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A Key Parameter in Design and Operation of Ocean Thermal Energy Conversion Plants

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ABSTRACT

Ocean thermal energy is one of the sustainable and green energies from ocean, which is from the temperature difference between the warmer surface water and the cooler deep water. Ocean thermal energy conversion (OTEC) plants applies the ocean thermal energy to produce electric power. Unfortunately, the temperature difference in the ocean is not big. Even in the tropical and equatorial regions, the surface water temperature can only reach up to 25^{o}C and the deep water temperature is as low as 4^{o}C. The thermal efficiency of the OTEC plants, therefore, is low. In order to improve the plant thermal efficiency by using the limited ocean temperature gradient, some OTEC plants use the approach of applying multiple stages or adding more equipment for better recovery of the ocean thermal energy, such as heat exchangers and circulating pumps. Obviously, the approach will increase the plant complexity and cost. An important adverse impact of the approach is the additional equipment needs to consume power too, which may affect the plant net power output, in turn the plant thermal efficiency. To address the issue, the author proposes a parameter, plant back work ratio ϕ, to evaluate if the added equipment is appropriate for the plant power net output and thermal efficiency improvement. In the paper, the author describes varied OTEC plants and conducts the performance calculation of an open-system OTEC plant. The author also illustrates the application of the back work ratio ϕ as a key parameter on the performance of the OTEC plants in the paper.

KEYWORDS: Ocean thermal energy, Ocean thermal energy conversion (OTEC), OTEC plant, plant back work ratio ϕ

1. INTRODUCTION

Oceans cover more than 70% of Earth's surface area which makes them as the world's largest solar heat collectors and a large energy source. Ocean energy is a renewable, sustainable, and clean energy. In general, there are three types of ocean energies: thermal energy from the sunrays, tidal energy from tidal streams, and wave energy from water fluctuation, as shown in Figure 1. Tidal energy and wave energy are mechanical energy forms. Ocean thermal energy is the heat form represented in ocean water temperature difference. In the tropical and equatorial regions, the surface water temperature can reach up to 25^{o}C and the deep water temperature is as low as 4^{o}C. Figure 2 shows the water temperature distribution in ocean depth.

The technology harnesses ocean thermal energy to generate electric power is called ocean thermal energy conversion (OTEC). The OTEC technology utilizes the temperature difference between ocean surface water and deep water for generating electric power. Based on the Carnot principle, the maximum thermal efficiency from an OTEC plant is

$$\eta_{\text{th}} = 1 - \frac{T_{\text{L}}}{T_{\text{H}}} \tag{1}$$

$$= 1 - \frac{(4+273)\text{K}}{(25+273)\text{K}} = 1 - \frac{277\text{K}}{298\text{K}} = 0.0705 = 7.05\%$$

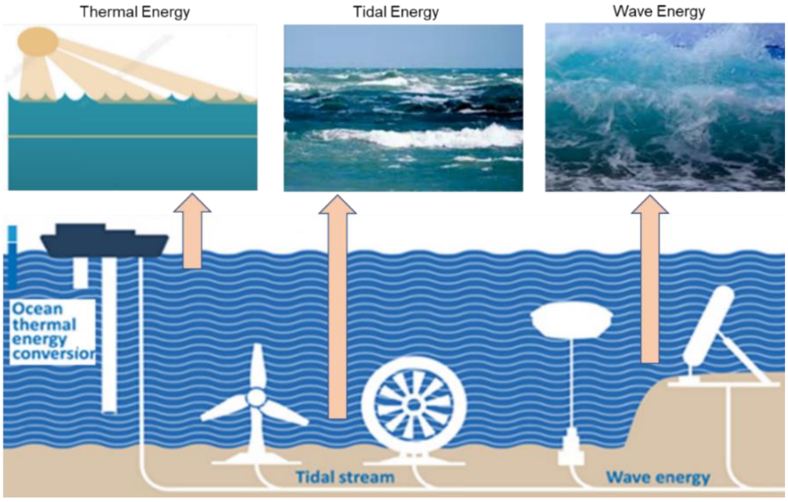


Fig. 1 Ocean energy types

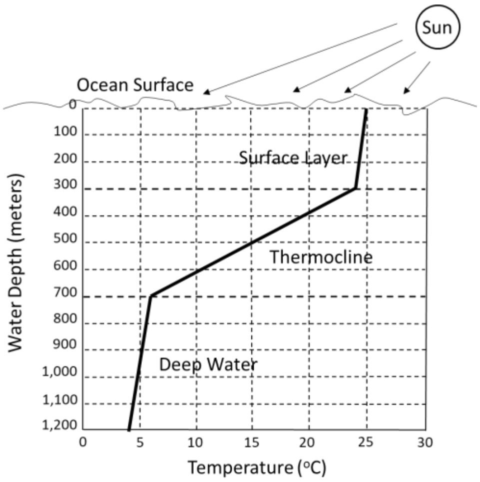


Fig. 2 Water temperature distribution in ocean depth

2. OCEAN THERMAL ENERGY CONVERSION PLANTS

OTEC plants operate on thermal cycles. The thermal cycle in the OTEC technology is the Rankine cycle. There are two basic OTEC plants: closed-system, open-system.

1) Closed-sysem

The closed-system OTEC plant uses the warm ocean surface water to vaporize the refrigerant (working fluid) with a low-boiling point, such as ammonia (NH_3) or R-134a, in a heat exchanger (evaporator). The vapor then expands in a steam turbine. The turbine in turn drives a generator to produce electrical power. The vapor exhausted from the turbine is cooled to be condensate by the cold deep water in a condenser. The condensate is discharged out of the condenser and pumped back to the heat exchanger to repeat the cycle. A typical closed-system OTEC plant is shown schematically in Figure 3.

2) Open-system

The open-system OTEC plant uses the warm ocean surface water directly to generate electric power. The warm surface water first is pumped into a vacuum chamber to be flashed into steam. Then the

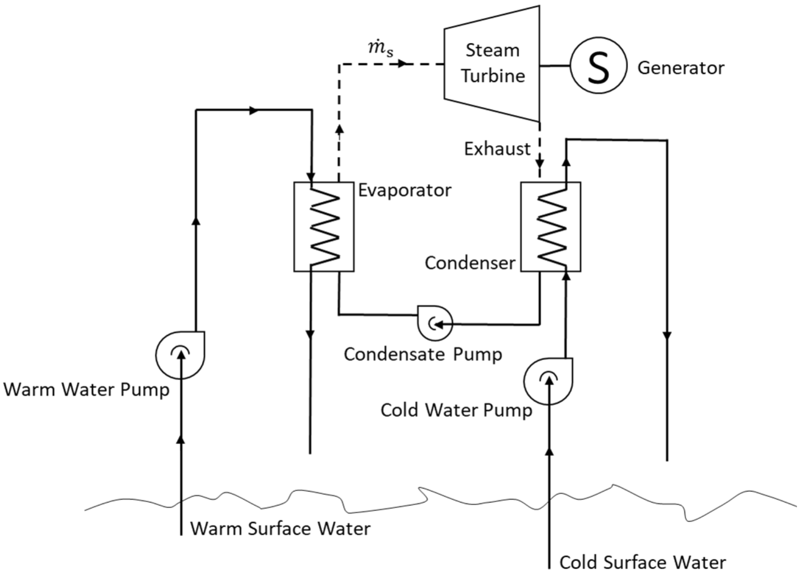


Fig. 3 Closed-system OTEC plant

steam drives a steam turbine-generator to produce electric power. The steam is condensed into desalinated water in a condenser by cold deep water. The open-system OTEC plant can not only produce electric power, but also provide desalinated water for drinking, irrigation, or aquaculture, etc. A typical open-system OTEC plant is shown schematically in Figure 4.

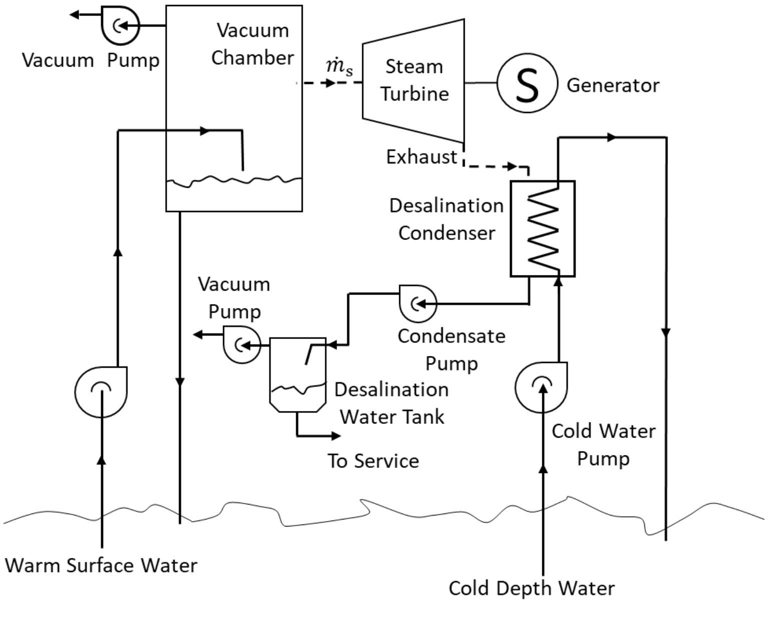


Fig. 4 Open-system OTEC plant

Based on the basic systems, a modified sysem called hybrid-system was developed.

3) Hybrid-system

A typical hybrid-system OTEC plant is shown schematically in Figure 5. The hybrid-system OTEC plant combines the features of the closed- and open-system OTEC plants. The warm ocean surface water vaporizes a refrigerant (working fluid) with a low-boiling point, such as NH_3 (ammonia) or R-134a, in a heat exchanger (evaporator). The refrigerant vapor drives a steam turbine-generator to produce electricity. While the ocean surface water enters a flash tank after the heat exchanger. The flashed vapor is cooled by the cold sea water in a heat exchanger to become desalinated water. The desalinated water is then supplied for drinking, irrigation, or aquaculture, etc.

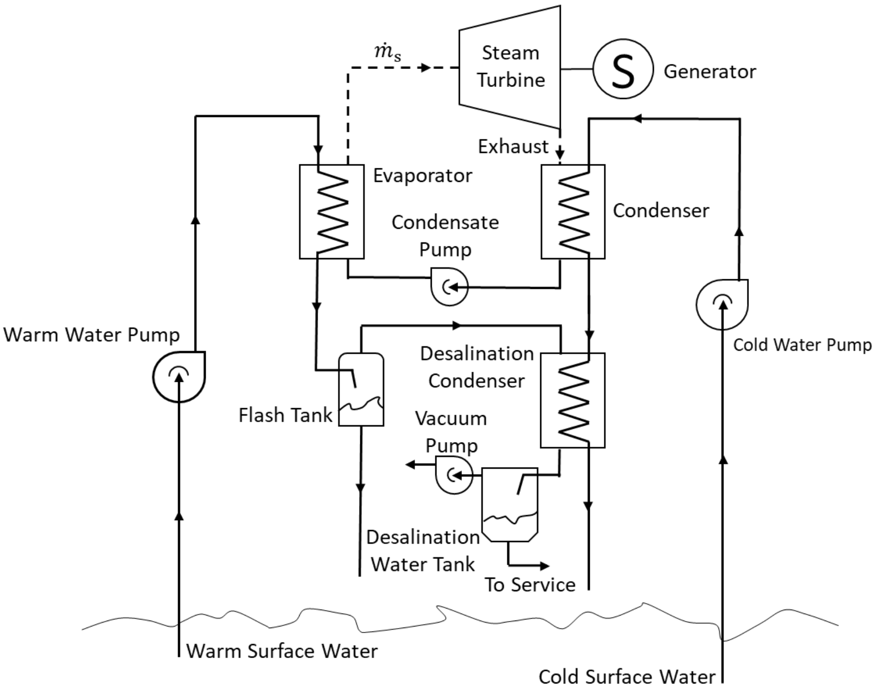


Fig. 5 Hybrid-system OTEC plant

OTEC plants can have options to be built in three locations: on land, offshore, or floating ship. Figure 6 shows schematics of three plant locations. Each option has its own advantages and disadvantages.

a) On land Plant

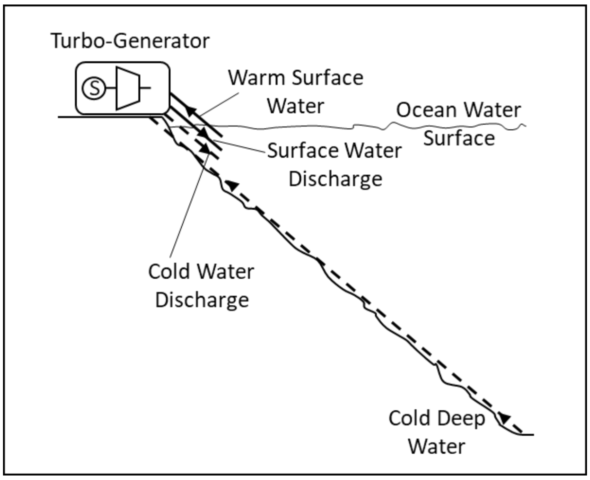
- Less concern regarding mooring and plant stability.
- Less work of maintenance and repair farther out in water.
- Plant byproduct, such as desalinated water, is conveniently supplied to home, irrigation, or aquaculture.
- A long cold deep water pipe may need.

b) Offshore Plant

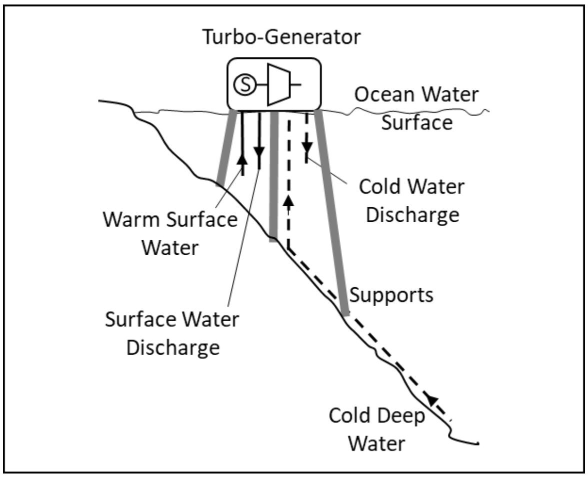
- Less concern regarding mooring and lengthy of pipes.
- More work to build a plant form and support structure.
- Power delivery to land becomes costly due to requiring long under water cables to land.

c) Floating Ship

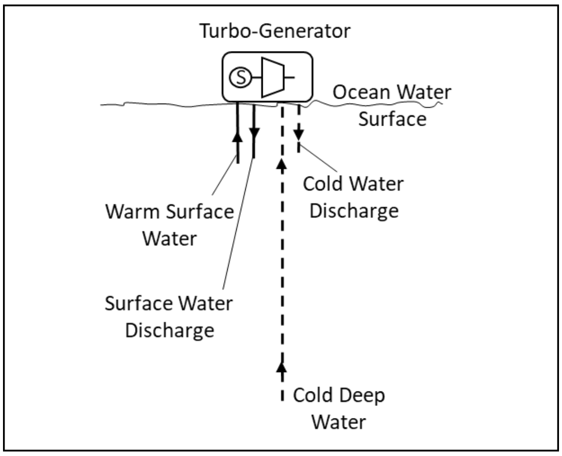
- Flexible location.
- Difficult mooring and stabilizing the plant.
- Power delivery to land becomes costly due to requiring long under water cables to land.



On Land



Offshore

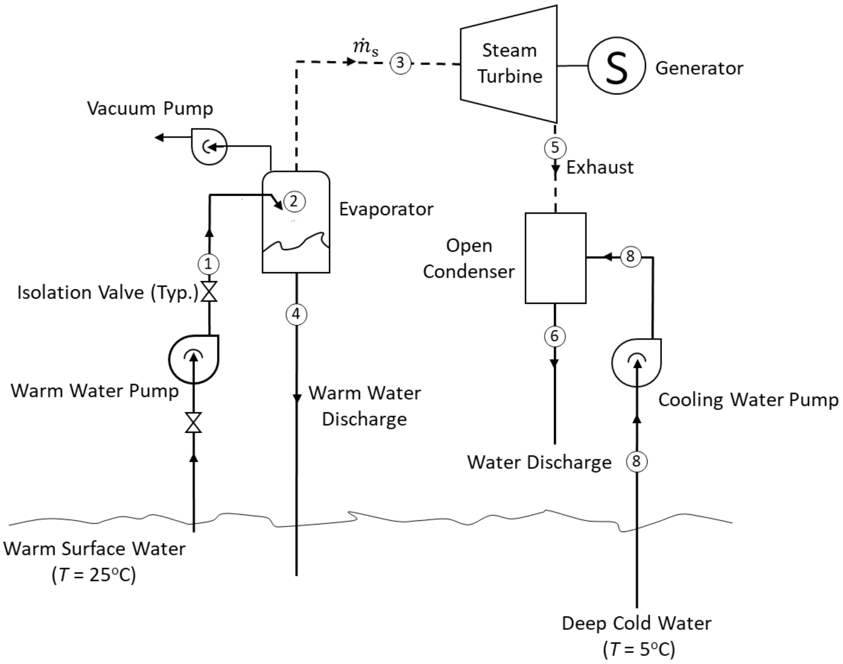


Floating Ship

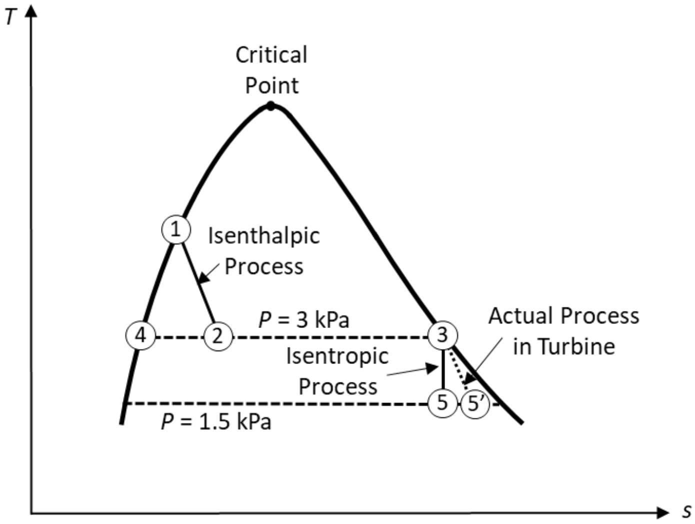
Fig. 6 Schematics of OTEC plant locations

3. PERFORMANCE CLACULATION OF OTEC PLANTS

Performance calculation of the OETC plants is based on the Rankine cycle. Figure 7(a) shows an open-system OTEC plant. In the plant, the warm surface water is pumped into the plant. The evaporator is maintained at a sub atmospheric (i.e., vacuum) pressure by a vacuum pump. As the warm water flows into the evaporator, its pressure and temperature decrease simultaneously, which results in a water-steam mixture. The steam production in the evaporator is an isenthalpic process since the process is adiabatic and there is no work interaction as shown in the *T*-*s* diagram in Figure 7(b). Steam and water are separated in the evaporator. The steam enters the pipeline towards the steam turbine. The water is discharged back to sea. After the steam turbine, the exhaust steam goes to the open condenser (mixing



(a) Schematic of the open-system OTEC plant



(b) *T*-*s* property diagram

Fig. 7 The open-system OTEC plant and *T*-*s* property diagram for performance calculation chamber at a lower pressure). The cold deep water is supplied in the condenser to turn the exhaust steam to the condensate. The water discharged out from the condenser goes back to sea.

The plant operates with specifications:

Warm surface water temperature	25°C
Cold deep water temperature	5°C
Evaporator pressure	3 kPa
Condenser pressure	1.5 kPa
Mass flow rate of surface water	150 kg/s
Turbine isentropic efficiency	87%

In light the specifications, following properties at states are found,

- State 1: (compressed water, $T_1 = 25^{\circ}\mathrm{C}$)

$$h_1 = h_{f@30^{\circ}\mathrm{C}} = 104.83 \text{ kJ/kg}$$

$$\dot{m}_1 = 150 \text{ kg/s}$$

- State 2: (water-steam mixture, $P_2 = 3$ kPa)

$$h_2 = h_1 = 104.83 \text{ kJ/kg}$$

The quality of the water-steam mixture at state 2 is

$$x_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{104.83 - 100.98}{2443.9} = 0.0016 = 0.16\%$$

- State 3: (saturated steam, $P_3 = 3$ kPa, $x = 1$)

$$h_3 = h_{g@3\mathrm{kPa}} = 2554.8 \text{ kJ/kg}$$

$$s_3 = s_{g@3\ \mathrm{kPa}} = 8.5765 \text{ kJ/kg,}$$

The mass flow rate of the steam $\dot{m}_s$ to the steam-turbine becomes

$$\dot{m}_s = \dot{m}_3 = x_2\dot{m}_1 = 0.0016(150 \text{ kg/s}) = 0.24 \text{ kg/s}$$

- State 4: (saturated water, $P_4 = 3$ kPa, $x = 0$)

$$h_4 = h_{f@3\mathrm{kPa}} = 100.98 \text{ kJ/kg}$$

$$\dot{m}_4 = \dot{m}_1 - \dot{m}_3 = (150 - 0.24) \text{ kg/s} = 149.76 \text{ kg/s}$$

- State 5: (exhaust steam, $P_5 = 1.5$ kPa)

$$s_5 = s_3 = 8.5765 \text{ kJ/kg.K}$$

$$x_5 = \frac{s_5 - s_f}{s_{fg}} = \frac{8.5765 - 0.1956}{8.6314} = 0.971 = 97.1\%$$

$$h_5 = 54.688 \text{ kJ/kg} + 0.971(2470.1 \text{ kJ/kg}) = 2453.2 \text{ kJ/kg}$$

Using the definition of the turbine isentropic efficiency,

$$\eta_{\mathrm{turb}} = \frac{h_3 - h_{5'}}{h_3 - h_5}$$

the actual enthalpy of the exhaust steam after the steam-turbine is determined as

$$h_{5'} = h_3 - (h_3 - h_5)\eta_{\mathrm{turb}}$$

$$= 2554.8 \text{ kJ/kg} - (2554.8 - 2453.2)0.87 = 2466.4 \text{ kJ/kg}$$

Therefore, the performance of the power output is,

- Power output:

$$\dot{W} = \dot{m}_3(h_3 - h_{5'}) \tag{2}$$

$$= (0.24\ \text{kg/s})(\,2554.8 - 2466.4)\text{kJ/kg} = 21.216\ \text{kW}$$

- Energy or heat input:

$$\dot{Q} = \dot{m}_1 h_1 - \dot{m}_4 h_4 \tag{3}$$

$$= (150\ \text{kg/s})(104.83\ \text{kJ/kg}) - (149.76\ \text{kg/s})(100.98\ \text{kJ/kg}) = 601.74\ \text{kW}$$

- Thermal efficiency of the plant:

$$\eta_{\text{th}} = \frac{\dot{W}}{\dot{Q}} = \frac{21.216\ \text{kW}}{601.74\ \text{kW}} = 0.0353 = 3.53\% \tag{4}$$

The maximum thermal efficiency of the heat engine working on the same temperature condition will be

$$\eta_{\text{th}} = 1 - \frac{(5+273)\text{K}}{(25+273)\text{K}} = 1 - \frac{278\text{K}}{298\text{K}} = 0.0671 = 6.71\%) \tag{5}$$

Comparing the results in Equation (4) and (5), it can be seen the thermal efficiency of OTEC plants is quiet low. In order to enhance power out and improve thermal efficiency of OTEC plants with the limited ocean temperature gradient, the approach of applying multiple stages or adding additional equipment, such as heat exchangers and circulating pumps, is developed. Figure 8 schematically shows a two-stage OTEC plant using a refrigerant, NH_3 (ammonia) or R-134a, as a working medium. The contradictory of such an approach, however, is the additional equipment and stage will consume power too. In addition, the more equipment will increase the plant complexity and cost. To address the issue, the author proposes a parameter called the back work ratio ϕ of the OTEC plant to evaluate if adding additional equipment is appropriate in terms of the plant thermal efficiency improvement.

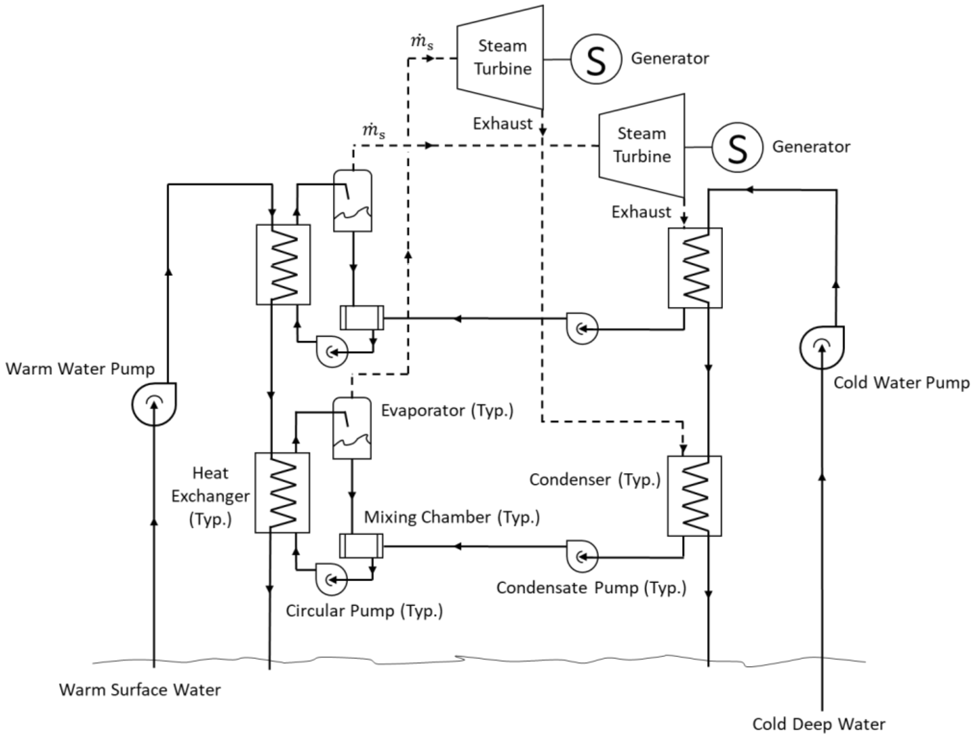


Fig. 8 Two-stage closed-system OTEC plants

4. OTEC PLANT BACK WORK RATIO ϕ

The proposed the back work ratio ϕ of the OTEC plant is defined as

$$\phi = \frac{\dot{W}_{\text{internally}}}{\dot{W}_{\text{plant}}} \tag{6}$$

where

$\dot{W}_{\text{internally}}$ – power consumed internally in the OTEC plant. (kW)
$\dot{W}_{\text{plant}}$ – power produced from the OTEC plant. (kW)

The value of ϕ has a range, if

$$\begin{aligned} \phi &= 0 \text{ (impossible OTEC plant)} \\ 0 < \phi &< 1 \text{ (actual OTEC plant)} \\ \phi &= 1 \text{ (useless OTEC plant)} \end{aligned} \tag{7}$$

There is a relationship between the plant thermal efficiency η_{th} and plant back work ratio ϕ,

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \frac{\dot{W}_{\text{plant}}}{\dot{Q}_{\text{in}}}(1- \phi) \tag{8}$$

For a certain type of OTEC plant, $\dot{Q}_{\text{in}}$ is a constant. Thermal efficiency of an OTEC plant depends on the capacity of the plant. From Equation (8), it can be seen the bigger the plant capacity is, the more room for adding additional equipment the plant may need. It is also can be seen, the plant back work ratio ϕ is bigger than a certain value, the plant basically has no potential for application since the plant thermal efficiency is too low. Figure 9 shows the impact of ϕ to the plant thermal efficiency.

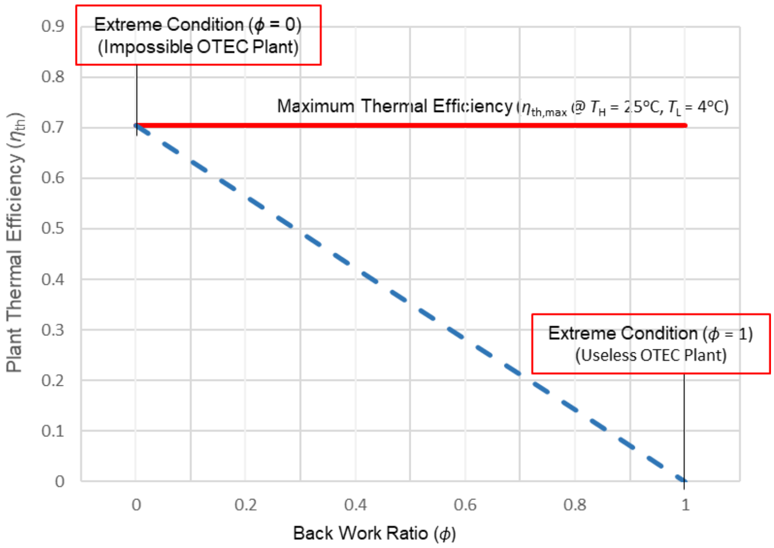


Fig. 9 Impact of ϕ to the plant thermal efficiency

For example, as ϕ is larger than 0.3, it may not be necessary to consider in construction or operation of such an OTEC plant in light of justified economically, which will be discussed separately in details in another paper.

6. SUMMARY

1. The operation performance calculation is based on the Rankine cycle. The maximum thermal efficiency of OTEC plants is about 7.05%.

2. The approach of applying multiple stages or adding additional equipment, such as heat exchangers and circulating pumps, to enhance power out and improve thermal efficiency of OTEC plants may not be appropriate and will increase the plant complexity and cost.
3. The plant back ratio ϕ is proposed as a key parameter to weight if it is appropriate to add additional equipment for improving the plant thermal efficiency.
4. ϕ value is between 0 to 1. An OTEC plant is impossible at $\phi = 0$ and is useless at $\phi = 1$. The ϕ value actual OTEC plants should be $0 < \phi < 1$.
5. The bigger the plant capacity is, the more room for adding additional equipment the plant has.
6. As the plant back work ratio ϕ is bigger than a certain value, the plant basically has no potential for application since the plant thermal efficiency is too low. For example, as ϕ is larger than 0.3, it may not be necessary to consider in construction or operation such an OTEC plant in light of justified economically.

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