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Evaluation of hybrid ocean thermal energy conversion system plantwide performance

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Abstract. Ocean Thermal Energy Conversion (OTEC) is a renewable energy source in which energy is produced by converting the heat stored in the sea or the ocean thermal energy into valuable work, based on the temperature difference between the warm surface seawater and the cold deep seawater. One of the OTEC system requirements is to have a seawater temperature difference at a minimum of 20 °C within a depth of 1000 m below sea level. Recognizing the importance of optimum sea water temperature, several studies have been conducted to optimize the OTEC system. However, none of these studies was attempted under a hybrid ocean thermal energy conversion (H-OTEC) setup. A H-OTEC system is a combination of closed-cycle and open-cycle OTEC system. The objective of this study is to evaluate the performance of the H-OTEC process system based on the impact of seawater temperature variation by simulating H-OTEC process system. Aspen HYSYS was used as a chemical process simulation platform for conducting this study. After the model was completed, verification test was conducted before the simulated data was recorded. The data for the pump work input and the turbine work output were acquired to determine the net power output and system efficiency. The net power output, Carnot efficiency, and thermal efficiency were recorded approximately 1.39 kW, 5.7%, and 1.45%. The data for net power output and the efficiencies of the system was recorded for every 1 °C of increment in surface seawater temperature. The results showed that the net power output increased slightly by 0.5kW, with efficiency difference for both Carnot cycle and actual cycle, recorded to be less than 3% and 0.1% respectively.

Keyword : H-OTEC; Seawater Temperature; Simulation; Cycle Efficiency.

1. Introduction

Ocean Thermal Energy Conversion (OTEC) is a type of renewable energy technique in which energy is generated by converting the heat stored in the sea or the ocean thermal energy into electrical energy, or energy product equivalent, such as hydrogen, based on the difference in temperature between the warm surface seawater and the cold, deep seawater. It is a base-load energy generation system, that uses the natural thermal gradient from the ocean to drive a cycle that produces power [1]. The ocean, which is the world's largest solar radiation collector, covers more than 70% of the earth's surface. OTEC is acknowledged to be viable option as an alternative energy source particularly in many remote islands of tropical countries, where sustainable electricity is met, along with potential generation of sustainable economic activities. The needs of such technology is due to the capability of OTEC in providing free energy and the prospect of decreasing the usage of non-renewable fossil fuels; in the case of Malaysia, the country's dependency on imported coal from other countries could be reduced which could lead to the reduction of greenhouse gas emissions [1].

The OTEC system have three types of design: closed-cycle, open-cycle, and hybrid-cycle. These designs are distinguished by the type of working fluid used. In a closed-cycle OTEC system, a low boiling point working fluid, such as ammonia, undergoes vaporization through receiving heat inside a heat exchanger by warm surface seawater. After that, the vapor passes through the turbine connecting to a generator that produces electricity. After that, the exhausted vapor undergoes condensation by cooling down through heat released from the vapor to the deep cold seawater that passes through the condenser. When the vapor that is condensed flows back into the evaporator, the thermodynamic cycle is then completed in one closed loop. For the open-cycle system, the working fluid used is warmer surface seawater where it enters the low-pressure compartment and flash-vaporizes to become steam that has low density, which will drive a low-pressure turbine. The steam from the turbine undergoes condensation by the cold deep seawater, which occurs either in direct contact condenser or indirect contact through surface condenser, which then the water will be discharged from the plant.

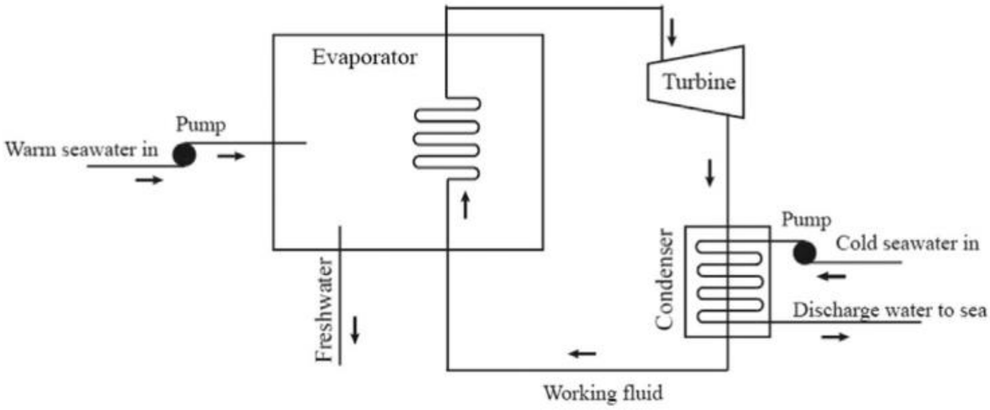

Figure 1. Schematic flow diagram of hybrid ocean thermal energy conversion system [2]

A new hybrid OTEC system that was later introduced, is a combination of both closed and open cycle systems [2]. A hybrid OTEC system comprises of both open-cycle system that generates steam at low pressure compartment, and a closed-cycle system that is heated by the generated steam. As a result, the working fluid inside the closed-cycle is vaporized and passed to the turbine for energy generation. Studies were conducted on this system to increase efficiency and power output [2]. Apart from power generation, hybrid OTEC system, which is the latest and advanced OTEC technology, has the potential to be utilized for producing other side products such as desalinated water [2]. Furthermore, the deep seawater discharge used in an OTEC power plant could be exploited for the cultivation of blue economy for the benefits around island communities [3].This further highlights the OTEC's capabilities of fulfilling the United Nation (UN)'s Sustainable Development Goals (SDGs) such as goal 6 for Clean Water and Sanitation and goal 7 for Affordable and Clean Energy [4].

One of the main challenges in operating OTEC is to have an optimal seawater temperature difference at a minimum of 20°C which is typical achieved at the optimal depth of 1000 m below sea level. This limitation leads to small thermodynamic efficiency in OTEC for about 3 to 5 percent [5]. As a result, OTEC power plants require huge amount of seawater to make up for the smaller efficiency and temperature, acquiring larger water pumps and pipes to bring the seawater up below. This technical complexity inevitably leads to additional capital costs, hampering commercialization effort in large-scale OTEC facilities.

Considering the importance of the optimum seawater temperature, several studies have been conducted, focusing on efforts for optimizing OTEC systems [6]–[8]. However, none of these studies were conducted under the hybrid-cycle OTEC system. In this report, Aspen HYSYS which is established chemical process engineering software is used as the main platform in assessing overall hybrid OTEC performance under the scope of chemical process engineering, based on a set of process conditions obtained from a reference hybrid OTEC system. The simulated process serves as a basis before it is later subjected to change in any operating conditions, in this case for intake sea water temperature. Any significant changes as the result of the operational adjustment are then evaluated, where focus in this study is on the overall thermodynamic efficiency of the process via evaluation on net power generated from OTEC system.

2. Methodology

2.1 Tools/Software

This research evaluates Hybrid Ocean Thermal Energy Conversion (H-OTEC) process system by simulating the process flow system using Aspen HYSYS, where the software provides a platform for simulating certain chemical processes of which it is designed to handle range of existing data base of species, robust and additional features that are suitable for simulating overall mass and energy balance in the hybrid OTEC system. The data for the H-OTEC process system was acquired and used as the reference to create the simulation model of the H-OTEC system in Aspen HYSYS.

2.*2 Methods*

a) Validation was made by comparing data between the simulated model and actual data, based on overall mass and energy specifications of the H-OTEC process. This is crucial to ensure that the simulated model is able to represent, as much as it could, identical to the actual process condition. In this case, several operating parameters such as temperature, pressure, flow rate, power requirement were acquired, based on process specification from a proprietary H-OTEC system. Considering some limitation in simulating actual process condition in the simulated interface, a few assumptions were set up accordingly: 1) the system is assumed to be in steady state operation; 2) the system is fully insulated with negligible heat loss to surrounding and 3) no drastic pressure drop is considered across equipment.
b) The flowchart below (Figure 2) represents several steps required for simulating H-OTEC system using Aspen HYSYS Version 11:

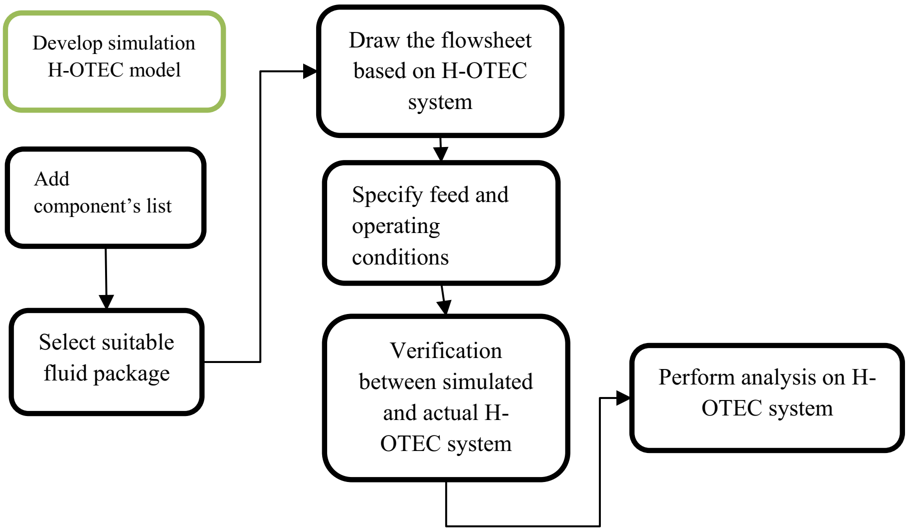

Figure 2. Flowchart of the process of simulation using Aspen HYSYS

i. For the base case simulation, the component lists for the simulation were chosen, in this case by considering seawater and ammonia as the main components of the process. The composition of the working fluid was pure ammonia (100 mol%). As for the seawater, the feed stream was defined using 0.97 mol% of water and 0.03 mol% of NaCl for representing typical seawater composition [9].
ii. The fluid package for the corresponding components were determined to ensure accurate and representable process simulation model. The chosen fluid package was Peng-Robinson Equation of State, as it is the most enhanced thermodynamic model in Aspen HYSYS[10].
iii. Each material stream was defined by specifying respective mass streams with basic process specifications such as composition, temperature, pressure, or the vapor fraction. The input data for specifying the material stream was adjusted until the system in the flowsheet was fully converged. The simulation was arranged in such that selected data variables were assigned to be adjusted or manipulated variables where any change made in this stream gave significant operational change to important equipment such as pumps and turbines. Plate heat exchangers was selected to represent the H-OTEC evaporator and H-OTEC condenser based on the mentioned example in the H-OTEC system.

2.3 Verification test

Once the system is fully converged, a verification test was carried out by calculating the percentage error using the data results of the variables from the simulation that was tabulated and compared with the preliminary data of the variables. The variables used are temperature, pressure, and mass flow rate. Equation (2.1) was used to calculate the percentage error:

$$\delta = \left|\frac{v_S - v_A}{v_A}\right| \times 100\% \qquad (1)$$

where, δ is the percent error, v_s is the simulated value from Aspen HYSYS, and v_A is the actual data.

2.4 Calculation of Net Power Output, Carnot Cycle Efficiency and Actual Cycle Efficiency

After the verification test, the power output and the thermal efficiency of the model were calculated to analyse the overall performance of the system. As the basis, the temperature of surface seawater was initially set at 25°C before it was adjusted accordingly. Equation (2) was used to calculate the power output.

$$W_{net} = W_{out,turbine} - W_{in,pump} \tag{2}$$

where, W_{net} is the net power output, $W_{out,turbine}$ is the power output of turbine, $W_{in,pump}$ is the total work input.

Equation (2) was used to calculate the heat transfer power input as shown below:

$$Q_H = \dot{m} \times h \tag{3}$$

where, Q_H is the heat transfer power input, $\dot{m}$ is the mass flow rate of surface seawater and h is the specific enthalpy.

Finally, Equation (4) and (5) was used to calculate the maximum cycle efficiency and the actual cycle efficiency of the system, respectively as shown below:

$$\eta_{carnot} = 1 - \left(\frac{T_L}{T_H}\right) \times 100\% \tag{4}$$

$$\eta_{cycle} = \frac{W_{net}}{Q_{H,}} \times 100\% \tag{5}$$

where, η_{carnot} is Carnot efficiency of the system, η_{cycle} is the thermal efficiency of the system, T_L is the temperature of the deep seawater, T_H is the temperature of surface seawater.

2.5 Analysis of the performance of H-OTEC system based on differences in temperature of surface seawater

Simulated data acquisition was carried out by changing the temperature of surface seawater from 25°C to 35°C with 1°C temperature increment. The temperature of deep seawater, the cold-water intake was kept fixed at 8°C. The temperature difference between the working fluid (ammonia) and seawater at the outlet of the H-OTEC evaporator was fixed at 1.2°C. The collected data obtained from every temperature of surface seawater adjustment in the simulated H-OTEC model, were the power output of the turbine and the pump work, which were used to calculate the net power output. The effect of the adjusted surface seawater temperature towards the net power output, the maximum cycle efficiency and the actual cycle efficiency of the system was presented in Figure 4, Figure 5 and Figure 6.

3. Results and discussion

Table 1 displays the summary of streams included in the simulated H-OTEC process system in HYSYS. Figure 3 represents the layout of H-OTEC process simulated in Aspen HYSYS. The percentage error from the calculation of the actual data and the simulated data from Aspen HYSYS were discussed in Section 3.1. In Section 3.2, the performance evaluation of the H-OTEC system based on the net power output, Carnot efficiency and thermal efficiency were discussed. In Section 3.3, the discussion on the effect of surface seawater temperature differences towards net power output, Carnot efficiency and thermal efficiency of the system are presented.

Table 1. Stream summary of simulated H-OTEC process system in HYSYS

Material Stream	Fluid	Temperature (°C)	Pressure (kPa)	Flowrate (ton/hour)
2.5	Seawater	25.99	3.3	0.20
3	Seawater	25.00	3.3	0.20
4	Seawater	25.99	3.3	33.97
5	Seawater	26.00	150	33.97
21	Ammonia	23.80	958	0.39
22	Ammonia	15.23	727	0.39
23	Ammonia	11.40	717	0.39
24	Ammonia	14.60	968	0.52
25	Ammonia	23.80	958	0.52
26	Ammonia	23.80	958	0.13
41	Cooling water	8.08	150	25.20
42	Cooling water	12.57	120	25.20

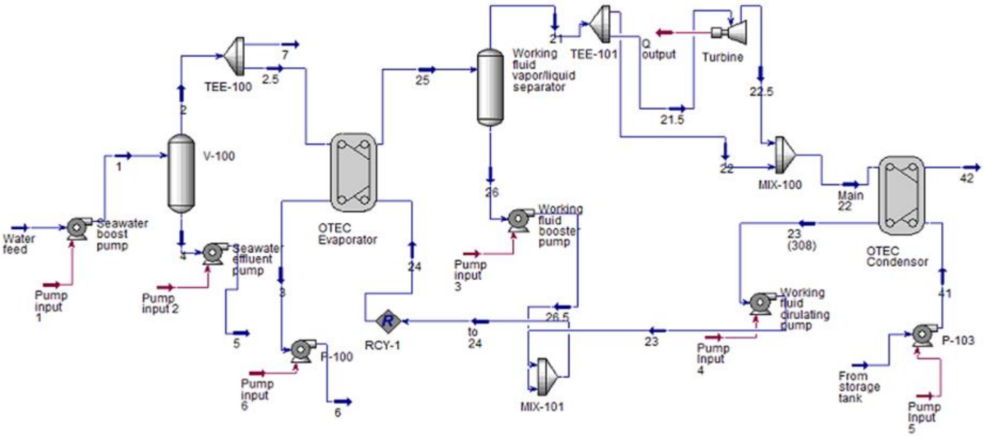

Figure 3. Flowsheet of simulated H-OTEC process system in HYSYS

3.1The Percentage Error

Based on Table 2, most of the variable's percentage differences from the simulated data to the data given were within an acceptable range of not more than 5%, especially for pressure. For temperature, Material Stream 22 and 23 showed percentage differences higher than 5%, which are 10% and 21.4%, respectively. For flowrate, Material Stream 4,5,21,22,23,24,25 and 26 also had percentage difference greater than 5%. The most significant percentage difference was at Material Stream 26, which is 35%. One of the possible reasons for this high percentage difference is that the equipment selected that represents the H-OTEC vapour/liquid separator was not able to simulate or mimic the exact conditions where the vapour/liquid separation of the working fluid takes place inside the separator, within the limitations of the fluid package in the Aspen HYSYS.

Table 2. Percentage differences of the variables from simulated model at seawater temperature of 25°C.

Percentage difference (%)				
Material Stream	Fluid	Temperature	Pressure	Flowrate
2.5	Seawater	-1.93	0.00	0.00
3	Seawater	0.00	0.00	0.00
4	Seawater	-1.93	-2.94	-12.00
5	Seawater	-1.89	0.00	-12.00
21	Ammonia	1.26	1.05	-12.89
22	Ammonia	-10.41	0.00	-12.89
23	Ammonia	-21.40	0.00	-12.89
24	Ammonia	0.00	0.00	16.14
25	Ammonia	1.26	0.00	-18.61
26	Ammonia	1.26	0.00	-35.40
41	Cooling water	0.94	0.00	0.00
42	Cooling water	-3.31	0.00	0.00

3.2 Performance Evaluation of the simulated H-OTEC model

Based on Table 3, the net power output obtained from calculation with the resulting data was 1.39 kW, which is smaller, even compared with a demonstration OTEC plant with the expected power output of 3kW. This may be due to the limitations of the simulation's inadequacy of mimicking the actual conditions of the system, as well as the lack of details about the turbine used in the real system. For calculating the net power output, it should be noted that the pumps for the surface seawater and cooling water were excluded from the calculation. This is because the values of the efficiencies will be very low if the pumps mentioned are included.

Table 3. Performance analysis of the simulated model at seawater temperature of 25°C.

Parameters	**Value**
Turbine work output	1.45kW
Pump work input	59.18W
Net power output (W_{net})	1.39 kW
Carnot efficiency (η_{carnot})	5.70%
Thermal efficiency (η_{cycle})	1.02%

As evident in Table 3, the Carnot efficiency (5.70%) is considered to be higher than the standard range for Rankine cycle efficiency with ammonia as the working fluid, which is 3%, and also within the range of theoretical value for maximum ideal Carnot cycle efficiency which is from 5% to 6% [11]**.** On the other hand, the thermal efficiency (1.02%) obtained is smaller than the thermodynamic efficiency for the standard OTEC cycle (3%), which was considered very low for economic viability [2].

3.3 The effect of surface seawater temperature on the performance of the H-OTEC system

The results from the calculation were included in Figure 3 to Figure 5, in which the dependent variables are net power output, Carnot cycle efficiency and actual cycle efficiency, with surface seawater temperature as the independent variable, as shown below:

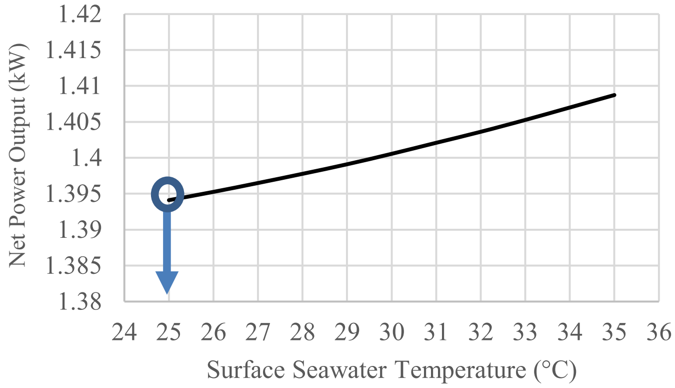

Figure 4. Net power output (kW) for surface seawater temperature variation (°C). The blue arrow indicates the original seawater temperature (25°C) before the adjustment of seawater temperature

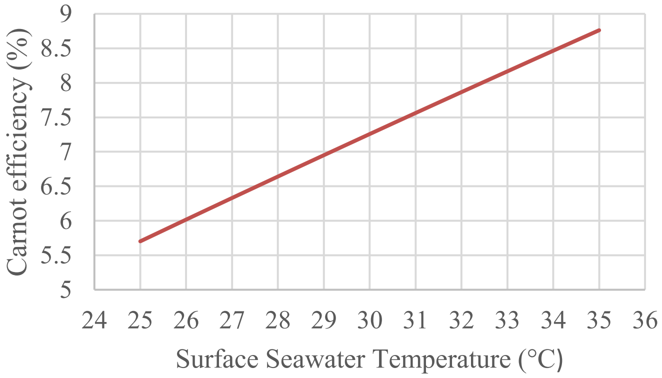

Figure 5. The Carnot cycle efficiency (%) measured for every increment in surface seawater temperature (°C)

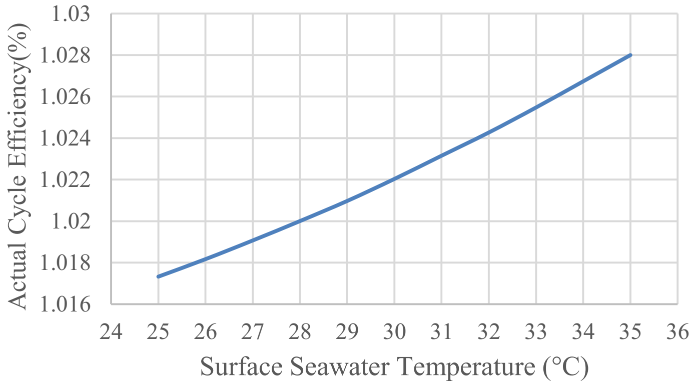

Figure 6. Actual Cycle Efficiency (%) measured for every increment in surface seawater temperature (°C)

Based on the simulated data shown from Figure 4 to Figure 6, the net power output increases linearly by approximately 1%, from 1.39kW to 1.41kW, the Carnot cycle or the maximum cycle efficiency and the actual cycle efficiency slightly increased by less than 3% and 0.1%, respectively, as the surface seawater temperature increased. These graphs show a linear increase when the surface seawater temperature increases, though the difference in value is notably very miniscule.

The results from Figure 3 to Figure 5 are consistent to the results reported by Gresham et al., in which the net power output increased linearly with an ascending value in surface seawater temperature, though this work only focuses on the actual cycle efficiency of the system, where the graph shows a polynomial function with an increasing trend when surface seawater temperature increases[12]. The rising trend from the results, although negligible in value, is expected since hypothetically, warmer surface seawater as the low-grade heat source provides more heat to vaporize the working fluid into expanded vaporized fluid, which drives the turbine to generate electricity, which in turn contributes to the performance. If the assumption that the enthalpy would increase linearly with temperature is considered, the rise in net power output would be plausible. Furthermore, the negligible difference in value after the changes in surface seawater temperature are in line with one of the conclusions made in a journal article by Vera et al in 2020, in which the net power output remains mostly unchanged with the changes in surface seawater temperature, which is in contrast to the changes in deep seawater temperature that greatly affects the net power output [8]. It should be noted that since the simulation is under steady state condition, the results obtained do not fully reflect the real conditions of the system which is always dynamic.

4. Conclusions

A working and fully converged H-OTEC process system model was created using Aspen HYSYS, and the model was used to record the simulated data results after manipulating surface seawater temperature. The simulation of the H-OTEC process system was conducted to study and evaluate the performance of the H-OTEC process system. This project shows that it is possible to use Aspen HYSYS, a software primarily used for petroleum and chemical engineering, for simulating and evaluating the performance of the H-OTEC process system. This study learned the principles of the OTEC system and applied the basic knowledge of using Aspen HYSYS for the simulation. This project could motivate future researchers to continue their performance evaluation studies through improved methods that could contribute to the future development of OTEC.

Acknowledgement

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