A performance study of R717 and R22 as the working fluid for OTEC plant

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Abstract. The purpose of this paper is to compare the thermal efficiency of an ocean thermal energy conversion (OTEC) cycle using R717 and R22 working fluids. An OTEC system typically operates at the temperature difference between the average warm surface seawater of 30 °C and the cold deep seawater of 8 °C. The temperature difference will then power a turbine to produce electricity. R22 and R717 are two potential working fluids to be used in the OTEC cycle to absorb heat due to their saturation temperature. However, R22 is associated with higher global warming potential and the global warming potential (GWP) of 1,760, compared to R717 with zero GWP. The study shows that the thermal efficiency of R22 is 0.211% higher than R717. Moreover, the thermal power required by the water circuit to cool/heat the OTEC circuit for R717 is 13% higher than R22. However, the required working fluid flow rate of the R717 system is 81.5% lower than R22, making the former significantly smaller in size.

1. Introduction

R717 is a refrigerant with zero global warming potential (GWP) compared to R22 with a GWP of 1,760 [1]. This means that R717 is more environmentally friendly than R22. The purpose of this research is to compare the thermal efficiency, thermal power, and mass flow rate required to run the ocean thermal energy conversion (OTEC) cycle by both working fluids. The working fluid selection is intended for the new OTEC power plant to be introduced as Malaysia's new renewable energy source [2]. The design process of an OTEC power plant starts by determining the power requirement and mass flow rate of working fluid. After that, the heat exchanger can be sized to achieve the required operating condition.

The operating condition of the OTEC power plant is shown in Figure 1. The power plant operates based on the temperature difference between the warm surface seawater and the cold deep seawater. This means that the temperature difference will be the limiting factor and the temperature difference is small. This is realized by first pressurizing the working fluid to a higher pressure of 968 kPa to bring it to a superheated phase. It is then passed into an evaporator to recover the heat energy from the warm surface seawater of 30 °C [3]. The evaporated working fluid, now at around 25 °C due to the heat absorbed from the warm surface seawater, will go through the turbine for the conversion of heat energy into kinetic energy. This energy will be used to drive an electric generator to generate a sustainable electricity source. The working fluid coming out of the turbine will have a lower pressure of 727 kPa and a temperature of 15 °C due to the temperature and heat used to power the turbine. The working fluid will then be cooled by a condenser using the cold deep seawater at 8 °C. Next, the condensed working fluid will be fed into the pump. The whole cycle will be repeated if the temperature difference between the surface seawater and the deep seawater is sufficient for the evaporation and condensation processes.

In order for the evaporator and condenser to work, the cold and warm water supply must match the flow rate of the OTEC cycle to remove and add heat energy to the condenser and evaporator, respectively. To achieve that, the enthalpy of the cycle is first determined, as shown in Table 1. Once the enthalpy has been determined, the Carnot efficiency and the thermal efficiency can be calculated. The net work, $\boldsymbol{W_{net}}$ of the cycle can be determined by subtracting the input work of the pump from the output work of the turbine. Then, $\boldsymbol{W_{net}}$ will be used to determine the actual flow rate, $\dot{m}$ that the OTEC cycle needs, which is used to determine the rate of heat transfer, $\dot{\mathbf{Q}}$ of the OTEC cycle. The mass flow rate of the warm and cold water circuit will need to match the $\dot{\mathbf{Q}}$ of the OTEC cycle for condensation and evaporation to take place.

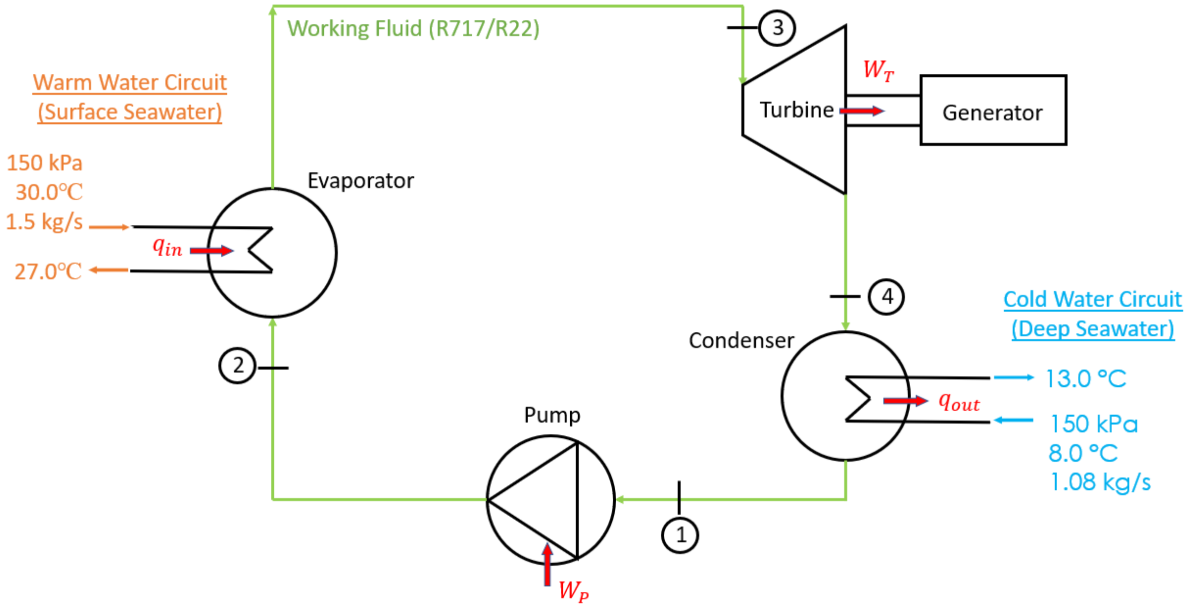

Figure 1. Schematic diagram of OTEC cycle.

2. Methodology

In the beginning, the parameters (i.e., temperature and pressure) were set according to the actual condition of an OTEC power plant in the ocean. The calculation steps to obtain the Carnot efficiency, thermal efficiency, and thermal power needed to run the OTEC cycle are shown in Figure 2. The calculation steps were performed for both R717 and R22. The specific heat capacities and thermal properties of R717 and R22 to obtain the specific enthalpy, h were obtained from CoolProp, an open-source database that contains the thermodynamic properties of the refrigerant [5].

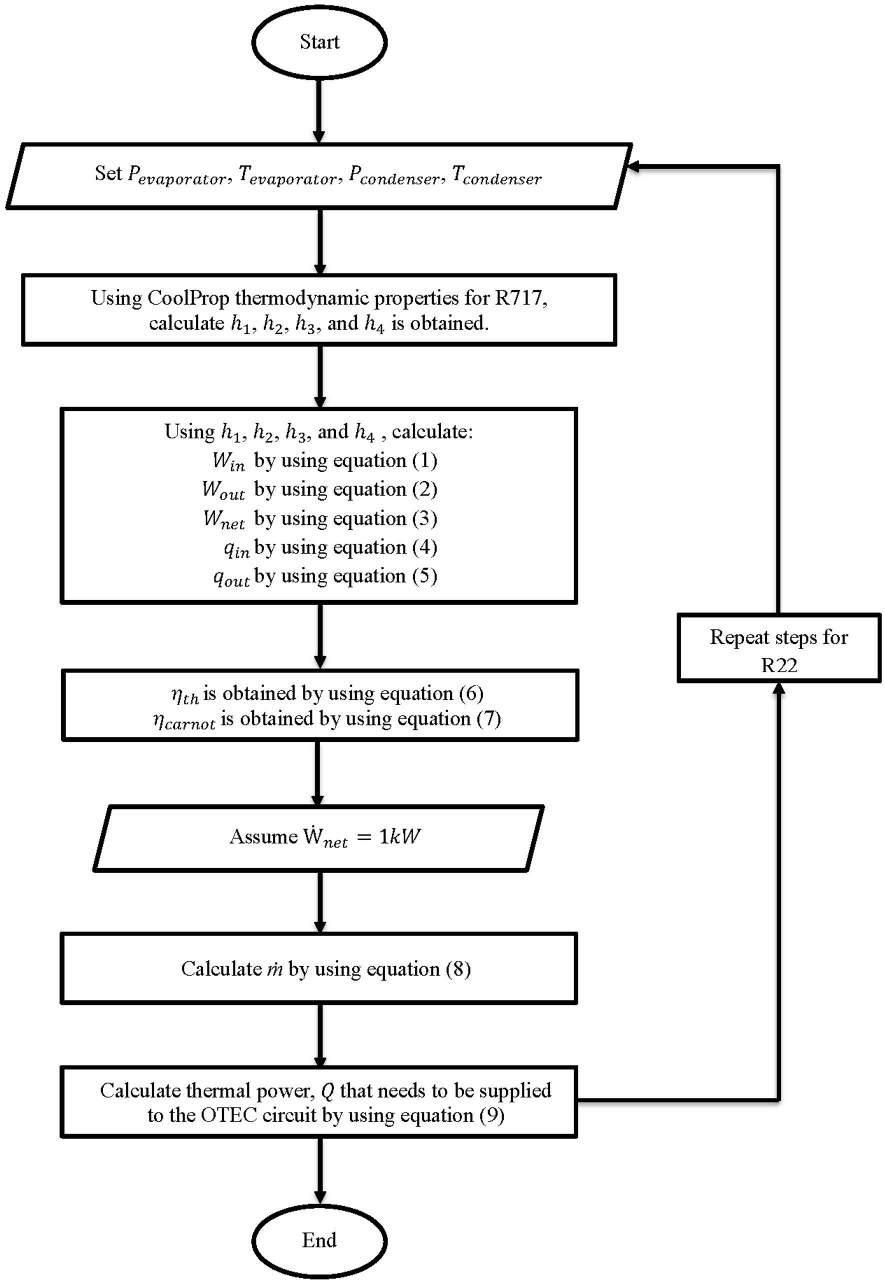

Figure 2. Calculation steps.

$$w_{pump,in} = w_P = h_2 - h_1 \quad (1)$$

$$w_{turbine,out} = w_T = h_3 - h_4 \quad (2)$$

$$w_{net} = w_T - w_P \quad (3)$$

$$q_{in} = h_3 - h_2 \quad (4)$$

$$q_{out} = h_4 - h_1 \quad (5)$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} \quad (6)$$

$$\eta_{carnot} = \frac{T_{min}}{T_{max}} \quad (7)$$

$$\dot{W}_{net} = \dot{m}\, w_{net} \quad (8)$$

$$Q = \dot{m}\, q \quad (9)$$

Table 1. List of symbols and notations used in this paper.

Symbol	**Description**
$w_{pump,in}$	Work done by the pump
$w_{turbine,out}$	Work produced by the turbine
w_{net}	Net work done in the cycle
q_{in}	Heat energy addition in the evaporator
q_{out}	Heat energy rejection in the condenser
η_{th}	Thermal efficiency
η_{carnot}	Carnot efficiency
$\dot{W}_{net}$	Rate of net work done in the cycle
Q	Rate of heat transfer
$\dot{m}$	Mass flow rate
C_P	Heat capacity (constant pressure)

3. Results and Discussion

As shown in Table 2, the enthalpy of the OTEC cycle is obtained based on the thermal properties from CoolProp. The Carnot efficiency, η_{carnot} of the OTEC cycle running on R717 is similar to R22 as the cycle operates on the small difference in temperature between the cold deep seawater of 8 °C and the warm surface seawater 30 of °C. The thermal efficiency, η_{th} of R717 is 0.211% smaller than R22. The mass flow rate, $\dot{m}$ of R717 is 81.5% lower than R22. The lower mass flow rate indicates that the diameter of the piping used can be smaller by roughly 1/5 times for R717 compared to R22. This means that the material used to construct an OTEC power plant running on R717 will be lesser and saves costs. The $\dot{m}$ is then used to determine the thermal power, $\dot{Q}$ required by the cycle. As shown in the table, the heat addition and heat rejection of R717 is 12.87% and 13.00% higher than R22, respectively, due to its high latent heat of vaporization. This means that R717 requires 13% more thermal power to run the OTEC cycle as compared to R22. As the water circuit will need to supply that amount of heat energy at that rate to the OTEC cycle, the actual total rate of heat transfer of the warm water, $\dot{Q}_{warm}$ and cold-water, $\dot{Q}_{cold}$ of the water circuit is found. As seen in the table, the actual thermal power needed for the warm water and cold water of R717 is 12.87% and 13.00% higher than R22, respectively. This implies that R717 is 12.87%–13.00% less efficient to run an OTEC cycle as compared to R22.

Table 2. Comparison between R717 and R22

Parameter	R717	R22	R717 to R22
Specific enthalpy at point 1, $\boldsymbol{h_1}$	390.03 kJ/kg	211.20 kJ/kg	84.7% higher
Specific enthalpy at point 2, $\boldsymbol{h_2}$	390.50 kJ/kg	211.20 kJ/kg	84.9% higher
Specific enthalpy at point 3, $\boldsymbol{h_3}$	1,635.80 kJ/kg	415.70 kJ/kg	293% higher
Specific enthalpy at point 4, $\boldsymbol{h_4}$	1,614.97 kJ/kg	411.73 kJ/kg	292% higher
Carnot efficiency, $\boldsymbol{\eta_{carnot}}$	3.974%	3.974%	-
Thermal efficiency, $\boldsymbol{\eta_{th}}$	1.635%	1.846%	0.211% lower
Mass flow rate, $\boldsymbol{\dot{m}}$	0.049 kg/s	0.265 kg/s	81.5% lower
Thermal power added to the cycle, $\mathbf{Q_{23}}$	61.144 kW	54.174 kW	12.87% higher
Thermal power removed from the cycle, $\mathbf{Q_{41}}$	60.144 kW	53.174 kW	13.00% higher
Power required by the warm water, $\mathbf{Q}_{\boldsymbol{warm}}$	61.144 kW	54.174 kW	12.87% higher
Power required by the cold water, $\mathbf{Q}_{\boldsymbol{cold}}$	60.144 kW	53.174 kW	13.00% higher

4. Conclusion

R717 has zero GWP and is more environmentally friendly than R22 with the GWP of 1,760 [1]. However, the thermal performance to operate the OTEC cycle with R717 is less efficient than R22. It was found that the thermal power required from the warm and cold water circuit for R717 working fluid is 12.87% and 13.00% higher, respectively, than that of R22. Consequently, a higher seawater flow rate (pump capacity) will be necessary for the R717 system. This resulted in lower net output power from the OTEC power plant as the seawater pump is self-powered by the plant. However, R717 has an advantage for constructing an OTEC power plant running on R717 as the plant will require approximately 1/5 times smaller footprint to construct because the mass flow rate required for R717 is 81.5% lower than R22.

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