MODULE 5: Sea Wave Energy: Introduction, Motion in the sea Waves, Power Associated with Sea Waves, Wave Energy Availability, Devices for Harnessing Wave Energy, Advantages and Disadvantages of Wave Power. Ocean Thermal Energy: Introduction, Principles of Ocean Thermal Energy Conversion (OTEC), Ocean Thermal Energy Conversion plants, Basic Rankine Cycle and its Working, Closed Cycle, Open Cycle and Hybrid Cycle, Carnot Cycle, Application of OTEC in Addition to Produce Electricity, Advantages, Disadvantages and Benefits of OTEC.

SEA WAVE ENERGY

Session 1

INTRODUCTION

The energy in ocean waves mainly comes in an irregular and oscillating form at all times of the day and night. Solar energy causes winds to blow over vast ocean areas, which in turn cause waves to form, gather, and travel huge distances to the shoreline of continents. The wave height, period, and direction are primarily dependent on the wind properties (speed, direction, and duration) and also the geometry of the sea (fetch length and depth). There is surprisingly little loss of energy in deep-water ocean waves, so as they travel to distant shores they continue to collect more and more wind energy.

MOTION in the Sea Waves

When the wind blows across smooth water surface, air particles from the wind grab the water molecules they touch. Stretching of the water surface by the force or friction between the air and the water creates capillary waves. Surface tension acts on these ripples to restore the smooth surface, and waves are formed.

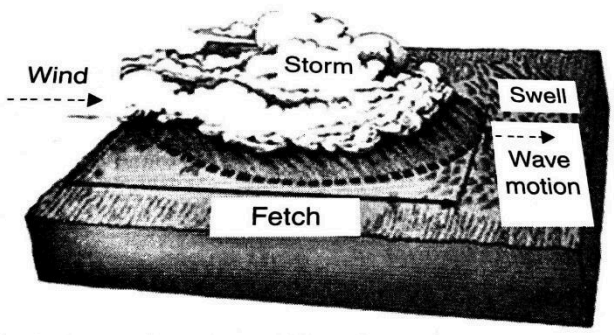

Figure 4.1 sea wave motion

The combination of forces due to the gravity, sea surface tension, and wind intensity are the main factors of origin of sea waves.

Wave speed is determined by wind speed and fetches (distance over which the wind excites the waves) and by the depth and topography of these abed (which can focus or disperse the energy of the waves).Sea waves have a regular shape at far distance from the fetch and is called swell. Wave information makes the water surface further rough and the wind continuously grips the roughened water surface and thus waves are intensified.

Waves are characterized by the following parameters

- ***Crest:*** The peak point (the maximum height) on the wave is called the crest.
- ***Trough:*** The valley point (the lowest point) on the wave is called trough.
- ***Wave height (H):*** It is a vertical distance between the wave crest and the next [5] trough(m).
- ***Amplitude(a):*** It is defined as H/2 (m).
- ***Wavelength (λ) :*** It is the horizontal distance either between the two successive crests or troughs of the ocean waves(m).
- ***Wave propagation velocity(v):*** The motion of sea water in a direction(m/s).
- ***Wave period(T):*** It measures the size of the wave in time(s). It is the time required for two successive crests or two successive troughs to pass a point in space.
- ***Frequency(f):*** The number of peaks that pass a fixed point per second is defined as the frequency of wave and is given by f=1/T (cycle/sec).

Power Associated with Sea Waves

It has been concluded by researchers through linear wave motion theory that the kinetic and potential energy (E) of a wave per meter of crest and unit of surface can be approximated as

$$E = \rho g a^2/2$$

where p = density of water; g = gravitational acceleration; and a = amplitude of the wave (approximately equals to half its wave height H).

The power that a meter of crest holds can be obtained by multiplying the amount of energy transported by the group velocity.

In deep water, dispersion relation (k) is given as

$$k = \omega^2/g,$$

Further, group velocity $(V_g) = \omega/2k = g/2\omega$

The total power (P) is obtained as $P = EV_g = [\rho g\, a^2/2](g/2\omega) = \rho g^2 a^2/4\omega$

Further, wave period $(T) = 2\pi/\omega$ or $\omega = 2\pi/T$ and $a = H/2$

Therefore, $P = \rho g^2 a^2/4\omega = \rho g^2 H^2 T/32\pi$

For irregular waves of height H (m) and period T(s), an equation for power per unit of wavefront can be derived as

$$P_{\text{irregular}} = 0.4 \text{ (kW/m) of wavefront}$$

From the abovementioned equations, it is seen that the wave power is directly proportional to the square of wave height.

Review Questions

1. How sea wave is formed?
2. Define Crest and Trough.
3. What is frequency in sea motion.

Session 2

WAVE ENERGY AVAILABILITY

Density of water is about 800 times higher than air. Energy density of ocean wave are significantly several times more than air. The amount of energy available in ocean waves are tremendously high. It is considered as renewable, zero emission source of power. Estimation of the global ocean wave energy are more than 2TW according to the world energy council.

WAVE ENERGY AVAILABILITY IN INDIA

The coastal area of Maharashtra has an annual wave potential ranging between 4kW/m and 8kW/m wave front, which is quite high as 12-20kW/m during the monsoon. Offshore Location of wave power in Maharashtra

Site	Average Wave Power (kW/m) (Annual)	Average Wave Power (kW/m) (June–August)
Malvan Rock	6.91	16.73
Kura Inset	5.79	13.74
Redi	6.35	16.57
Vengurla Rock	8.01	20.61
Square Rock	6.79	16.64

DEVICES FOR HARNESSING WAVE ENERGY

There are four basic technologies for converting wave energy to electricity

- **Terminator devices:** It is a device oriented perpendicular to the direction of the wave and has one stationary and one moving part. The moving part moves up and down like a car piston in response to ocean waves and pressurizes air or oil to drive a turbine. These devices generally have power ratings of 500kW to 2MW, depending on the wave parameters and the device dimensions.
- ***Attenuator devices:*** *These devices are oriented parallel to the direction of the waves and are long multi segment floating structures. It has a series of long cylindrical floating devices connected to each other with hinges and anchored to the seabed. The segments are connected to hydraulic pumps or other converters to generate power as the waves move across.*
- ***Point absorber:*** *It is a floating structure with parts moving relative to each other owing to wave action but it has no orientation in any defined way towards the waves instead absorb the wave energy coming from any direction. It utilizes the rise and fall of the wave height at a single point for energy conversion. The pressurized water creates up and down bobbin type motion and drives a built in turbine generator system to generate electricity.*
- ***Overtopping devices :*** *These devices have reservoirs lie a dam that are filled by incoming waves, causing a slight build up of water pressure.Gravity cause released wter from reservoir to flow back into the ocean through turbine coupled to an electrical generator.*

Float or Buoy devices:

A series of anchored buoys rise and fall with the wave that creates mechanical energy to drive electrical generator for generation of electricity which is transmitted to ocean shore by underground cables.

Oscillating water column devices:

It is a form of terminator in which water enters through a sub-surface opening into a chamber, trapping air above. The wave action causes the captured water column to move up and down like a piston, forcing the air though an opening connected to a turbine to generate power. It is a concrete structure partially sub merged in sea water and encloses a column of air on top of a column of water.

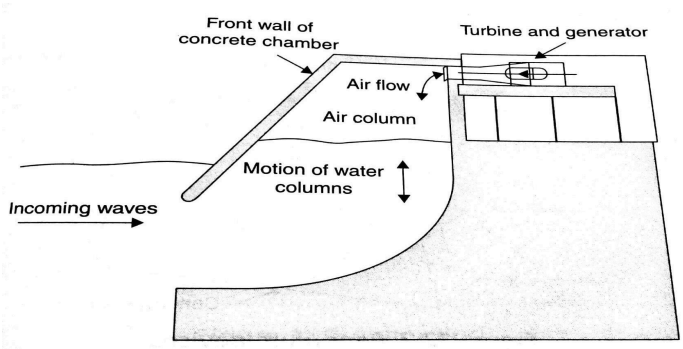

Figure 4.2 OWCD

Review Questions

1. What is Point absorber?
2. How oscillating water column device works.
3. Define Attenuator.

Session 3

Pendulum systems:

It is a shoreline device that consists of a parallel piped concrete box, which is open to the sea at one end A pendulum flap is hinged over this opening which swings back and forth by the actions of the waves. The back and forth motion of pendulum is then used to power a hydraulic pump and an electric generator.

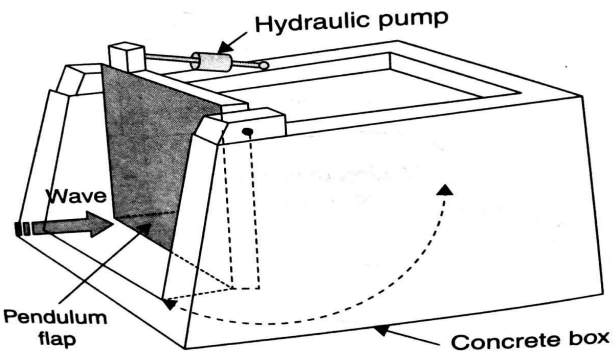

Figure 4.3 pendulum system

TAPCHAN(Tapered Channel):

It has a tapered channel connected to a reservoir constructed above the sea level at a height of 3-5m. They are relatively low power output devices and suitable for deep water shoreline and low tidal range.It is a very simple device. Waves collect into a channel, which tapers into a large reservoir. The PE of water stored in the reservoir is extracted by releasing the reservoir water back to the sea through a low head Kaplan turbine coupled to an electrical generator.

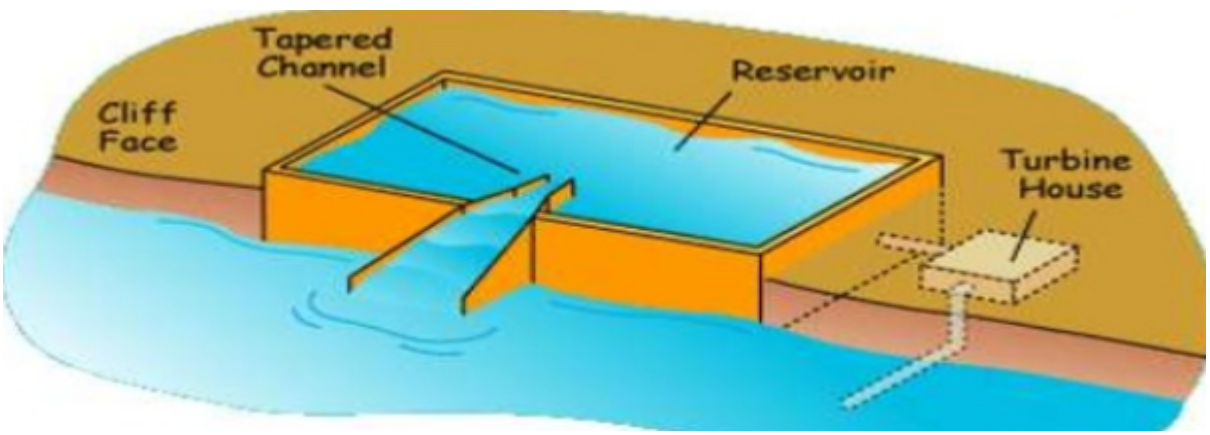

Figure 4.4 Tapered Channel

Salter's Duck system:

It is an egg shaped device that moves with the motion of the waves. The shape of leading edge of the duck is in such a way that the approaching sea wave pressure is

exerted on the duck. It forces the duck to rotate about a central axis and the tip of the cam bobs up and down in the water. As the salter duck moves up and down on the sea waves, pendulum connected to electrical generator swings forward and backward to generate electricity. Two sets of cables are attached to the device one to pendulum inside the device and the other to a fixed arm outside the device.

The cables attached to the internal pendulum contain hydraulics that pumps as the device moves back and forth with the waves. This movement of the pressurized oil pumped into hydraulic machine that drives electric generators.

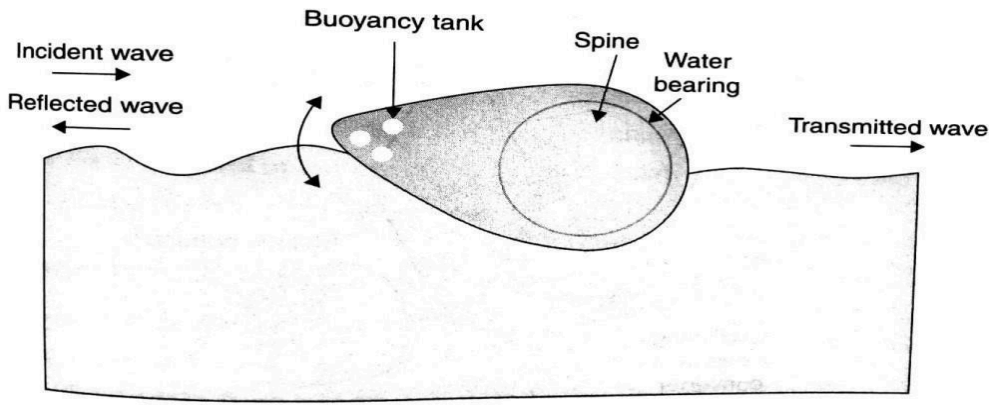

Figure 4.5 salter duck system

Offshore Wave Dragon system:

It is an overtopping device that elevates ocean waves to a reservoir above sea level

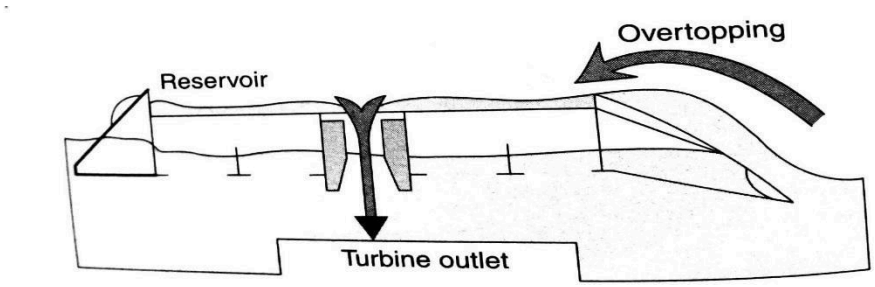

Figure 4.6 wave dragon system

Water is let out through a number of turbines and in this way it is transformed into electricity. It consists of two large arms that focus waves up ramp into a reservoir. The

water returns to the ocean by the force of gravity via a low head hydro turbine that drives an electric generator.

Review Questions

1. How TAPCHAN works.
2. How pendulum system works.

Session 4

Bristol cylinder:

It consists of a floating cylinder that collected the wave's movement. The cylinder is mechanically connected to the energy unit by flexible joints and rods. The rods are moving slowly with cylinder and the reciprocating motion is transferred to the axels in converter unit.

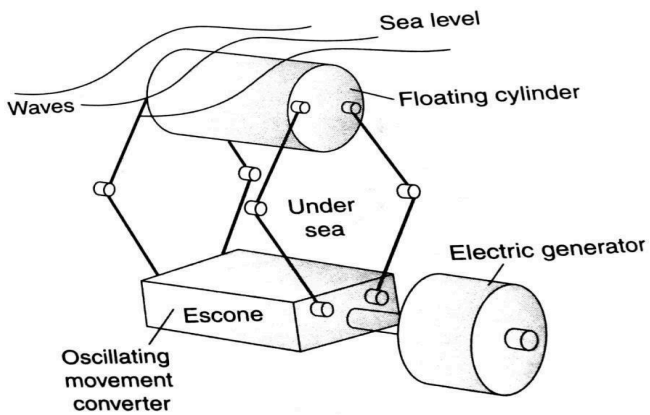

Figure 4.7 bristol cylinder system

Archimedes wave swing devices:

It is an underwater buoy of which the upper part moves up and down in the wave, while the lower part stays in position. The floater is pushed down under a wave crest and moves up under a wave trough. The interior of the system is pressurized with air and serves as an air spring. The mechanical power is converted into electrical power by means of a power take 30 off system.

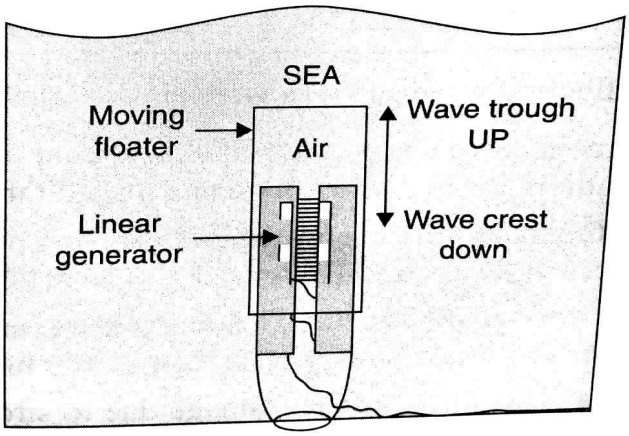

Figure 4.8 Archimedes system

ADVANTAGES AND DISADVANTAGES OF WAVE POWER

Advantages

1. Sea waves have high energy densities and provide a consistent stream of electricity generation capacity.
2. Wave energy is clean source of renewable energy with limited negative environmental impacts.
3. It has no greenhouse gas emissions or water pollutants.
4. Operating cost is low and operating efficiency is optimal.
5. Damage to ocean shoreline is reduced.

Disadvantages

1. High construction costs.
2. Marine life is disrupted and displaced.
3. Damage to the devices from strong storms and corrosion create problems.
4. Wave energy devices could have an effect on marine and recreation environment.

Review Questions

1. How Bristol cylinder works.
2. Give any 2 advantages of sea wave energy.
3. Give any 2 disadvantages of sea wave energy.

Session 5

OCEAN THERMAL ENERGY

Broadly the ocean sources of energy are Ocean Thermal Energy Conversion (OTEC) and the Tidal energy, Wave energy and fourth form of the energy that emanates from the sun-ocean system stems from the mechanism of surface water evaporation by solar heating i.e. hydrological cycle.

The conversion of solar energy stored as heat in the ocean into electrical energy by making use of the temperature difference between the warm surface water and the colder deep water. The facilities proposed for achieving this conversion are commonly referred to as OTEC plants or sometimes as solar sea power plants (SSPP).

OTEC systems use the ocean's natural thermal gradient to drive a power-producing cycle. The temperature difference between warm surface water and cold deep sea water is

greater than about 20°C.The operation of the OTEC plant is based on a well-established physical (thermodynamic) principle. If a heat source, is available at a higher temperature and a heat sink at a lower temperature, it is possible in principle, to utilize the temperature difference in a machine or prime mover (e.g. a turbine) that can convert part of the heat taken up from the source into mechanical energy and hence into electrical energy. The residual heat is discharged to the sink at the lower temperature.

In the OTEC system, the warm ocean surface water is the heat source and the deep colder water provides the sink.

The temperature gradient can be utilized in a heat engine to generate power. This is called ocean thermal energy conversion (OTEC).

OCEAN THERMAL ENERGY CONVERSION

- ☐ Low temperature heat obtained from renewable energy sources is presently converted into electricity and utilized for direct heating applications.
- ☐ OTEC is an energy technology that converts solar radiation to electric power through heat of ocean water.
- ☐ Oceans are vast renewable resources with the potential to produce thousands of kW of electric power.

PRINCIPLE OF OTEC

- ☐ The warm water from the ocean surface is collected and pumped through the heat exchanger to heat and vaporize a working fluid, and it develops pressure in a secondary cycle.
- ☐ Then the vaporized working fluid expands through a heat engine coupled to an electric generator that generates electrical power.
- ☐ Working fluid vapour coming out of heat engine is condensed back into liquid by a condenser.
- ☐ Cold deep ocean water is pumped through condenser where the vapour is cooled and returns to liquid state.
- ☐ The liquid is pumped again through heat exchanger and cycle repeats.
- ☐ Some fractions of electrical power generated by OTEC plants are used for operating and controlling equipments involved in power plants, and high electrical power is used for feeding to several other energy consumers.

Review Questions

1. What is the criteria for OTEC plant.
2. What are the principles of OTEC.

Session 6

OCEAN THERMAL ENERGY CONVERSION PLANTS

Land based power plant

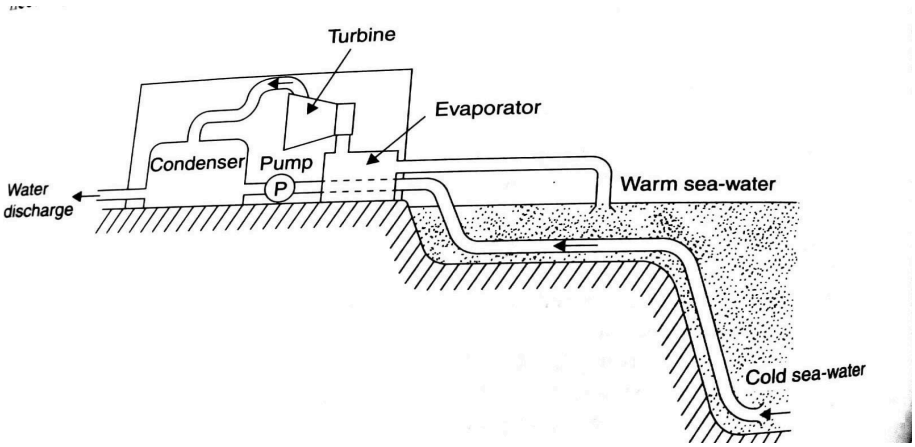

Figure 4.9 pendulum system

It is constructed on shore and accommodates all parts of OTEC plants. It requires laying down long pipes from plant site on shore to two extreme points of necessary temperature gradient. One pipe is used to collect warm ocean surface water through screened enclosure near the shore. Another long pipe lay down on the slope deep into the ocean to collect cold water. A third pipe is used as outlet to discharge used water again in ocean via marine culture ponds deep down the ocean. Cost of pipe installation and maintenance is very expensive, and land based plant is also very expensive. Since large electricity is used to pump water through long pipes, the net electricity reduces considerably. This plant has the advantage of savings on electrical transmission line and connectivity to electrical power grid.

Floating power plant:

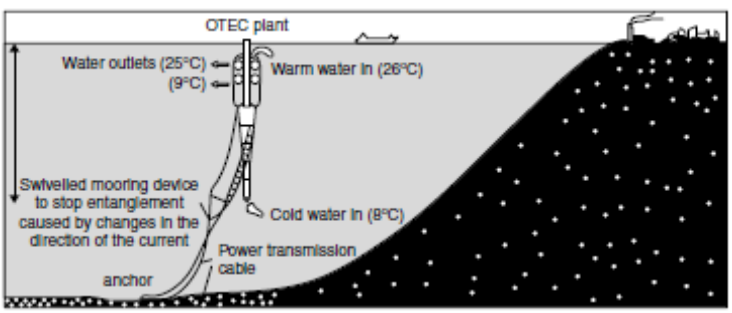

Figure 4.10 pendulum system

- ☐ It is built on a ship platform exactly where required temperature gradient sufficient for OTEC plant is available.
- ☐ Working principle is same as land based power plant.Long transmission line is required to transmit electrical power from plant to sea shore.
- ☐ Installation cost is more.
- ☐ Efficiency is less.

Review Questions

1. What are the advantages of Land based power plant.
2. What are the advantages of Floating OTEC power plant?

Session 7

BASIC RANKINE CYCLE AND ITS WORKING

The basic Rankine cycle shown in below Figure consists of the following:

1. An evaporator
2. A turbine expander
3. A condenser
4. A pump
5. A working fluid

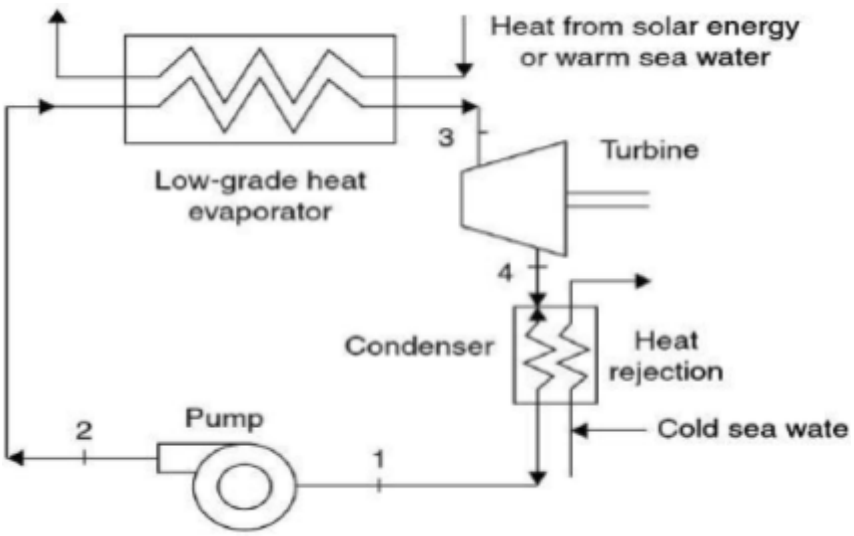

Figure 4.11 Rankine cycle

In open-cycle OTEC, warm sea water is used as working fluid, whereas in closed-cycle type,low-boiling point ammonia or propane is used.

Warm ocean surface water flows into the evaporator which is the high-temperature heat source. A fluid pump is utilized to force the fluid in a heat evaporator where liquid fluid vapourizes.

Then, the vapour of boiling fluid enters the turbine expander coupled with an electrical generator to generate electrical power. The vapour released from the turbine enters into condenser where it condenses. The cold deep sea water is pumped through the condenser for heat rejection from vapour fluid and condenses it as liquid fluid. The liquid fluid is again pumped through evaporator and cycle repeats.

As temperature difference between high- and low-temperature ends is large enough, the cycle will continue to operate and generate power.

Selection of working fluids:

The working fluid has the following properties:

1. **Chemical stability and compatibility:** Certain organic fluids are more prone to decompose when subjected to high pressure and temperature which results in material corrosion of different parts of plants, explosion etc. Thus, working fluid should be chemically stable and compatible with materials and structures of OTEC plants.
2. Heat transfer coefficient: Low-thermal resistance of working fluids improves heat transfer.
3. Flash point: A working fluid with a high flash point should be used in order to reduce flammability.

4. Specific heat: A working fluid with a low specific heat should be used to reduce load on the condenser.
5. Latent heat: A working fluid with a high latent heat should be used in order to raise the efficiency of heat recovery.
6. Safety: Working fluid should be non-corrosive, non-toxic, and non-inflammable having maximum allowable concentration and explosion limit for safe and efficient operation of OTEC plants.
7. Environmental acceptability: Low-toxicity working fluid minimizes water pollution. The environmental risk of OTEC plant is low.
8. Cost and availability: The ease of availability and low cost of working fluid is also important.

Review Questions

1.What are the steps involved in Rankine Cycle
2 What is Chemical stability and compatibility of working fluids.

Session 8

OPEN CYCLE OTEC

An open-cycle OTEC uses the warm ocean surface water as working fluid. It is a non-toxic and environment friendly fluid. The major components of this system are shown in Figure 4.12

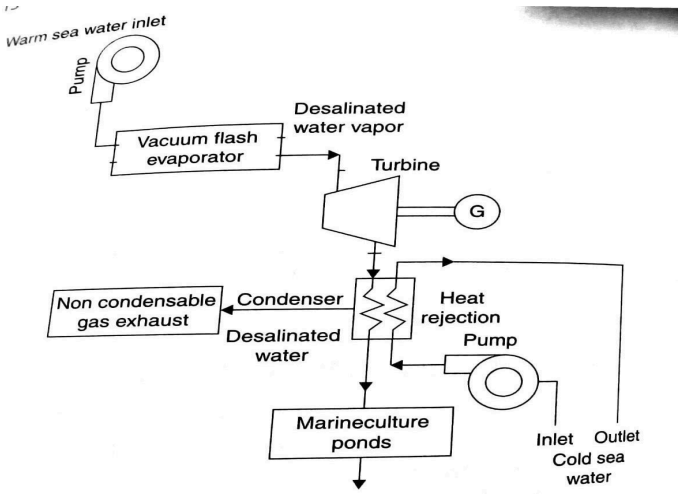

Figure 4.12 Open cycle OTEC

Warm sea water instantly boils in flash evaporator has reduced pressure than atmosphere. It results in reduced vapourization pressure of warm sea water. A large turbine is required to accommodate large volumetric flow rates of low pressure steam which is needed to generate electrical power.

During vaporization process in an evaporator oxygen, nitrogen and carbon dioxide dissolved in sea water are separated and are non-condensable. The steam is cooled in a condenser by cold deep sea water.

The condensed non saline water is discharged either directly in deep sea cold water. The non-condensable gases are compressed to pressure and exhausted simultaneously.

CLOSED CYCLE OTEC

The schematic of closed-cycle OTEC is shown in Figure. It has different arrangement when compared to open-cycle OTEC

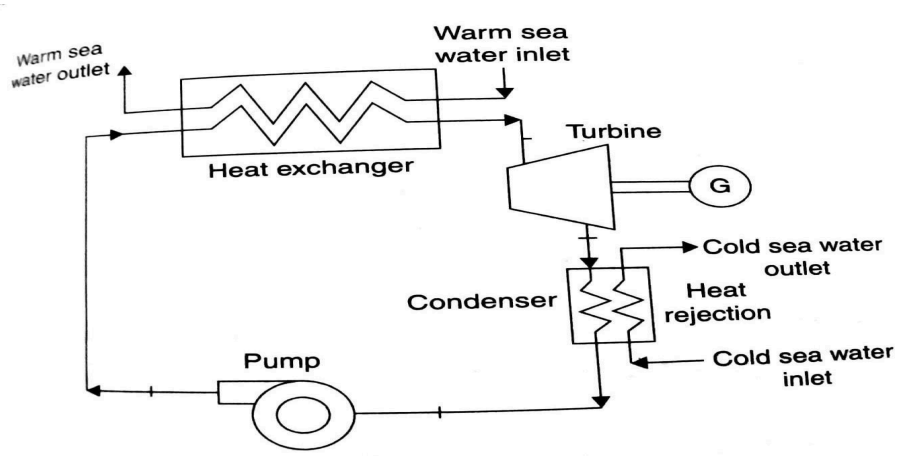

Figure 4.13 Closed cycle OTEC

Working principles of closed-cycle OTEC are as follows:
1. Working fluid is pumped through heat exchangers in a closed loop cycle which is perfectly leakage proof.
2. Warm sea surface water is pumped through separate pipe in heat exchanger in close contact with fluid closed loop cycle
3. Warm sea water transfer its heat energy to working fluid in heat exchanger and working fluid vapourizes.
4. The fluid vapour makes the turbine to rotate and drive an electrical generator to produce electricity.
5. Fluid vapour leaving the turbine is cooled and condensed as liquid fluid and is pumped again to repeat cycle.
6. Cold deep sea water is pumped through a separate pipe in condenser for providing efficient cooling of working fluid.

OTEC HYBRID CYCLE

As shown in Figure , a hybrid cycle combines the features of both closed-cycle and open-cycle systems

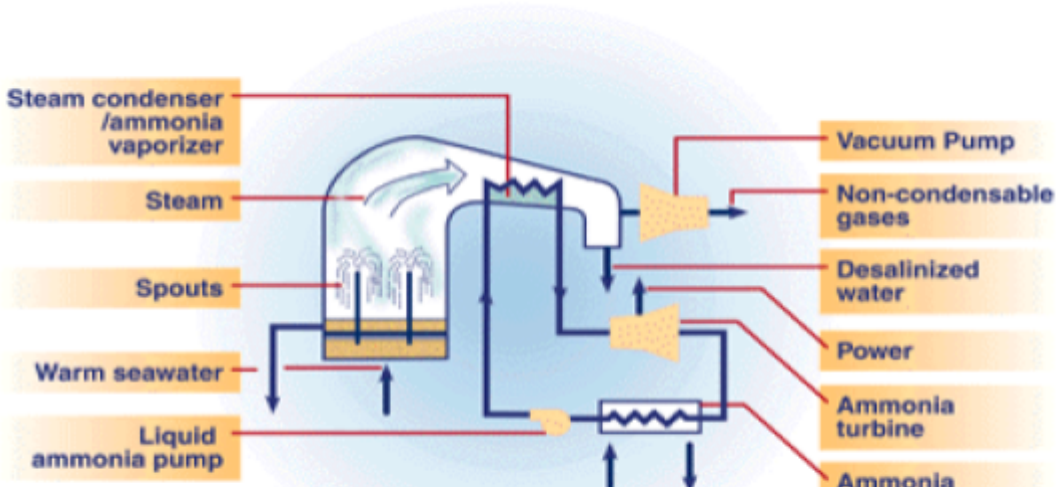

Figure 4.14 OTEC Hybrid cycle

Warm sea water is pumped into a vacuum chamber where it is used to flash and produces steam. Working fluid in another closed cycle loop is evaporated and vapourized by steam in vacuum chamber. The fluid vapour rotates the turbine and drive an electric generator to produce electricity. The fluid vapour will be condensed by cold sea water in a condenser and re circulated in a closed cycle. The condensed steam or desalinated water is used for marine culture plants. Non condensable gases are exhausted

CARNOT CYCLE

A Carnot cycle is defined as an ideal reversible closed thermodynamic cycle. Four successive operations are involved: isothermal expansion, adiabatic expansion, isothermal compression, and adiabatic compression.

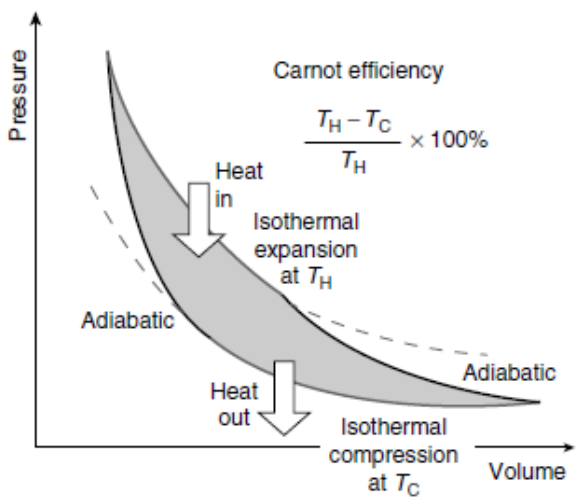

Figure 4.15 Carnot efficiency P-V diagram

- Let W be the work done by the system
- QH be the heat put into the system.
- Tc be the absolute temp of the sea surface
- Th be the absolute temperature of the deep sea water hot reservoir.
- Carnot efficiency is given as

$\eta = W/QH = 1 - Tc/Th$

APPLICATIONS OF OTEC IN ADDITION TO ELECTRICITY

OTEC schematic diagram and applications are shown in Figure Ocean thermal converting plants provide several products for use by mankind. These are explained as follows:

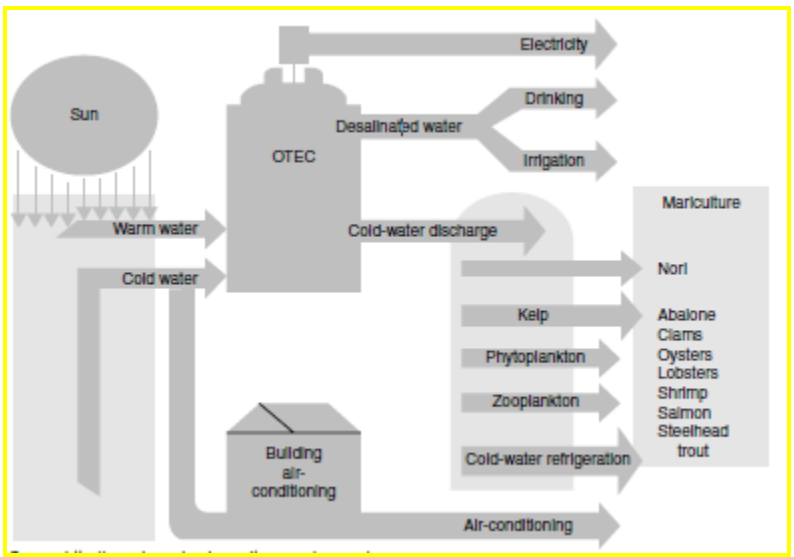

Figure 4.16 OTEC plant and applications

1. **Electricity:** Electrical energy is the primary product of OTEC plants. Laying down long transmission and distribution cables up to the sea shore for domestic and industrial applications is not practical from economic view point. OTEC plants are, therefore, considered for other products and applications.
2. **Hydrogen production:** Electricity produced from OTEC plants is used for separating water in hydrogen and oxygen by the method of electrolysis of water. Hydrogen is considered and OTEC electricity for hydrogen production signifies the important applications of OTEC plants.
3. **Ammonia and methanol production:** OTEC electricity can be used to obtain by-products, such as ammonia and methanol that can be transported either by tankers or through pipe lines to on shore applications.
4. **Desalinated water:** Desalinated water is produced in an open-cycle and hybrid-type OTEC plants through surface condenser. It is freshwater and widely used as water resource for drinking, agriculture, and industry.
5. **Aquaculture:** Nutrient-rich cold deep sea water provides sufficient environment for fish farming which may create a profitable business activities.
6. **Chilled soil agriculture:** Chilled soil agriculture is another application of OTEC plants. Cold deep sea water flowing through underground pipes chills the surrounding soil. The temperature difference is maintained between plant roots in the cool soil and plant leaves in the warm air, and thus, the tree and plants grows. The amount of food

that can be produced in this way is very large, larger in market value than the electric power produced by the plant.
7. **Air conditioning:** Because the temperature is only a few degrees, cold water can be used as a fluid in air condition systems.

ADVANTAGES, DISADVANTAGES AND BENEFITS OF OTEC

Advantages
1. Ocean thermal energy is a renewable, clean natural resource available in abundance.
2. It is pollution-free and has no greenhouse effects.
3. It is a good source of freshwater and portable water.

Disadvantages

1. High cost: Electricity generated by OTEC plants is more expensive than electricity produced by chemical and nuclear fuels.
2. Complexity: OTEC plants must be located where a difference of about 20°C occurs year round. Ocean depths must be available fairly close to shore-based facilities for economic operation. Floating plant ships could provide more flexibility.
3. Acceptability: For the large-scale production of electricity and other products, OTEC plants are poorly acceptable due to their high costs.
4. Ecosystem damage: It is obvious by setting OTEC plants.
5. Lower efficiency: A higher temperature difference between ocean surface warm water and cold deep ocean water is required for highly efficient operation of plant.

Benefits as a Measure of the Value of OTEC

Economic and other benefits are the value of OTEC plants. These include the following:
1. It is a clean, renewable natural resource available in plenty.
2. It has no environmental problems and greenhouse effects.
3. It is a source of base load electricity and fuels such as hydrogen, methanol, and ammonia.
4. It provides freshwater for drinking, agriculture, and industry.
5. It encourages chilled agriculture and aquaculture.
6. Self-sufficiency, no environmental effects, and improved sanitation and nutrition are the added benefits for island.

Review Questions

1. What is Carnot cycle of OTEC.
2. Give any 2 applications of OTEC.
3. List the advantages of OTEC.