ENHANCED PERFORMANCE OF OTEC PLANT USING SOLAR COLLECTOR

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Abstract— Ocean Thermal Energy Conversion (OTEC) is a process that employs the natural temperature difference between the ocean surface and the depths of the ocean. It is observed that thermal efficiency and the output power of system will increase with increasing operating temperature difference. Increasing turbine inlet temperatures also increase the efficiency and the work done by the turbine. The efficiency and the power output increases with increasing ratio of warm water to cold water flow rates. A solar collector is utilized to provide auxiliary heat into the system. The add-on solar is installed to preheat the warm sea water before entering the evaporator. The heat absorbed from solar collector by warm seawater will then heat the working fluid caused the enthalpy drop across the turbine increase.

Index Terms—OTEC, Co-Generation, solar energy, thermal efficiency, Warm surface water

1. INTRODUCTION

This research work is based on the concept of Ocean Thermal Energy Conversion (OTEC). This is a power cycle that is in turn a heat engine, which powers a low-pressure turbine. Ammonia will be used as the working fluid in the cycle due to its low vaporizing point. Surface water temperature is enough to cause the working fluid to vaporize, and then cold water from approximately 1000 meters deep will be pumped to the surface to condense the working fluid. The system analyzed here will operate in a closed cycle.

The vapor is then condensed in the condenser using cold deep seawater pumped to the surface. The condensed working fluid is pumped back to the evaporator and the cycle is repeated. Figure 1 shows a schematic diagram of a closed cycle OTEC plant [1].

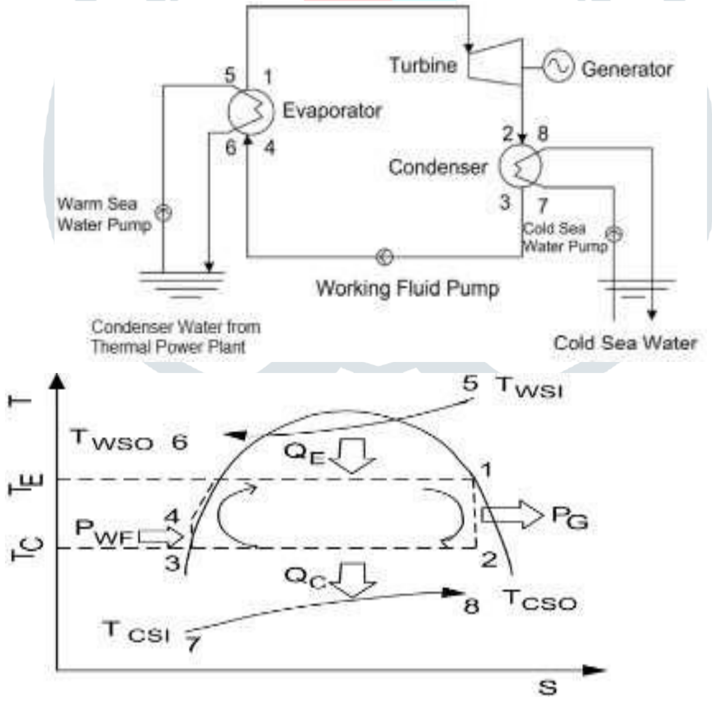

Fig 1: Schematic diagram of a closed cycle OTEC plant

1.1 OUTLINE OF OTEC SYSTEM

Principle of OTEC is fundamentally the same as the other commercial power plants and clean power plants except for its heat source and working fluid. The Heat source of OTEC is Sea Surface water and the working fluid is not the fresh water but the ammonia or the mixture of ammonia and the water. In the Institute of Ocean Energy, Saga University (IOES), OTEC basic experimental equipment was constructed. The OTEC basic experimental equipment adopts the Uehara Cycle [7]. Figure 1 shows a diagram of the 30 Kw. 1. The working fluid of the binary mixture of water and ammonia is sent to the evaporator, and the vapor generated by the heat exchange of the warm sea water in the evaporator. 2. Two phase flow of the working fluid generated in the evaporator is separated into vapor and liquid in separator. Then, the vapor sent to the turbines and liquids sent to the regenerator .3. The vapor that is sent to the turbines generated the electric power by rotating generator connected to it.

1.2 BACK GROUND HISTORY

Ocean Thermal Energy Conversion (OTEC) is a process that employs the natural temperature difference between the surface and the depths of the ocean. First introduced in 1881, OTEC has been described as an effective andrenewableenergysource.OTECsystemsmustbedesigned with regard to potential efficiency issues. These issues should be properly researched in order to design OTEC systems that are effective. OTEC plants can be a feasible source of cost effective renewable energy in tropical coastal regions that have high shipping costs for fuels andfoods

A 100 kW OTEC pilot plant was constructed on-land for demonstration purposes in there public of Nauru in October 1981 by Japan. The system operated between the warmsurface water and a cold water source of 5-8°C at a depth of 500-700 m, with a temperature difference of 20°C [2]. The tests done were load response characteristics, turbine, and heat exchanger performance tests. The plant had operated by two shifts with one spare shift, and a continuous power generation record of ten days was achieved. The plant produced 31.5 kW of OTEC net power during continuous operation and was connected to the main power system[2].

Uehara et al. [3] presented a conceptual design for an OTEC plant in the Philippines after taking extensive temperature readings to determine a suitable site. The ocean surface water had a temperature range of25to29ºCthroughout the year while the cold water remained between 4 to 8 ºC at a depthof500–700m.Atotalof14sitesweresuggested.

Uehara and Ikegami [4] performed an optimization study of a closed cycle OTEC system. They presented numerical results for a 100 MW OTEC plant with plate heat exchangers and ammonia as the working fluid.

Yeh et al. [5] conducted a theoretical investigation on the effects of the temperature and flow rate of cold sea water on the net output of an OTEC plant. They found out that the maximum net output exists at a certain flow rate of the cold seawater. The output is higher for a large ratio of warm to cold seawater flow rate.

Yamada et al. [6] did a performance simulation of a solar-boosted ocean thermal energy conversion plant, termed as SOTEC. The temperature of warm sea water used in the evaporator was increased by using a solar thermal collector. The simulation results showed that the proposed SOTEC plant can increase the overall efficiency of the OTEC system. Tong et al. [7] proposed a solar energy reheated power cycle to improve performance. They suggested that a solar collectorintroduced at the evaporator will greatly improve the temperature difference and thus the cycle performance.

Table 1: Properties of AMMONIA and AIR

Substance	Molar Mass *M*, kg/kmol	Gas Constant *R*, kJ/keg*	Specific Heat Data at 25 º C *cp*,kJ/kg·K *cv*,kJ/kg·K	
Air	28.97	0.2870	1.005	0.7180
mmonia, NH3	17.03	0.4882	2.093	1.605

Table 2: Boiling and freezing point properties:

Substance	: Ammonia	
ling Data at l atm	Normal Boiling Point º C	-33.3
	Latent Heat of Vaporization *hfg*, kJ/kg	1357
Freezing Data	Freezing Point º C	-77.7
	Latent Heat of Fusion *hif*, kJ/kg	322.4
Liquid Properties	Temperature º C	-33.3
	Density ρ, kg/m3	682
	Specific heat *cp*, kJ/kg· K	4.43

Anhydrous ammonia (NH_3) exists naturally in a gaseous state under atmospheric pressure and temperature. Under moderate pressure it changes easily to a liquid, becoming a gas again when the pressure is reduced. Industries take advantage of this characteristic by shipping and storing liquefied ammonia in pressurized railway cars, tank trucks and cylinders of various sizes. It is primarily used as fertilizer. It is also widely used as a refrigerant and in manufacturing nitric acid, explosives and plastics. The above tables (1) and (2) shows the different properties of ammonia.

Anhydrous ammonia is one of the most water-soluble of all gases, but it should not be confused with aqueous ammonia, which is a 15 to 30 per cent solution of ammonia in water. As a gas it is color less and has a specific gravity of 0.597 (air = 1.0) at 25°C under standard atmospheric pressure. Generally, ammonia has good warning properties because of its characteristic pungent and irritating odour. With rising temperature ammonia expands rapidly, increasing the internal pressure in vessels and pipes, etc. This must be considered in the design and operation of ammoniasystem

Hazards:

***Fire*:**Ammoniagashasanexplosiverangeof16to25percent by volume in air. Although it is classified as non-flammable under the Workplace Hazardous Materials Information System (WHMIS) and the Transportation of Dangerous Goods Regulations, its flammability potential is only slightly lessthan that of some gases that do meet the official flammability criteria.

***Explosion*:** Contact of ammonia with certain chemicals including fluorine, chlorine, bromine, iodine, mercury and silver oxide can create explosive compounds. Moist ammonia will vigorously attack silver, copper, zinc and many of their alloys. Aluminum is attacked to a lesser extent. Iron and steel are inert to ammonia.

***Health*:** Anhydrous ammonia, either as liquid or gas, is a strong irritant to skin, eyes and the respiratory tract. Direct exposure by contact can cause severe burns. For ammonia the time-weighted-average exposure value is 17 mg/m3 (25 ppm). The short-term exposure value is 24 mg/m3 (35 ppm).

2. OTEC SEAWATER COMPONENTS

The OTEC seawater system consists of the pipes and pumps required to supply warm and cold seawater streams to the OTEC heat exchangers and allow for the return of effluents to the ocean. The concept considered for the cold water pipe (CWP) is an 8.7 m. FRP sandwich pipe suspended from the OTEC platform to a depth of 1,000 m. Warm seawater will be drawn in through two 10 m. pipes from a depth of about 20 m. [9] The mixed effluent will be returned through two 12.3 m . FRP pipes at a depth of 60 m. This depth has been selected to minimize the environmental impact.

Parameter	Value
Inside Diameter	8.7 m
laminated (face sheet) thickness	14 mm
Core (synthetic foam) thickness	60 mm
Laminate Density	1760 kg/m3
Outside Diameter	8.9 m
Core Density	670 kg/m3
Dry (air) Weight	2,460 kg/m
Wet(submerged) Weight	3 kg/m
Flexural Rigidity, EI	19.2 x 1010 N-m2 (46.4 x 1010 lb-f2
Laminate Modulus of Elasticity	20,680 MPa (3 x 106 psi)
Core Modulus of Elasticity	2,370 MPa (0.344 x 106 psi)

3. INSPECTION, MAINTENANCE AND REPAIR (IM&R)

The same procedure is required for maintenance and repair for this Co-Generation plant .From the perspective of inspection, maintenance and repair (IM&R), three general areas can be identified throughout the OTEC Platform: the

components on board the plant ship, such as heat exchangers, turbine-generators, and pumps; the platform hull and appendages; - the deep water components, such as CWP, water hose and mooring devices. Closed Cycle OTEC plant working on temperature difference of Thermal Power Plant Condenser Water and Cold Sea Water .The closed-cycle OTEC power plant was the first OTEC cycle proposed by D'Arsonval in 1881. This cycle uses a working fluid with a low-vaporizing point, usually propane or ammonia, in a closed flow path (Takahashi and Trenka, 1996) can be utilizes. The working fluid is pumped into the evaporator where it is vaporized and in turn moves a turbine. Closed-cycle plants operate on a Rankine cycle. The first stage of this cycle is referred to as isentropic expansion, which occurs in the steam turbine. Isobaric heat rejection in the condenser follows. This stage the water vapor becomes a liquid and therefore the entropy is decreased. The next stage is the isentropic compression in the pump (Takahashi and Trenka, 1996). During this step, the temperature increases due to the pressure [10].The boiler then supplies isobaric heat causing the working fluid to vaporize. In an OTEC system the thermal power plant condenser warm water would be pumped into the evaporator where the liquid ammonia would be pressurized. This pressure causes the ammonia to boil or become vapor. This works due to the ideal gas law that states that the temperature is directly proportional to the pressure; therefore if the pressure increases in a system, the temperature does too. The vapor ammonia then expands by traveling through a turbine. This turns the turbine making electricity. The ammonia vapor pressure at the outlet of the turbine is 7º C higher than the cold seawater temperature. The cold seawater is therefore brought up from the depths where heat exchange occurs and ammonia vapor is changed back into a liquid. The liquid ammonia is then pressurized by a pump started the cycle once more (Thomas, 1993). A Rankine cycle, in theory, are able to produce non-zero net power due to the fact that less energy is required to increase the pressure of a liquid then is able to be recovered when the same fluid expands as a vapor. It is for this reason that phase changes are essential when producing energy this way. The advantages of using a closed- cycle system are that it is more compact then an open-cycle system and can be designed to produce the same amount of power. The closed-cycle can also be designed using already existing turbo machinery and heat exchanger designs.

A closed cycle OTEC plant is designed with refrigerant R134-A as a working fluid. R134-A was used because it is not flammable at the low operating pressure and temperature of the experimental OTEC system.[8] Also, R134-A is one of the limited refrigerants that could be used in the refrigerant pump in the current setup. Figure 2 shows a schematic of the demonstration plant.

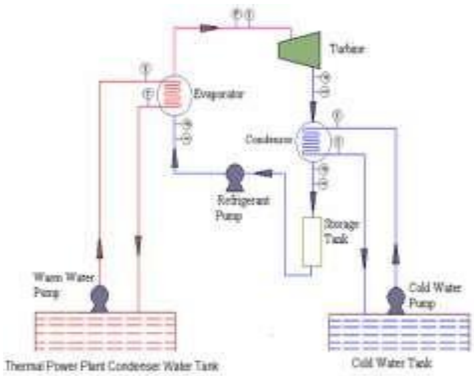

Fig 2. Schematic diagram of the proposed plant

In order to compare the performance of conventional OTEC and solar OTEC, a turbine-generator power of 100kW was numerically conducted using FORTRAN programming. The equations of each component were calculated by applying an iteratively method with initial assumptions of outlet of warm seawater and cold seawater. The pinch point temperature difference at evaporator and condenser were set on this study. The evaporator and condenser temperature were then used to calculate the saturation pressure and temperature of the working fluid by using PROPATH. Besides, the enthalpy, entropy and specific volume at each point can be obtained from this program (i.e. h1-4, s1-4 and v1-4) as well. Once all the value at each point are calculated, the energy values at evaporator, condenser and evaporator, i.e. Eqs. (6), (9) and (13) must be balance. Then, the calculation of mass warm seawater flow rate, cold seawater and working fluid, respectively were conducted. After specifying the flow rate of warm and cold seawater, the pumping power of cold seawater and warm seawater were determined by applying. Figure 1 and 2 shows the schematic diagram of conventional closed-Rankine OTEC cycle and the proposed solar boosted OTEC cycle. These figures show the general arrangement of the heat exchangers, pumps, piping, turbine generator, solar collector and PEM electrolyzer. In Figure 2, a solar collector is utilized to provide auxiliary heat into the system. The add-on solar is installed to preheat the warm seawater before entering the evaporator. The heat absorbed from solar collector by warm seawater will then heat the working fluid caused the enthalpy drop across the turbine increase. A simulation of 100 kW solar boosted OTEC is carried out to see its performance and the results were then compared with that of a conventional OTEC plant. The effect of solar collector on hydrogen production was also investigated. Hydrogen has a significant advantage as it can be produced without pollution and this increases the feasibility of an OTEC plant system. The simulated results are presented to compare the improvement of the system performances in terms of thermal efficiency.

4. SIMULATION MODEL

In order to compare the performance of conventional OTEC and solar OTEC, a turbine-generator power of 100kW was numerically conducted using FORTRAN programming. The equations of each component were calculated by applying an iteratively method with initial assumptions of outlet of warm seawater and cold seawater. The pinch point temperature difference at evaporator and condenser were set on this study. The evaporator and condenser temperature were then used to calculate the saturation pressure and temperature of the working fluid by using PROPATH. Besides, the enthalpy, entropy and specific volume at each point can be obtained from this program (i.e. h1- 4, s1-4 and v1-4) as well. Once all the value at each point are calculated, the energy values at evaporator, condenser and evaporator, i.e. Eqs. (6), (9) and (13) must be balance. Then, the calculation of mass warm seawater flow rate, cold seawater and working fluid, respectively were conducted. After specifying the flow rate of warm and cold seawater, the pumping power of cold seawater and warm seawater were determined by applying Eq. (14) until (25). Figure 1 and 2 shows the schematic diagram of conventional closed-Rankine OTEC cycle and the proposed solar boosted OTEC cycle. These figures show the general arrangement of the heat exchangers, pumps, piping, turbine generator, solar collector and PEM electrolyzer. In Figure 2, a solar collector is utilized to provide auxiliary heat into the system. The add-on solar is installed to preheat the warm seawater before entering the evaporator. The heat absorbed from solar collector by warm seawater will then heat the working fluid caused the enthalpy drop across the turbine increase. A simulation of 100 kW solar boosted OTEC is carried out to see its performance and the results were then compared with that of a conventional OTEC plant. The effect of solar collector on hydrogen production was also investigated. Hydrogen has a significant advantage as it can be produced without pollution and this increases the feasibility of an OTEC plant system. The simulated results are presented to compare the improvement of the system performances in terms of net thermal efficiency, net power output and solar collector area.

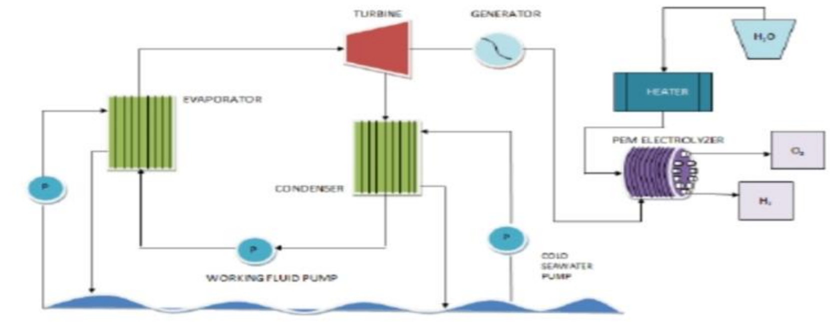

Figure 1 Schematic diagram of conventional OTEC cycle

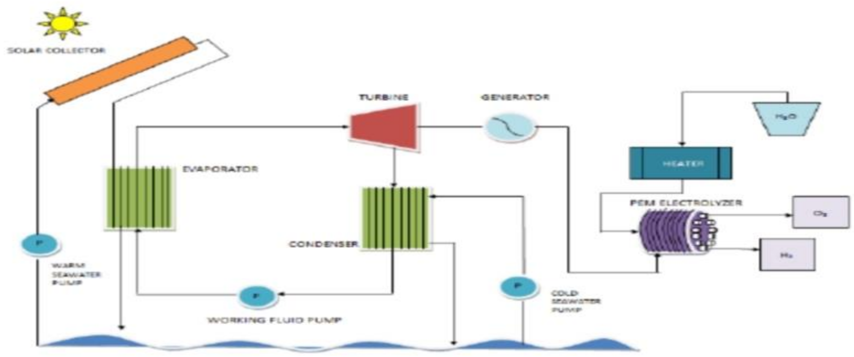

Figure 2 Schematic diagram of solar boosted OTEC cycle

5. RESULTS

Firstly, the conventional 100kW OTEC was simulated and the results of heat transfer areas of evaporator and condenser were determined. The results obtained were AE =293.6 m2 and Ac=318.2 m2 respectively. In order to minimize the required heat transfer capacity to avoid exceeding the value obtained by conventional OTEC system, the flow rates of warm and cold sea water need to optimize. Table 1 is the initial condition that assumed to be constant for this simulation study. Table 2 shows the compilation results of a 100 kW OTEC and 100 kW solar boosted OTEC cycle. The results of 100 kW OTEC cycle indicated a good agreement with Ref [6] which also used a similar scale designed OTEC plant. The noticeable difference seen was due to the initial condition considered in this study. The results of a solar collector boost TE by 20 K was also provided in this table. The theoretical thermal efficiency of a preheating solar OTEC showed an increment of 8.6%. This shows that adding on a solar plate into the system enables it to increase the net thermal efficiency by compensating for the losses of pumping power.

Figure 3 shows the T-S and P-H diagram of solar boosted OTEC system. Point 1 is at saturated vapor, where at this point the working fluid is 100% in vapor state. Point 2 is located at the outlet of turbine and inlet of condenser, where the working fluid is a mixture of vapor and liquid. Point 2 is known as wet vapor state. Then, point 3 is a saturated liquid state (100% liquid of working fluid) and point 4 is a compressed liquid state which the points after the working fluid pump. A solar boosted ocean thermal energy conversion (OTEC) was proposed to enhance the system performance with improvement in thermodynamic performance. In the preheated OTEC, the solar collector is installed at the inlet of evaporator with the function to preheat and provide additional heat to the warm seawater before entering the evaporator. Both results in Figure 4 and Figure 5, shows the effect of utilizing solar power absorption equivalent to 1000 kW.The maximum net power output from various readings of mass warm seawater flow rate was plotted as shown in the Figure 4. The graph shows that when mass warm seawater flow rate decreases, the net power output of the system is increases in line with the increase of inlet temperature of solar collector. However, when the mass of warm seawater flow rate continuously decrease, the value of net power cannot be read anymore. From the Eq. (1), the mass of warm seawater flow rate is inversely proportional to the inlet temperature of solar collector. Therefore, if the flow rate is decreased, the temperature will increase. However in this case, the maximum temperature of ammonia working fluid is 132°C. So, if the solar collector outlet temperature exceeded the maximum temperature of ammonia by lowering the flow rate of warm seawater, this is where the value of net power cannot be read any further. This is why in Figure 4 the net power output increased but then stopped at (Wnet=70 kW). This inefficient use of absorbed solar energy is because of limited surface area of the evaporator and condenser. Figure 5 shows the relationship of net power output

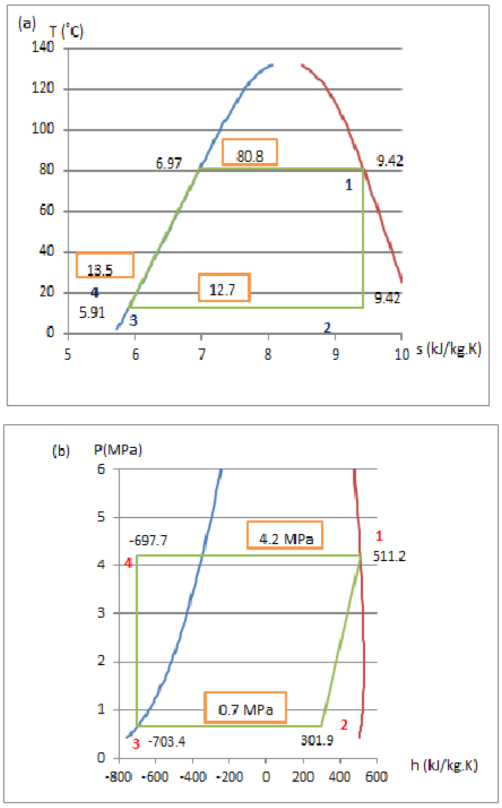

Figure 3 (a) T-S diagram of solar boosted OTEC system. (b) P-H diagram of solar boosted OTEC system of solar boosted OTEC system.

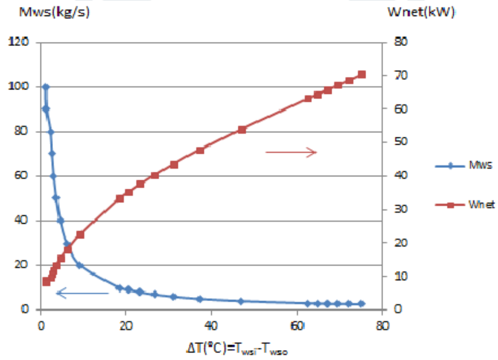

Figure 4 The relationship of net power output and mass warm seawater flow rate

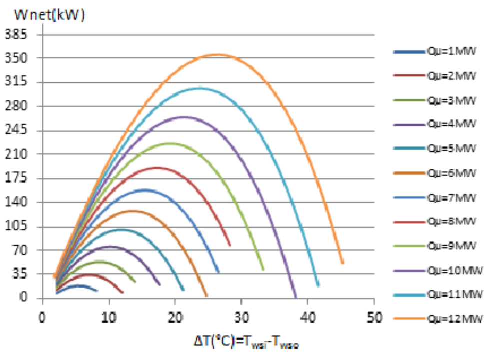

Figure 5 The solar power absorption as a function on net power output. (UAE=UAC=100kW)

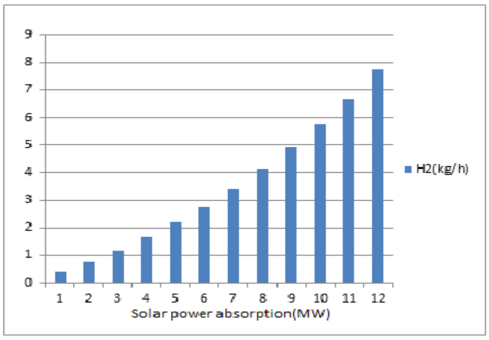

Figure 6 The hydrogen production as a function of solar power absorption

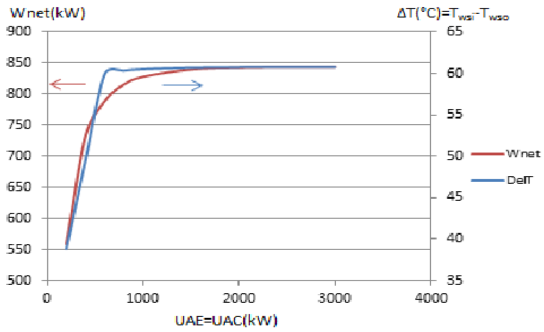

Figure 7 The relationship of overall heat transfer area of evaporator and condenser on net power generation and temperature difference.

6. CONCLUSION

A solar boosted OTEC plant was used in this study and simulations involving several parameters were carried out. The results showed that adding solar collector at inlet of evaporator enhances the thermal efficiency of the conventional OTEC plant. The results also reveal that increasing the solar power absorption will increase the net power output and net thermal efficiency as well. Besides, hydrogen production also showed an increment when solar power absorb by solar collector increased. It is planned that in future studies, a more precise simulation including utilizing different types of working fluid will be conducted. Another consideration will be to carry out a variation of the study using superheated solar OTEC cycle. The results will provide insights from a thermodynamic perspective when combining sustainable energy with solar thermal energy to improve the system performance, which then indirectly increase the rate of hydrogen generated

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