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BMM4753 RENEWABLE ENERGY RESOURCES

Chapter 9. Ocean Thermal Energy

Prof Dr Shahrani Haji Anuar
Energy Sustainability Focus Group

Chapter 9. Ocean Thermal Energy

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Summary

9.1 Introduction

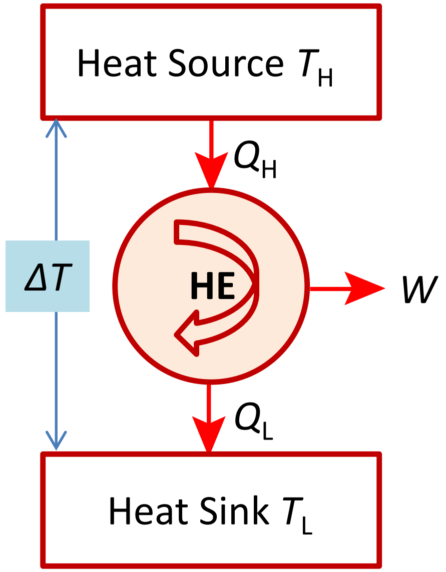
Oceans and seas cover about 70% of earth, constantly receiving solar radiation and act as the largest natural solar collector with an enormous storage capacity. Ocean Thermal Energy Conversion (OTEC) is a new technology and basically converts the thermal energy, available due to temperature difference between the warm surface water and the cold deep water, into electricity. Features:-

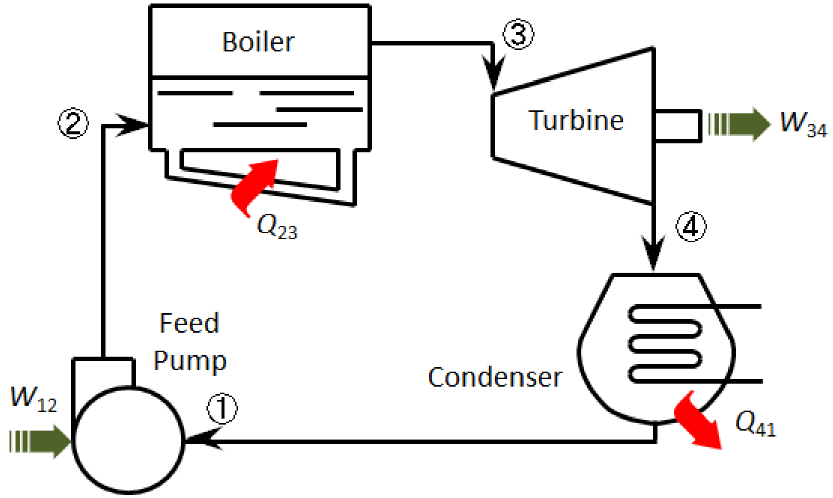
- Renewable and eco-friendly
- Can operate in remote islands and sea-shore continuously
- Very low grade solar thermal energy
- Efficiency of energy recovery is quite low

However, since the ocean thermal energy is dispersed over a large ocean surface area, it has a big potential and enormous opportunity to tap this renewable source of energy.

9.2 Working Principle – Conventional steam power plant

Temperature gradient between the surface and the deeper parts of the ocean is utilized to generate electricity. The basic process is to bring the warm surface water and the cold water from a certain depth of the sea through pipes so as to act as 'heat source' and 'heat sink' of a heat engine, similar to conventional steam power plant but without consuming fuel.





Steam Power Plant

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9.2 Working Principle – Ideal Carnot Power Cycle

Assumptions

i. The efficiency of conversion following Carnot cycle.
ii. The electrical, transmission efficiency is assumed to be 100%.
iii. The pipes are clean and fouling is absent.

Thermal energy from ocean temperature gradient , $P_o = \dot{m} \times C_p \times \Delta T$

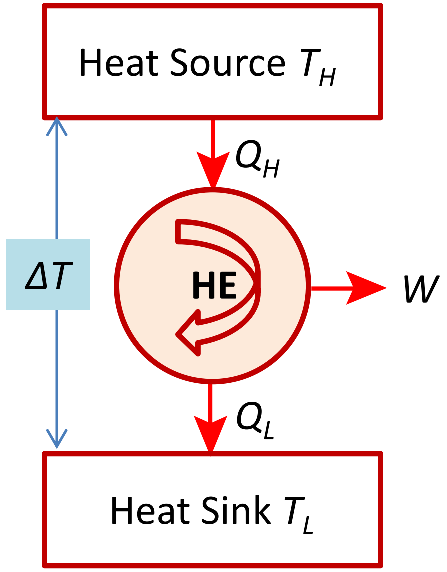
Maximum efficiency from Carnot , $\eta = \frac{T_H - T_L}{T_H} = \frac{\Delta T}{T_H}$

Equating extracted energy P_T to ocean thermal energy P_o

$$P_T = \eta \times P_o = \frac{\Delta T}{T_H} \times \left(\dot{m} \times c_p \times \Delta T\right) = \frac{\Delta T^2}{T_H} \times \dot{m} \times c_p$$

Mass of ocean water to be pumped, $\dot{m} = \frac{P_T \times T_H}{c_p \Delta T^2}$

Volume flow rate of water, $\dot{V} = \frac{\dot{m}}{\rho} = \frac{P_T \times T_H}{\rho c_p \Delta T^2}$



9.3 Ocean Thermal Energy Conversion (OTEC) – Power plants

Basic Features

- Utilizes temperature differences in the ocean as it gets colder the deeper, warmer on the surface from the sun
- A difference of at least 20°C required for OTEC to make energy.
- Used in Japan and in Hawaii in some demonstration projects.
- Warm surface seawater is pumped through a evaporator where a low-boiling point ammonia is vaporized.
- Expanding vapor turns a turbine driving an electrical generator.
- Cold deep seawater, pumped through a second heat exchanger, condenses the vapor back to a liquid, which is then returned to the first heat exchanger.

9.3 Ocean Thermal Energy Conversion (OTEC) – Power plants

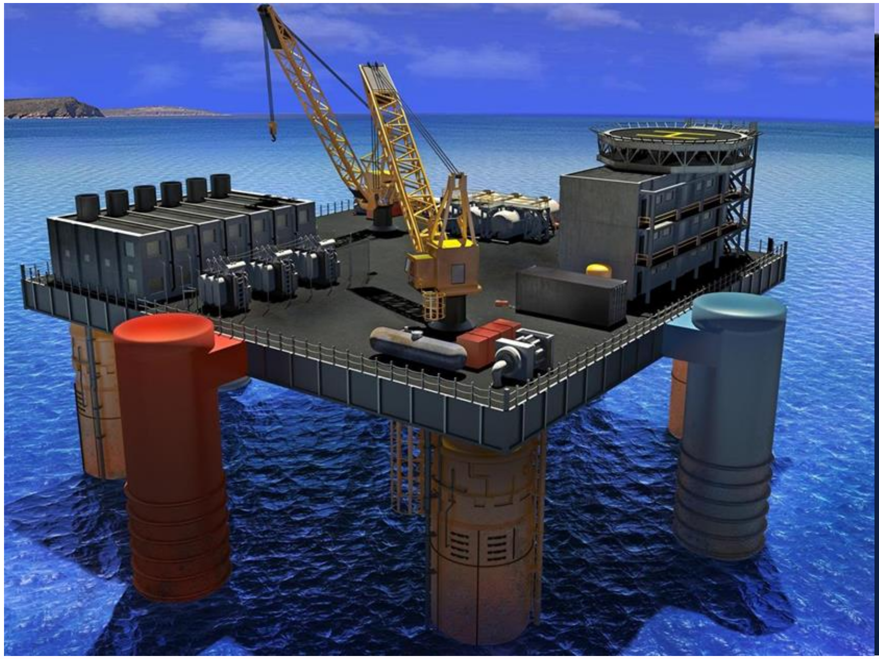
Development, Mini-OTEC

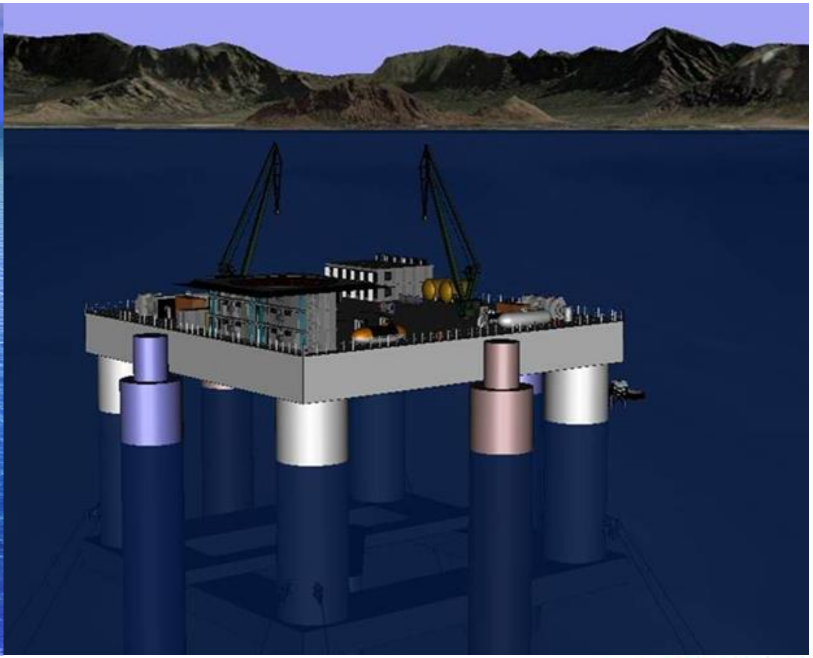
- 1979 project of the State of Hawaii, achieved the first successful at-sea production of net electrical power
- Ammonia vaporized in titanium plate heat exchangers turned a turbine-generator
- gross power output of 50 kW before condensing
- titanium plate heat exchangers cooled by 823 m deep seawater
- 60-cm diameter polyethylene pipe.
- The seawater pumps/auxiliaries consumed 40 kW
- 10 kW available to light bulbs, run computers and television sets on the Mini-OTEC barge that was moored about 2.4 km offshore.

9.3 Ocean Thermal Energy Conversion (OTEC) – Power plants

Development, Future OTEC Power Plants

It is possible that in the near future , OTEC platform spewing up to replace the oil rig platform in the search for greener earth and energy security from energy powered by the sun and the ocean.

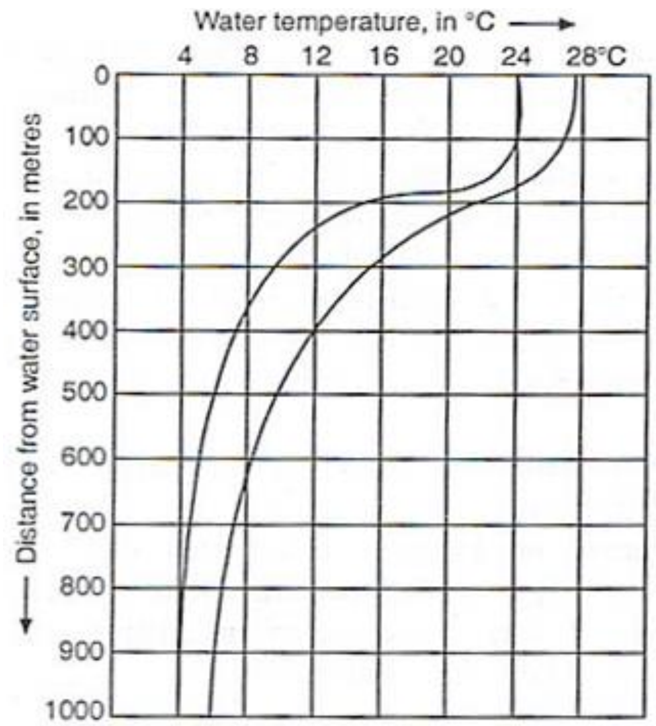




9.3 Ocean Thermal Energy Conversion (OTEC) – Power plants

Temperature Gradient

There exists a temperature difference of about 20°C between the warm surface water of the sea (receiving and absorbing solar radiation) and the cold deep water (which flows from the Arctic regions in deep layers) in equatorial areas between latitude 30°S and 30°N. Solar heat energy is absorbed by ocean water. It can be explained by 'Lambert's law of absorption'. The law states that "each water layer of identical thickness absorbs an equal fraction of light that passes through it". Thus, the intensity of heat decreases with the increase in water depth. Due to large heat transfer at the ocean surface water, the highest temperature is attained just below the top surface.



Ocean water temperature variation with distance from water surface

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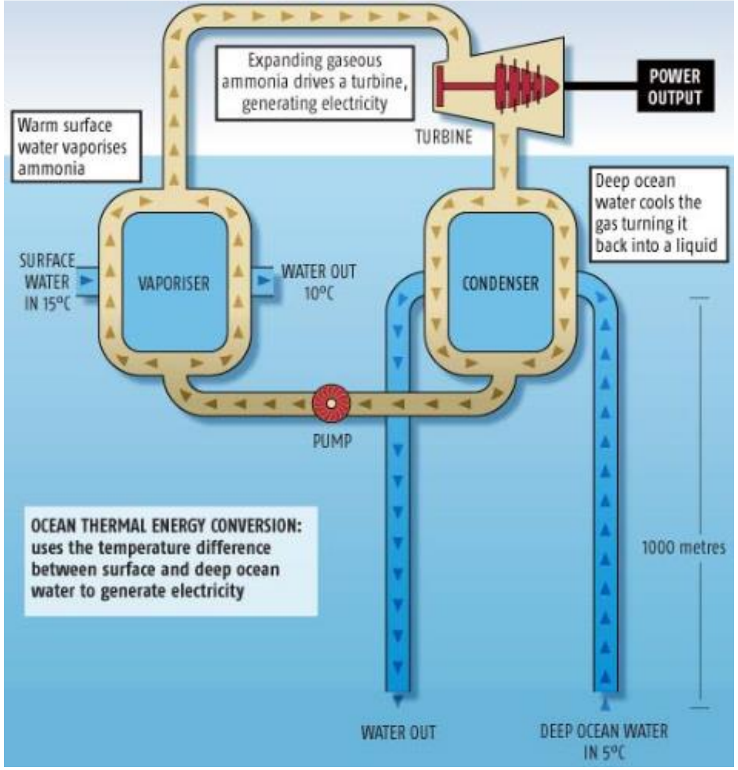
9.3 Ocean Thermal Energy Conversion (OTEC) – Power plants

The ocean surface water gets heated from the sun and attains a higher temperature than the colder water at deeper levels. Temperature gradient at many places in the ocean is up to 20°C and the available energy, ocean thermal energy (OTE) can be converted into usable form to operate a thermal power plant and generate electricity. Ocean Thermal Energy Conversion (OTEC) uses the warm surface water to boil low-boiling temperature liquid like ammonia or a chlorofluorocarbon (CFC)



and produces high pressure vapors to turn the turbine a generate electricity. The colder water from the deeper ocean is pumped up to cool the used up vapors and convert them again into a liquid.

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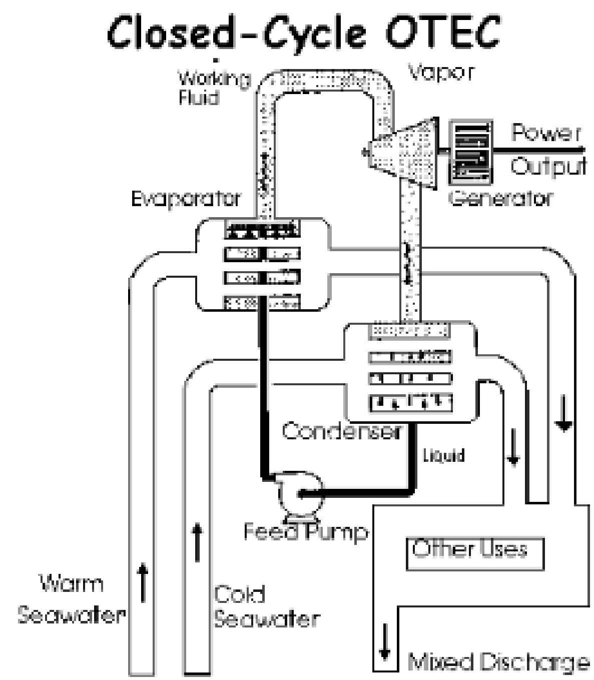
9.4 Closed-Cycle OTEC

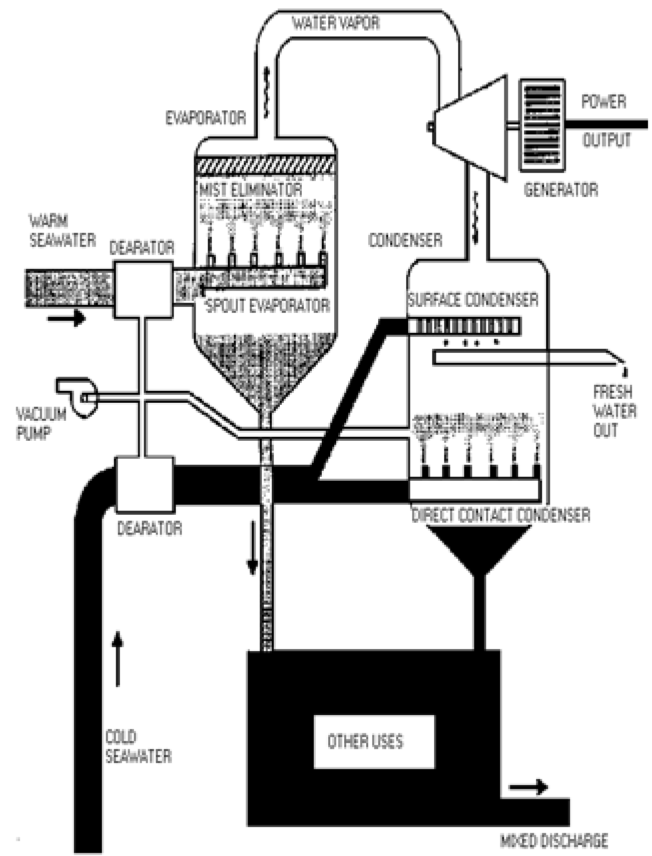
- Warm seawater vaporizes low-boiling point working fluid, ammonia, flowing through evaporator
- Vapor expands at moderate pressures and turns a turbine coupled to a generator that produces electricity.
- The vapor is then condensed in condenser using cold seawater pumped from the ocean's depths
- Condensed working fluid is pumped back to the evaporator to repeat the cycle
- The working fluid remains in a closed system and circulates continuously.



9.5 Open-Cycle OTEC

- Warm seawater working fluid "flash"-evaporated in a vacuum chamber to produce steam at an absolute pressure 2.4 kPa
- Saturated steam is generated by spouting the surface sea water in an evaporator
- Steam expands through a low-pressure turbine , coupled to generator
- Exiting steam from turbine is condensed by cold seawater from the ocean's depths.
- If a surface condenser is used in the system, the condensed steam remains separated from the cold seawater and provides a supply of desalinated water.
- Record operation
  - 50 kW at **Keyhole Point** Hawaii **in 1993**
  - 40 kW from Japanese system 1982
  - Development of new, cost-effective turbines
- Corrosion-resistant material for most cost-effective application

Open-Cycle OTEC



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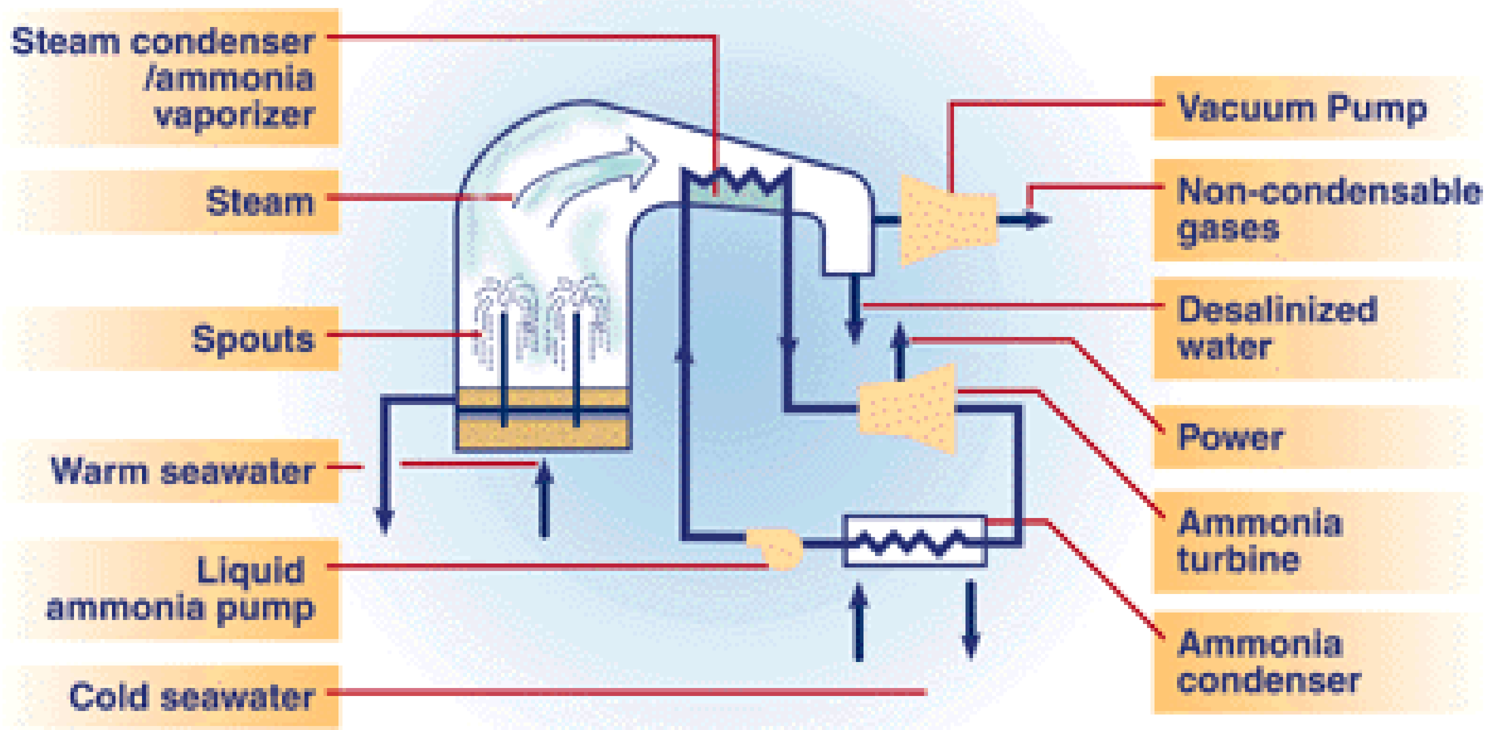
9.6 Hybrid OTEC System



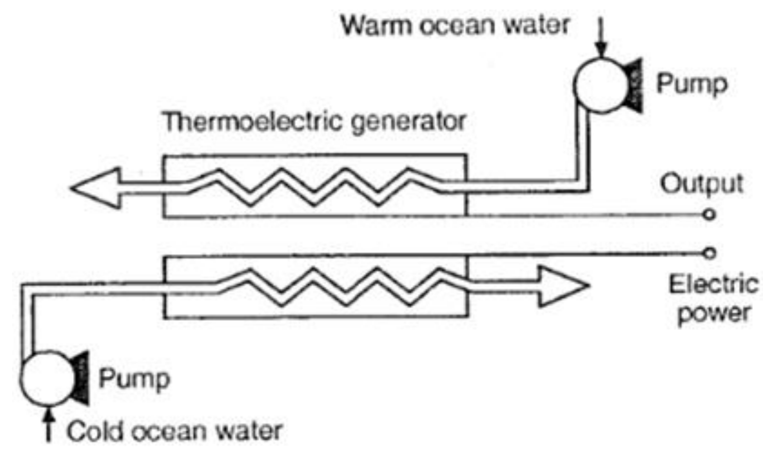
9.6 Hybrid OTEC System

- Combines the features of both the closed/open-cycle systems.
- Warm seawater enters a vacuum chamber where it is flash-evaporated into steam as in open-cycle evaporation process
- Steam vaporizes the working fluid of a closed-cycle loop on the other side of an ammonia vaporizer
- Vaporized fluid then drives a turbine that produces electricity
- Steam condenses within the heat exchanger and provides desalinated water.
- Electricity produced delivered to utility grid or use to manufacture methanol, hydrogen, refined metals, ammonia, and similar products.

9.7 Thermoelectric OTEC

The thermoelectric OTEC system was developed by Solar Energy Research Institute Colorado USA, during 1979. The OTEC system which operates on the thermoelectric principle is simple in construction and economical. Semiconductors are used to design two separate packs covered by a thin thermal conducting sheet . Warm water from the surface of the ocean is circulated over one device and the cold water pumped from the depth of the ocean is allowed to flow over the other device. The temperature difference between two waters with the solid state semiconductor devices generates the electric power. The OTEC plant economy is dependent on large variation of water temperature used from the surface and the deep ocean (20°C).

A part of electric power generated is used to operate the pumps and other equipment. For commercial operation of OTEC plants, it is better to install land-based OTEC equipment on shores of those islands where the ocean is steep for easy access to cold water.

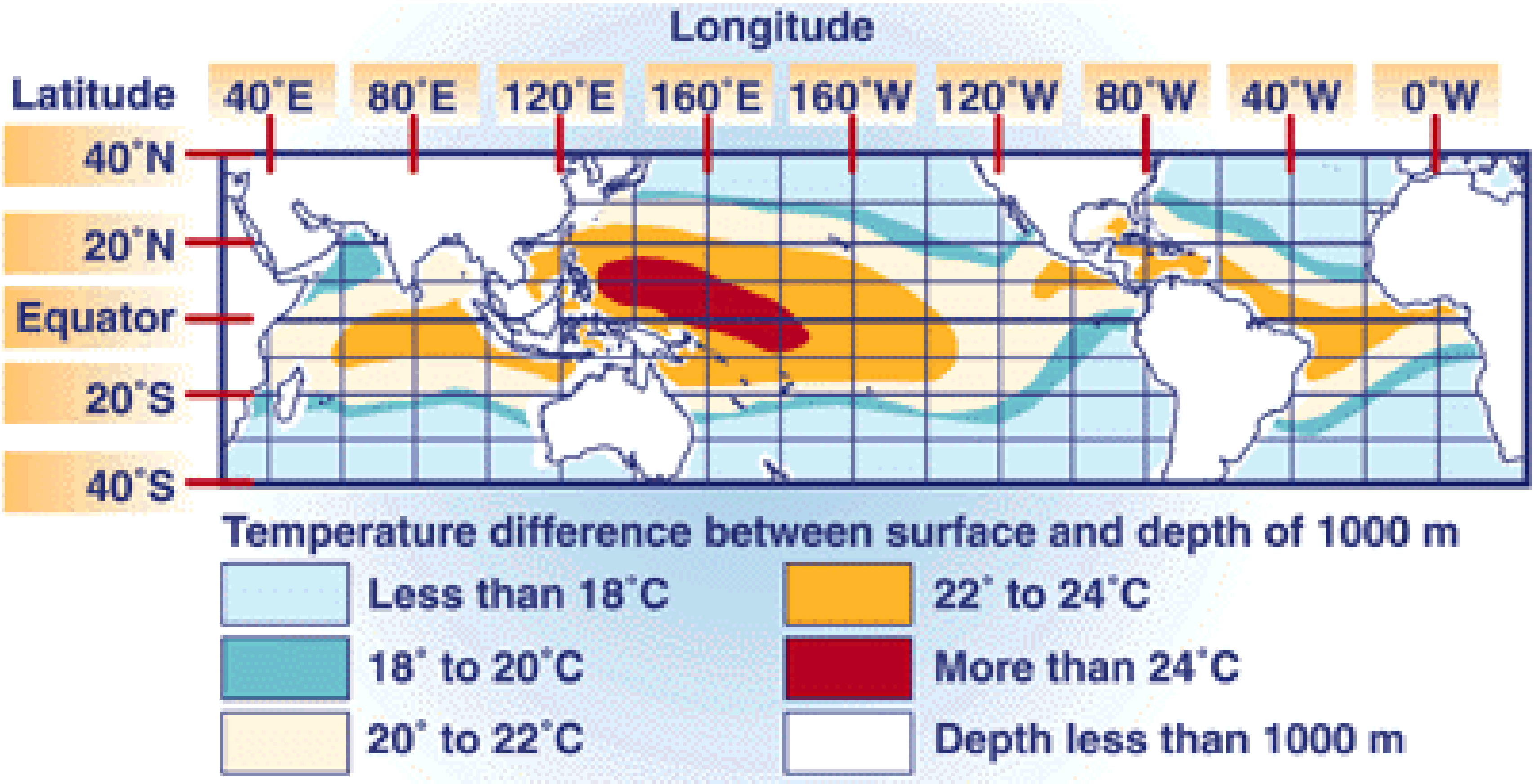


6.8 Bio-fouling in Ocean Thermal Energy Conversion Plants

The raw ocean water which is pumped in for evaporator and condenser, contains microorganisms which stick on the water side of both the heat exchangers. This biological impurity of sea water that deposits and grows on the evaporator and condenser metal surfaces, creating thermal resistance for heat transfer, is known as 'bio-fouling'. A thin layer of slime, i.e. a sticky substance from marine organism, also known as micro-fouling, continuously grows thicker by attaching to itself more and more biological contents from sea water; a serious problem for heat transfer and reduce the OTEC plant efficiency .

To maintain the optimum plant performance and efficiency, bio-fouling should be cleaned mechanically in addition to chemical treatment by chlorination. The problem of bio-fouling is more pre-dominent in closed-cycle OTEC plants. In open-cycle plants the flow rate of sea water is quite large, so organisms have a less chance to stick with the heat exchanger surface, thus causing little bio-fouling. However, as per the present approach in OTEC, a closed-cycle system needs to be installed for harnessing the ocean thermal energy. Necessary design input is required in OTEC plants to off-set bio-fouling effects, especially in evaporators where warmer water is more conducive to the growth of micro-organism.

6.9 Location of OTEC Plants



6.9 Location of OTEC Plants

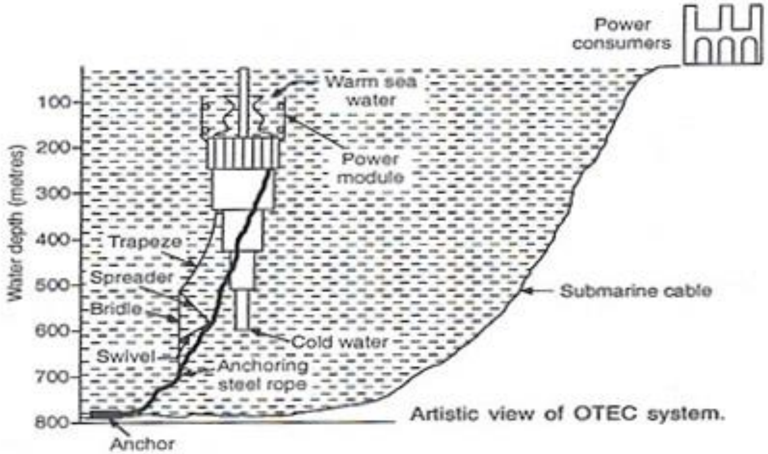
The selection of a suitable site for an OTEC plant needs a temperature difference of about 20°*C* between the surface and the deep sea ocean water. If the temperature difference is higher the site becomes more suitable as it will increase the power output, consequently the per unit cost will reduce. Such sites are available in 'Torrid and Temperate Zone' of the globe between latitudes 30ºS and 30ºN.

The most economic form of plant is the shore-based one which can be installed where considerable water depth occurs near the shore. With this type of plant there is no need to use expensive special cables for transmitting power. Further, one does not need any special floating type platform or mooring device which is needed for floating type plants. Many islands and certain continental sites are suitable for land-based plants.

6.9 Location of OTEC Plants

An OTEC plant can be either based on the land next to the sea, or placed on a floating platform anchored out in the sea. For a land-based plant, the cold water pipe has to be brought in from an adequate distance so as to provide 600-800 meter depth of sea. A place where the slope falls off sharply from the land may be ideal, so that the length of the cold water pipe is kept to a minimum.

The floating type plant produces electrical power on the platform, which has to be transmitted by a submarine cable to the shore and costly. In the plant ship variety, the plant is placed on the ship which can move on the sea to get the maximum temperature difference and the energy generated is consumed on the ship itself, where even an industrial unit may operate to manufacture a suitable product.

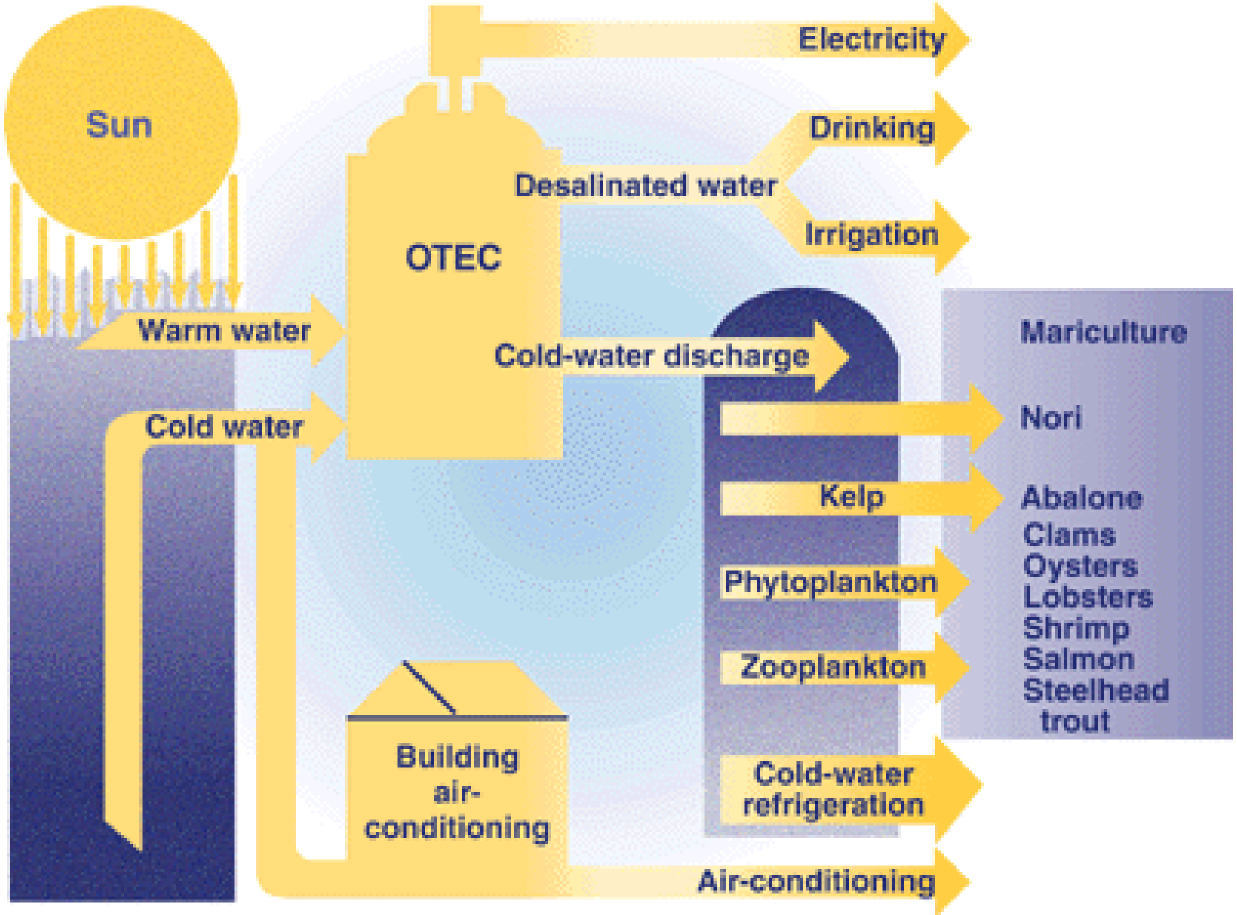


6.10 Economics Benefits of OTEC Plants

Given favorable geographical and easy conditions and a sufficient difference in temperature between the surface and the deeper sea, the OTEC plant can produce electricity at rates which are comparable with conventional oil or coal-based electric power at certain locations. However, as the price of oil and coal rise, the number of sites where the OTEC will be competitive shall increase

It is estimated by the United Nations that 99 nations have direct access to a possible OTEC thermal resource with an average monthly temperature difference exceeding 20°C within their own exclusive economic zone of sea. The world's potential of OTEC electric power projects is about 100,000 MW. As a rule of thumb, for each megawatt power generation, an OTEC plant requires a sea surface of about 1 sq. km, which acts in a way like a solar collector, since it is the sun which warms the surface water. There is a constraint on the capacity of a turbine generator unit which is limited to 25 kW only, due to limitations of small temperature difference of 20°C between the warm and cold water. It entails a large flow of warm and sea water, so the capacity of a single unit has a limit keeping in view the engineering workability.

6.10 Economics Benefits of OTEC Plants



6.10 Economics Benefits of OTEC Plants

1. Non-polluting renewable energy resource
2. Consistent 24-hour-a-day potential
3. Fresh Water up to 5 liters for every 1000 liters of cold seawater.
4. Food--Aquaculture products can be cultivated in discharge water - AND temperate, agriculture products can be grown in the tropics by cooling the roots with the discharged cold seawater.
5. Efficient air-conditioning or industrial cooling - even after it has passed through the OTEC plant.
6. Generate electricity
7. Desalinate water
8. Support deep-water marine culture
9. Refrigeration and air-conditioning
10. As aid in crop growth
11. Mineral extraction

6.10 Economics Benefits of OTEC Plants

Cultivation of "sea vegetables"

Strawberries

Korean Pak Choi

Problem 9.1: OTEC mass flow rate

An ocean thermal energy conversion plant (OTEC) can conceptually extracts thermal energy of P_T from a depth below a water surface at temperature of T_H by which the temperature gradient is ΔT. Derive the expression for theoretical rate of sea water circulation in kg/s. State all assumptions.

Assume: 100% **e**fficiency Carnot, electrical/transmission & zero fouling

Thermal energy from ocean temperature gradient

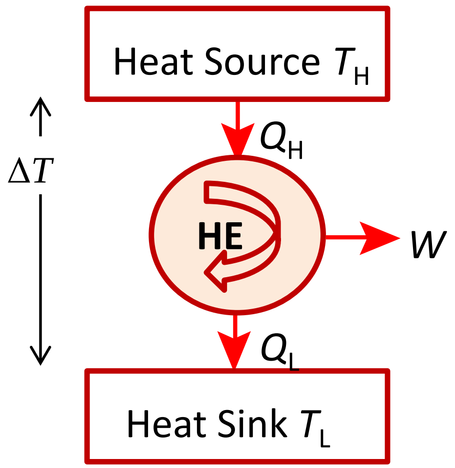
$$P_o = \dot{m} \times C_p \times \Delta T$$

Extracted energy to ocean thermal energy

$$P_T = \eta \times P_o = \frac{\Delta T}{T_H} \times \left(\dot{m} \times c_p \times \Delta T\right) = \frac{\Delta T^2}{T_H} \times \dot{m} \times c_p$$

Mass flow rate of ocean water to be pumped

$$\dot{m} = \frac{P_T \times T_H}{\Delta T^2 \times c_p}$$



Problem 9.2: OTEC volume flow rate

Determine the quantity of water to be pumped to an OTEC plant from a depth of 900 m and temperature 5°C to extract 1.2 MW of thermal energy working with a temperature gradient of 20°C. Assume the density of ocean water as 1010 kg/m³ and the specific heat of water as 4200 J/kg K. State all other assumptions made in the analysis.

Thermal energy to be extracted $P_T = 1 \times 10^6$ W

Temperature at exit/exhaust $T_H = T_L + \Delta T = (5 + 20)°C = 273 + 25 = 298K$

Thermal energy from ocean temperature gradient $P_o = m \times C_p \times \Delta T$

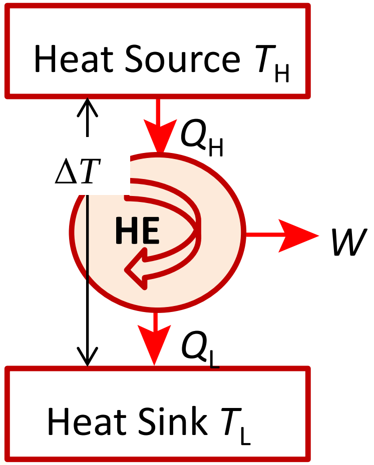
Maximum efficiency from Carnot $\eta = \frac{T_H - T_L}{T_H} = \frac{\Delta T}{T_H}$

Equating extracted energy to ocean thermal energy

$$P_T = \eta \times P_o = \frac{\Delta T}{T_H} \times (m \times c_p \times \Delta T) = \frac{\Delta T^2}{T_H} \times m \times c_p$$

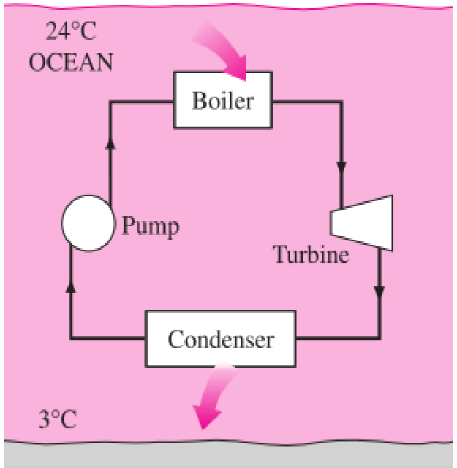
Mass of ocean water to be pumped $m = \frac{P_T \times T_H}{\Delta T^2 \times c_p}$

Volume flow rate of water $V = \frac{m}{\rho} = \frac{1}{\rho} \frac{P_T \times T_H}{\Delta T^2 \times c_p} = \frac{1.2 \times 10^6 \times 298}{1010 \times 20^2 \times 4200} = 0.21075 \ \frac{m^3}{s}$



Problem 9.3: OTEC thermal energy

In tropical climates, the water near the surface of the ocean remains warm throughout the year as a result of solar energy absorption. In the deeper parts of the ocean, the water remains at a relatively low temperature since the sun's rays cannot penetrate very far. It is proposed to utilized this temperature difference and construct a power plant that will absorb heat from the warm water near the surface and reject the waste heat to the cold water a few hundred meters below as shown. Determine the ocean thermal energy that can be extracted from 0.2 m^3/s flow rate of sea water, density 1025 kg/m^3 and the specific heat is 4.2 kJ/kg K.



$T_H = 24 + 273 = 297\text{ K}, \qquad T_L = 3 + 273 = 276\text{ K}$

$\Delta T = 24 - 3 = 21$

Carnot Maximum efficiency, $\eta = 1 - \frac{T_L}{T_H} = 1 - \frac{276}{297} = 7.07\%$

Thermal energy from ocean temperature gradient

$$P_o = \dot{m} \times C_p \times \Delta T = 0.2 \times 1025 \times 4.2 \times 21 = 18{,}080\text{ kW}$$

Equating extracted energy to ocean thermal energy

$$P_T = \eta \times P_o = 0.0707 \times 18{,}080 = \mathbf{1{,}278kW}$$

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