Based on the graph, the Wnet of 1MW turbine power will increase with decreasing the cold and warm seawater mass flow rate. Thus, by increasing the thermal conductance value, the mass flow rate of cold and warm seawater also decreased while the Wnet increases. From the results ,configuration value of the thermal conductance give an effect to the mass flow rate of the seawater intake and the Wnet as well .But , at a certain point , the value of the thermal conductance will become finite which means that the value of the mass flow rate and the Wnet will remains constant at its maximum net power output .This indicates that enhancement of the thermal performance of heat exchanger devices by means increasing the overall heat transfer coefficient .By increasing the heat transfer area also reflect finitely on the system performance. The larger mass flow rate of the warm and cold source of seawater will affect the net output power because the pumping power of the warm seawater and the cold seawater will increase with increasing the mass flow rate of seawater intake due to the head loss in the pumping system.

The diameter of pipe diameter also is the main parameter that affects the Wnet. From Figure 9, the net power output kept increasing with increasing the diameter of seawater pipe until the net power output remains constant by a further increase of the seawater pipe diameter. By increasing the diameter of pipe cause the flow velocity in the seawater pipe decrease which affect the head loss of seawater pipe of the warm and the cold source of seawater pipe.

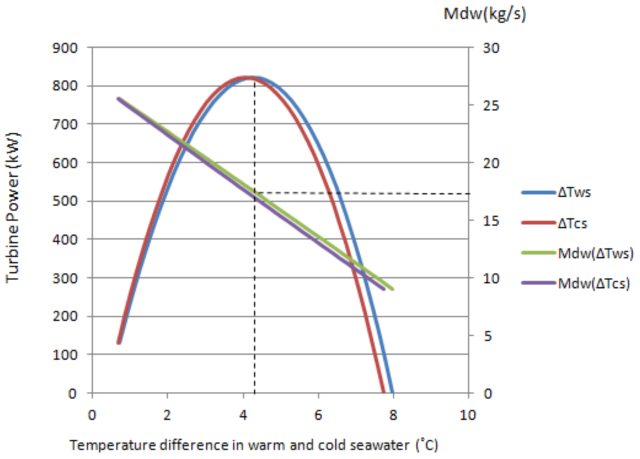


Figure 7 Work turbine, work net and pump work for warm seawater, cold seawater and working fluid with variable thermal conductance

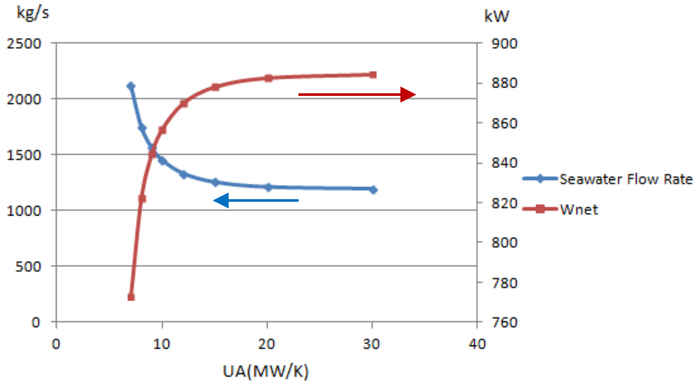


Figure 8 Seawater mass flow rate and net output power generation with variation of thermal conductance

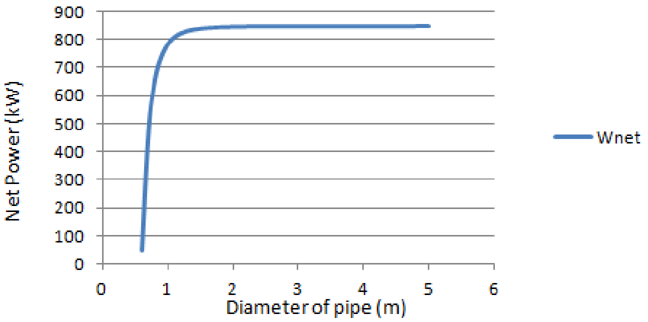


Figure 9 Variation of Net output power by different diameter of seawater pipe source

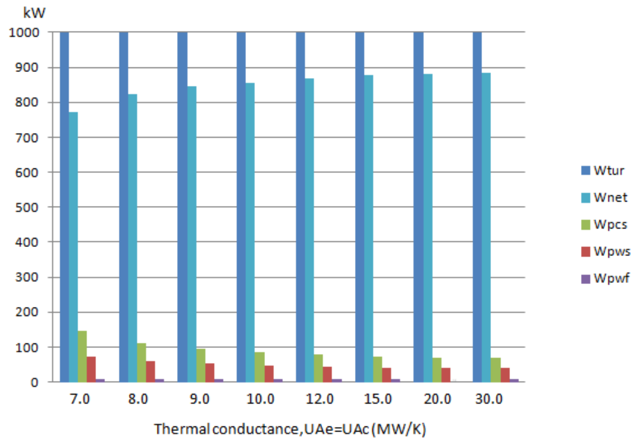


Figure 10 Work turbine,work net and pump work for warm seawater,cold seawater and working fluid with variable thermal conductance

OTEC plant work net output described the total turbine power output minus the total pumping work for warm seawater, cold seawater and working fluid. As discussed before, the net power output was also affected by the diameter of the pipe for the cold seawater and warm seawater. Figure 10 shows the 1MW OTEC plant output with the net power output and all pumping works with different thermal conductance. The value of the thermal conductance and the pipe diameter will have a certain value that given a finite value of turbine power. As shown in the graph, the pumping power for the cold seawater and warm seawater decreased in logarithmic-like relationship with increasing the thermal conductance of the evaporator and condenser. This is due to seawater intake for the cold and warm seawater decreased with increased of the thermal conductance to produce a specific maximum work turbine. For small value of thermal conductance, to achieved 1MW turbine power need more intake of the warm and cold seawater intake to the plant and vice versa for the large thermal conductance. The density difference and friction factor also give much effects to the pumping power which the pumping power for the cold seawater consume much energy due to depth of cold seawater rather than depth of warm seawater intake. The pumping work for ammonia working fluid is constant and same for the 1MW power output of working turbine which is 9.58 kW for all conditions of thermal conductance.

5.0 CONCLUSION

For OTEC-LTTD plant of the integrated OTEC plant can give several advantages and benefits to the coupled system which is power generation system and desalination system. All types of desalination plant will consume much energy consumption which is the main objective of the desalination project, which could give an energy-cost-effective power generation and desalination plant. The integrated plant also gives a several advantage of pumping and vacuum system of the plant. For power generation, OTEC will lead the green technology electricity generation and the integrated LTTD plant will produce freshwater that coupled with the power generation plant. Both plants are using the temperature gradient of the warm and the cold source of seawater that will be abundant of seawater available and a free source to use. As for 1MW OTEC-LTTD plant, it produced more than 1500 ton/d. It can be used to supply residential places which about 1.518t/d freshwater per 44kWh of electricity. The production of freshwater also boosted the OTEC plant which is very economical as using other desalination concepts. As an energy efficient, RO is needed about 221.5kW (3.5kWh/t) of specific energy consumption to produce 63.28t/h (17.58 kg/s) of freshwater. From the comparison, it can be concluded that OTEC plant will be beneficial and advantages with the LTTD plant. With the presence of LTTD plant in the OTEC cycle, the freshwater can be produced as a by product without consume much energy. There are many factors that influenced the OTEC and LTTD plant. From optimization, the best performance can be selected based on these criteria, which are the maximum plant output, the control system of the input parameters, and the cost by the optimum design. Interestingly, Malaysia has a potential to build an integrated OTEC-LTTD plant. This is due to the location of site around Sabah Trough which has more than 20°C temperature gradient and nearer to the populated island which needed the electricity and freshwater supply. The location, design and optimization presented based on the information on its thermal and topographic characteristic.

Nomenclature

A = area (m^2)
C_p = specific heat at constant pressure (J/kg.K)
Q= Heat transfer rate (kW)
f = friction coefficient
g = acceleration of gravity (m/s^2)
h = heat transfer coefficient (W/m^2.K)
l = length (m)
L = latent heat of vaporization (J/kg)
LMTD = logarithmic mean temperature difference (°C)
m = flow rate of mass (kg/s)
p = pressure (Pa)
P = power (W)
q = heat flux (W/m2)
R = specific gas constant (J/kg.K)
T =temperature (°C)
U= overall heat transfer coefficient (W/m^2.K)
V =velocity (m/s)

Subscripts

a = air
atm = atmospheric
avg = average
cs =cold seawater
dw = distilled water
f =friction
fc = flash chamber
i = inlet

I=Integrated
L = liquid
N=net
o = outlet
opt = optimum
p= pump
RO= Reverse Osmosis
sat= saturation
sp =specific
tot = total
vp =vacuum pump
ws = warm seawater

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