Ocean Thermal Energy Conversion

ME301: Energy Systems I

Project Report

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Abstract:

This report analyses Ocean Thermal Energy Conversion (OTEC) systems as sustainable energy sources, focusing on key components like working fluid selection, solar concentrators, and thermodynamic performance. It investigates the integration of solar concentrators to improve system efficiency along with the analysis of suitable working fluid and evaluates OTEC's performance. The report also includes an economic analysis and examines location-specific factors, such as temperature gradients and resource availability, to identify optimal implementation sites. Overall, it provides insights into the technical, environmental, and economic aspects of OTEC, highlighting its potential in sustainable energy systems.

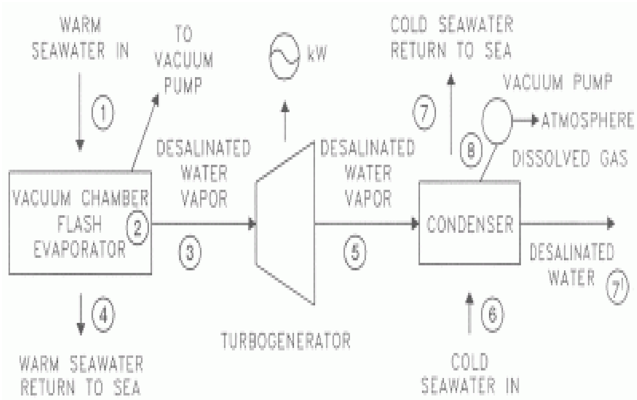
Introduction:

Ocean Thermal Energy Conversion (OTEC) is a renewable energy technology that generates electricity by harnessing the temperature difference ($\sim 20°C$) between warm surface water and colder deep ocean water. This temperature gradient powers a thermodynamic cycle that drives turbines, providing a reliable, baseload power source. In addition to electricity generation, OTEC systems offer benefits such as desalination of seawater, enhanced aquaculture, and potential applications in hydrogen production and coastal cooling. These advantages make OTEC a valuable solution for small island developing states (SIDS), addressing challenges related to energy, water, and food security while supporting sustainable development.

Base Cycles:

1.) **Open Cycle OTEC**

An open-cycle Ocean Thermal Energy Conversion (OTEC) plant generates power by using warm seawater as the working fluid in a thermodynamic process. Warm seawater is evaporated at low pressure, and the steam expands through a turbine to produce electricity. The steam is then condensed using cold seawater, producing desalinated water. Non-condensable gases are compressed and discharged to prevent clogging. Operating at very low pressures (1-3% of atmospheric pressure), the system requires careful sealing to prevent air leakage. The large specific volume of low-pressure steam necessitates high-capacity turbines, limiting power output to about 2.5 MW per module.



Analysis:

Heat added: $q_w = \dot{m}_{warm\,water}\, C_p \left(T_{warm_{water_{inlet}}} - \quad T_{warm_{water_{outlet}}}\right)$

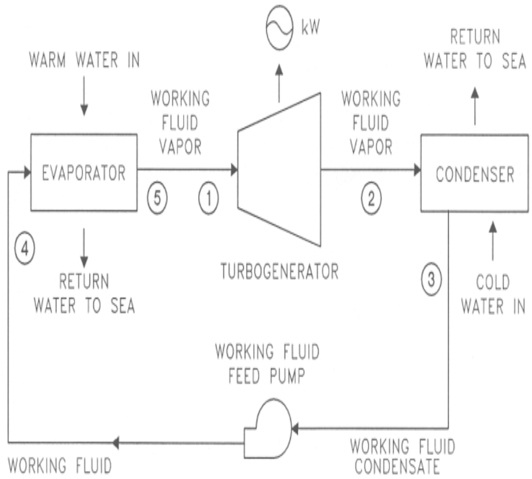
Steam Generation rate: $\dot{m}_s = \frac{q_w}{h_{fg}}$

Turbine work: $w_t \ = \dot{m}_s(h_3 - h_5)$

Heat Rejected: $q_c = \dot{m}_{coldwater}\, C_p(T_{warmwateroutlet} - T_{coldwaterinlet})$

2.) Closed Cycle OTEC

In a closed-cycle Ocean Thermal Energy Conversion (OTEC) plant, ammonia, a low-boiling-point fluid, is used as the working fluid. Warm surface seawater vaporizes ammonia in the evaporator, and the vapor expands through a turbine to generate electricity. Cold deep seawater then condenses the ammonia vapor back into liquid in the condenser, and a pump recirculates the liquid ammonia to the evaporator. The system maintains separation between the working fluid, surface seawater, and deep seawater. The surface seawater is returned cooler, and the deep seawater is returned slightly warmer, at depths of 60 meters or more to minimize ecosystem impact. This closed-loop system harnesses the ocean's temperature gradient to generate renewable energy without directly affecting marine environments.



Analysis:

Heat addition: $q_a = h_1 - h_4$

Turbine work: $w_t = h_1 - h_2$

Heat rejected: $|q_r| = h_2 - h_3$

Pump work: $|w_p| = h_4 - h_3$

Cycle net-work: $\Delta w_{net} = (h_1 - h_2) - (h_4 - h_3)$

Thermal Efficiency: $\eta_{th} = \frac{w_{net}}{q_A} = \frac{(h_1 - h_2)}{h_1 - h_4} - \frac{h_4 - h_3}{h_1 - h_4}$

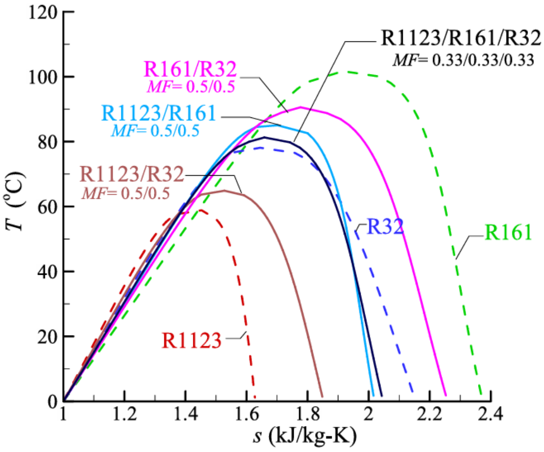
Improvements:

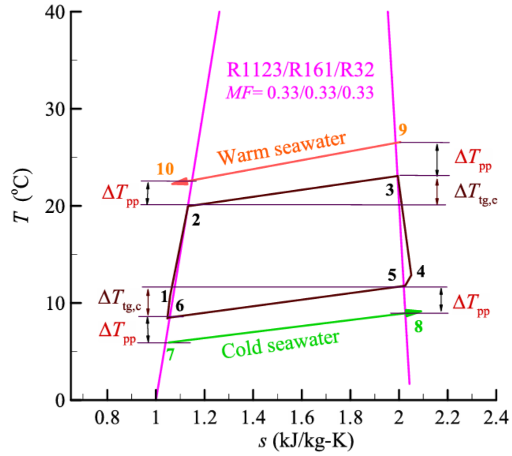
1.) Working Fluid

Ocean Thermal Energy Conversion (OTEC) generates electricity by utilizing the temperature difference between warm surface seawater and cold deep seawater (800–1,000 meters). Warm seawater vaporizes a working fluid, which drives a turbine linked to a generator. Cold seawater then condenses the vapor, sustaining a pressure differential for continuous operation. OTEC systems differ by working fluid: Open Cycle OTEC uses seawater, while Closed Cycle OTEC uses ammonia, which enables smaller turbines and heat exchangers. An alternative, the Kalina Cycle, uses a water-ammonia mix for efficiency.

Available suitable working fluid for cycle are: R1123, R161, R32 and their mixture in some specific ratio. Experiments and analyses indicate that, compared to a pure working fluid, a fluid mixture (such as R1123/R161 or R1123/R32) enhances OTEC performance by providing lower $'\beta'$and higher power output.

Positive Effect of zeotropic working fluid: Zeotropic fluids have the property of temperature glides i.e. the temperature difference in their phase change at constant pressure. This property is utilized in increasing the area of T-s diagram which implies increasing net-work output.





$$\Delta T_{pp} = Pin\ Point\ temperature\ difference$$

$$\Delta T_{tg,e} = Temperature\ glide\ in\ expansion$$
$$\Delta T_{tg,e} = Temperature\ glide\ in\ compression$$

<u>Thermodynamic Analysis for working fluid</u>

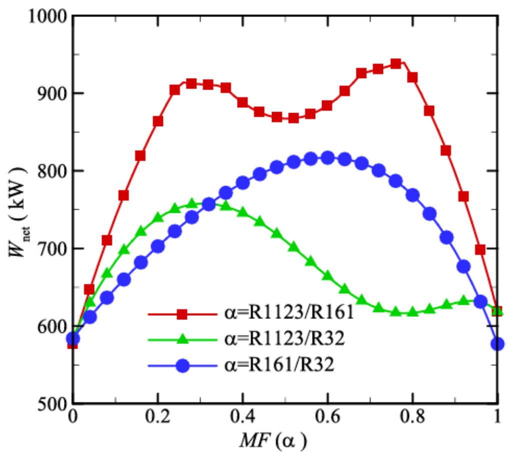
Heat transfer rate of the evaporator: $Q_e = m_{wf}(i_3 - i_1)$

the power obtained from the working-fluid expansion in the turbine: $W_t = m_{wf}(i_3 - i_4)\eta_t$

heat flow rate in the condenser : $Q_c = m_{wf}(i_4 - i_6)$

power consumed by the working fluid of the pump: $W_p = \frac{m_{wf}v_6(p_1 - p_6)}{\eta_p}$

pressure losses in the Seawater Pipes: $\Delta p_{sw} = f\,\frac{L_{sw}}{D_{ssw}}\frac{\rho_{sw}V_{sw}^2}{2}$

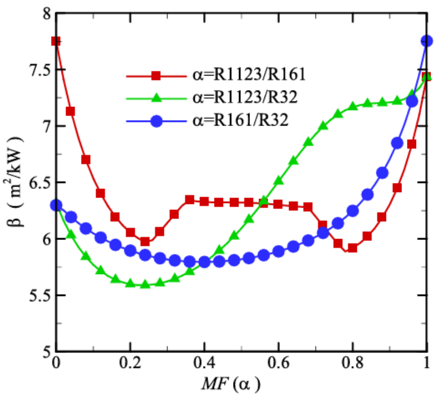


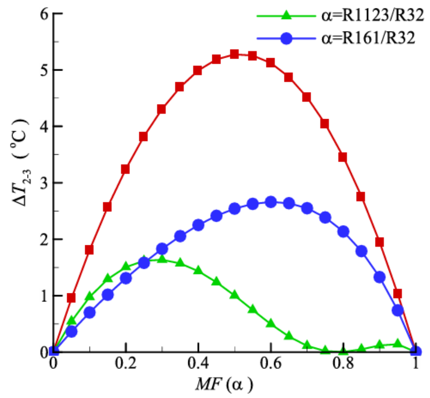
Power consumption related to seawater flow: $W_{p,sw} = \frac{m_{sw}\Delta p_{sw}}{\rho_{sw}\eta_p}$

Net power output of the system: $W_{net} = W_t - W_p - W_{p,csw} - W_{p,wsw}$

Thermal efficiency can be calculated as: $\eta_{th} = \frac{W_{net}}{Q_c}$, *MF = mass fraction*

$\beta = \frac{A_{tot}}{W_{net}}$



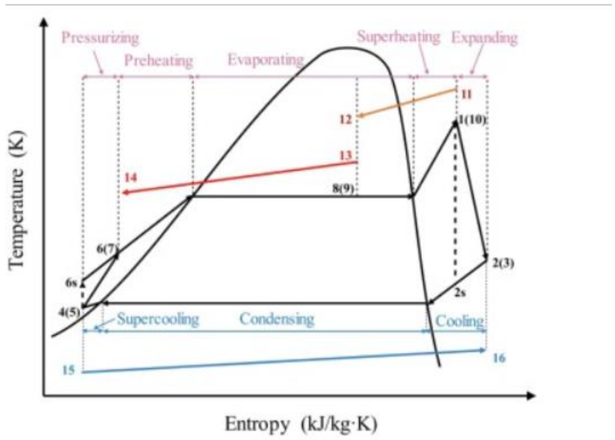


From analysis of above graphs, we can conclude that the optimum choice for working fluid composition would be:

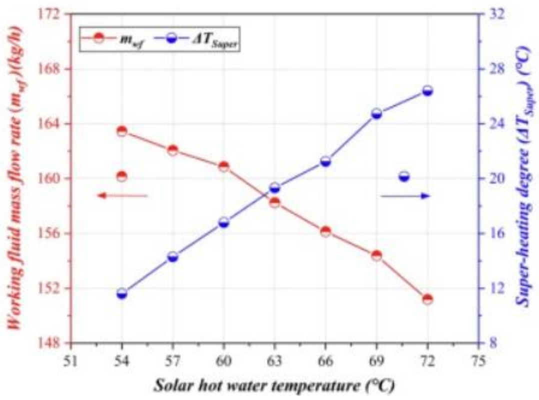
R1123/R161 at mass fraction = 0.8

2.) ***<u>Solar Water Heater for Superheating</u>***

In the S-OTEC system, integrating a solar hot water concentrator allows the working fluid to be superheated, enhancing its energy input before entering the expander. This superheating step boosts the efficiency of the power cycle by increasing the energy extracted from the vapor to drive the generator. When solar heating is active, the system operates as S-OTEC, offering a significant efficiency improvement compared to the standard cycle.



Generally, the temperature of warm seawater at evaporator inlet is around 31℃ and the temperature of solar water heater outlet is around 52℃.

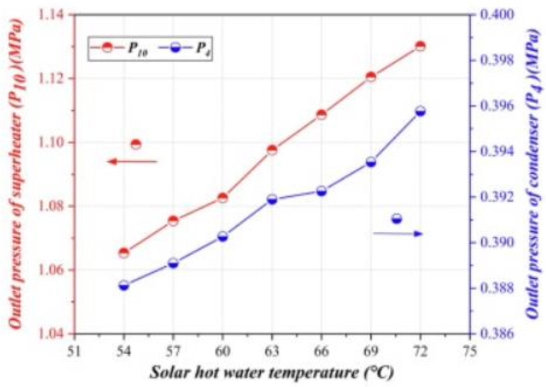


Effect on Heat Exchanger

As the temperature of the working fluid increases, both the outlet pressure of the superheater and condenser rise due to the higher saturation pressure, showing a steady increase within specific pressure ranges. This increase in temperature also reduces the working fluid flow rate (from 163.45 to 151.18 kg/h) due to lower density, while the superheating degree rises significantly (from 11.60 °C to 26.40 °C), as the fluid reaches a higher temperature at the superheater outlet.

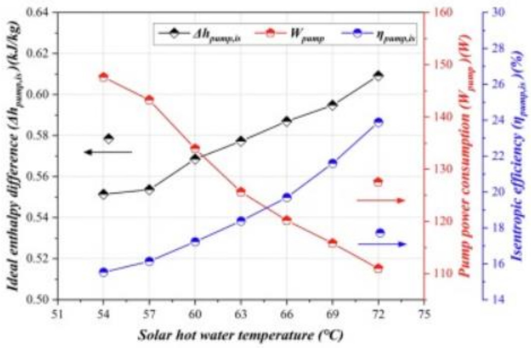
Effect on Fluid Pump

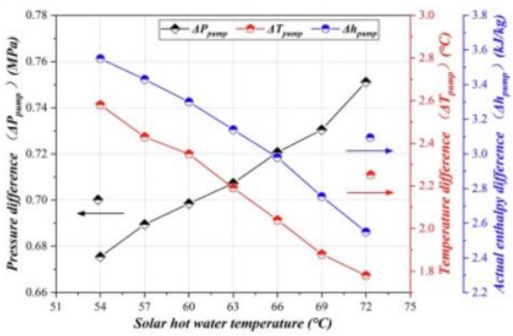
As the working fluid temperature rises, the pump's isentropic efficiency experiences a notable increase, climbing from 15.53% to 23.89%. This improvement is due to a slight rise in the ideal enthalpy difference of the pump as temperature decreases, which makes the pump operate more effectively with less energy loss. Simultaneously, the pump's power consumption declines steadily, from 147.63 W to 111.08 W, further indicating enhanced performance.



Effect on enthalpy and pressure differences

With higher temperatures, both the pump's enthalpy difference and temperature difference decrease, while the pressure difference increases modestly (from 0.68 MPa to 0.75 MPa). The reduced enthalpy difference (dropping from 3.55 kJ/kg to 2.55 kJ/kg) minimizes energy demands on the pump, leading to a reduction in exergy loss. These combined effects allow the pump to operate more efficiently, conserving energy and contributing to an overall increase in system efficiency.





Effect on Overall Performance

As T_{11}($depicted\ in\ the\ cycle$) increases, the system's output power (P_{out}), net output power (P_{net}), and power generation (P_{gen}) all rise steadily. This increase occurs because the rise in $P_{out}$is greater than the reduction in power loss, resulting in a continuous increase in P_{net}.

Factors Influencing efficiency

The efficiency of Ocean Thermal Energy Conversion (OTEC) is influenced by various factors, particularly location, system design, and environmental conditions. Following are few potential factors which can affect the OTEC's performance.

1. **Location and Temperature Gradient**

- **Ideal Regions**: OTEC is best suited to tropical regions where there's a substantial and stable temperature difference between warm surface waters (approximately 75-80°F) and deep ocean waters (around 35-40°F). This stable gradient, known as the thermocline, is essential for efficient energy conversion since the power output directly depends on this temperature difference.
- **Proximity to Deep Waters**: For both land-based and shelf-based plants, being close to deep water is beneficial. Floating platforms are an option for open ocean sites where deep waters are accessible.
- **Temperature Variation**: Seasonal variations in surface temperature (up to 10°F) can impact OTEC efficiency, although deep-water temperatures remain stable year-round. Efficient sites minimize seasonal temperature fluctuations.

2. **OTEC Site and Design**

- **Site Type**: There are three main OTEC setups — land-based, shelf-based, and floating platforms. Each has different logistical requirements and cost considerations. For instance, land-based plants require coastal access to deep water, while floating platforms are more suitable for remote, open ocean sites.
- **System Design**: Closed, open, and hybrid cycles each utilize different working fluids and mechanisms. Closed-cycle systems, which use ammonia due to its low boiling point, are typically more efficient than open-cycle systems, which directly use seawater.

- **Working Fluids**: Mixed fluids, such as R1123/161, have been shown to improve efficiency in closed cycles compared to single-component fluids like ammonia. These mixtures better match the phase transitions required for heat exchange, which can reduce losses.

3. **Environmental and Economic Factors**
   - **Environmental Impact**: While OTEC is a clean energy source with no greenhouse gas emissions, it can disturb marine ecosystems. The release of cold, nutrient-rich deep water to the surface can alter local aquatic environments, and any working fluid leaks could further impact marine life.
   - **Economic Viability**: OTEC remains costly due to high capital and operational expenses. The lack of long-term operational data and the absence of commercial plants contribute to uncertainties in economic projections. Current economic analyses mostly focus on Levelized Cost of Electricity (LCOE), but other metrics like payback period and Internal Rate of Return (IRR) are also relevant but often overlook

<u>Thermodynamic Analysis:</u>

$h_{mix} = h_1 + \alpha h_2$

$s_{mix} = s_1 + \alpha s_2,\ \ \alpha\ is\ the\ mass\ fraction\ of\ mixture\ fluid.$

For pump inlet:

$$h_1 = 218.9\ kJ/kg$$
$$T_1 = 8°C$$
$$P_1 = 5.736\ bar$$
$$v_1 = 1.7\ \times 10^{-3}\ m^3/kg$$

For superheated outlet:

$$T_5 = 24°C$$
$$h_5 = 1510.43\ kJ/kg$$
$$P_5 = 8.88\ bar$$

For turbine outlet:

$$h_6 = 1452.5\ kJ/kg$$
$$p_6 = 5.736\ bar$$

Work obtained through turbine:

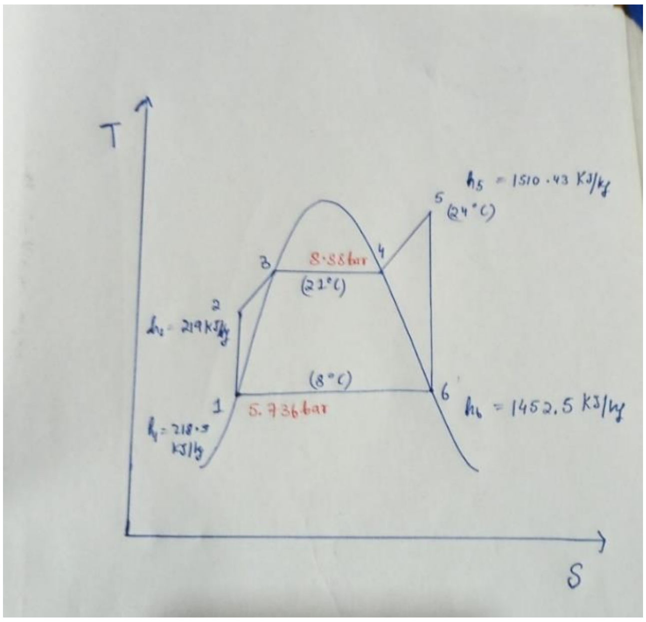
$$W_{tur} = h_5 - h_6$$
$$= 1510.43 - 1452.5$$
$$= 57.93\ kJ/kg$$

Work for pump:

$$H_{pump} = (p_2 - p_1)v_1$$
$$= (\ 8.88\ - 5.736) * 0.16$$
$$= 0.50304\ kJ/kg$$

Enthalpy at boiler inlet:

$$h_2 = h_1 + H_{pump} = 218.5 + 0.50304$$
$$= 219.003\ kJ/kg$$



Heat input in the cycle:

$$H_{inp} = h_5 - h_2 = 1510.43 - 219.003$$
$$= 1291.427\ kJ/kg$$

Efficiency of the cycle:

$$\eta_{th} = \frac{W_{tur}}{H_{inp}}$$
$$= \frac{W_{tur} - W_{pump}}{H_{inp}}$$

$$\eta_{th} = \frac{57.93 - 0.50304}{1291.427}$$

$$\eta_{th} = 4.44\%$$

Estimated Cost Analysis for OTEC plant:

Capital Cost (C_{cap}) = Rs 2746.37×10^7
Interest rate = 2.5%
Depreciation rate = 3%
Taxes = 4.5%
Time taken = 1 year

Wages = $20 \times 6 \times 10^5 = Rs\, 1.2 \times 10^7$
(Assuming personnel of 20 people earning an average of 6L per annum)
Repair and Maintenance = Rs 4.199×10^7
(Assuming 1.5% cost of initial investment)

Total energy produced = 50.75×10^7 kWh
(Assuming mass rate to be 1000 kg/s)

By using the following equations:

$$C_{tot} = \frac{(I+D+T)}{100} C_{cap\Delta} t + (W + R + M)$$

$$C_{tot} = \frac{(2.5+3+4.5)}{100} \times 2746.37 \times 1 \times 10^7 + (1.2 + 71.19) \times 10^7$$

$$C_{tot} = Rs\, 280.036 \times 10^7$$

$$Cost\ of\ electricity = \frac{C_{tot}}{KWh_{net}} = 5.51 \text{ Rs/unit.}$$

Conclusion:

The integration of solar concentrators and optimized working fluid mixtures in Ocean Thermal Energy Conversion (OTEC) systems has led to a 4.44% increase in efficiency and a cost of 5.51 Rs/kWh for electricity generation. This makes OTEC a promising, sustainable energy source, especially in tropical regions with strong ocean thermal gradients, as it provides baseload power generation and fresh water through desalination. While the initial cost may be higher compared to conventional energy, the potential for further efficiency improvements and reduced costs, along with its dual-purpose benefits for energy and water, make OTEC a viable solution for addressing energy and water scarcity in small island states and coastal regions.

References:

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