OCEAN THERMAL ENERGY

CONVERSION SYSTEM (OTEC)

INTRODUCTION

- The ocean can produce two types of energy: thermal energy from the sun's heat, and mechanical energy from the tides and waves
- The ocean is the world’s largest solar collector (60 million km^2)
- One fourth of $1.7x10^{17}$ W of solar energy absorbed by sea.
- Natural temperature difference occurs in tropical subtropical oceans of the world
- Temp Difference: 25^0C (surface) and 5^0C (1000 m depth)

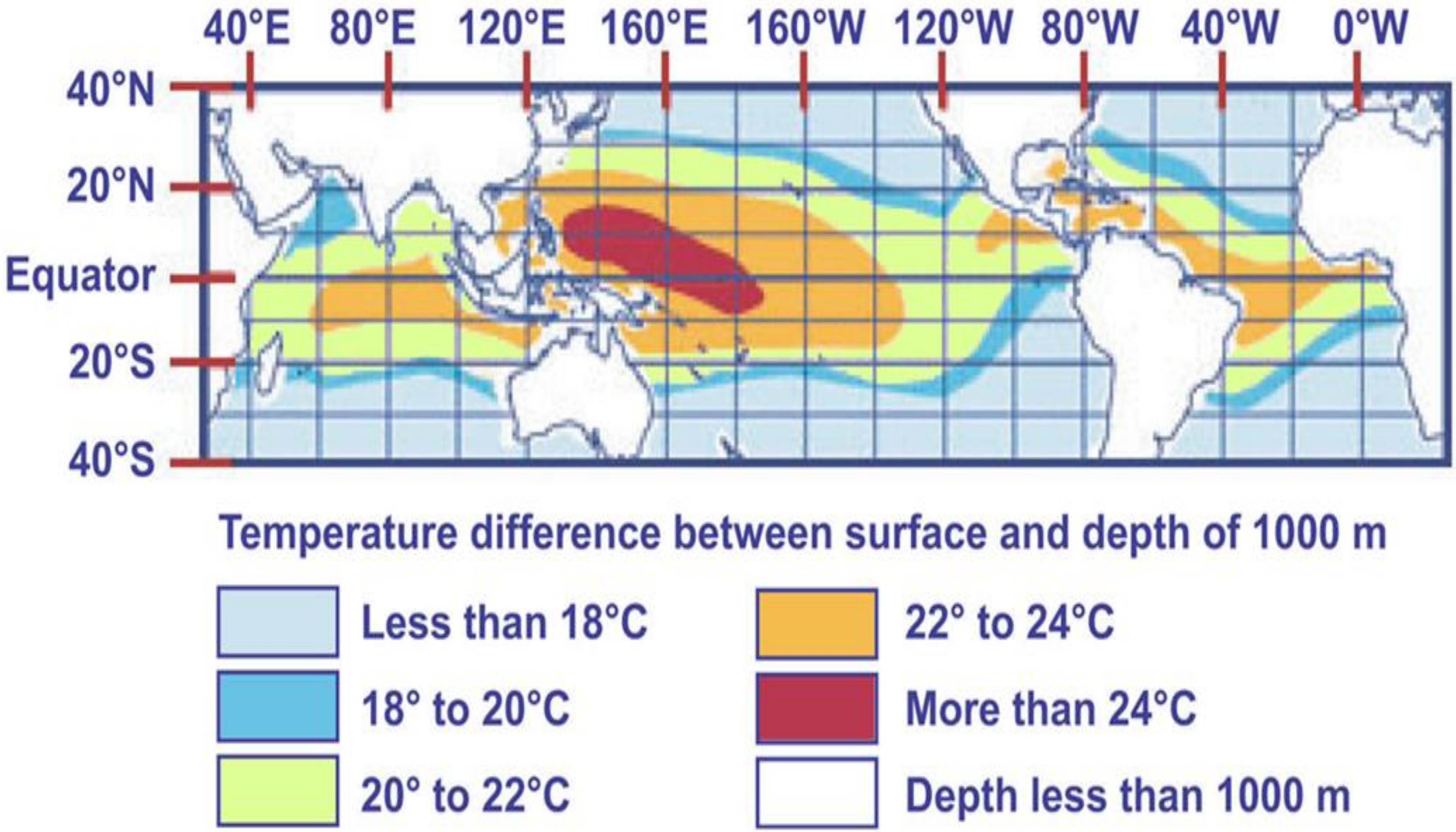
* OTEC concepts exploits this temperature differences to drive power plants

* First proposed by D’ Arsonval in 1881

* Claude first experimentally tested and built open OTEC plant in Cuba in 1930 (22 kW generating capacity)

* OTEC works best when the temperature difference between the warmer, top layer of the ocean and the colder, deep ocean water is about 20°C
* These conditions exist in tropical coastal areas.

Background Information



* Equatorial waters, lying between 10°N and 10°S are adequate

* 80% of the energy obtained from the sun is absorbed in the upper 10 m.

* Heat content equal to about 250 billion barrels of oil.

* Ocean losses the heat through the emission of long wave radiation and evaporation

* Solar radiation penetrates the water surface is attenuated by absorption and conversion into heat.

TEMPERATURE VARIATION IN SEA

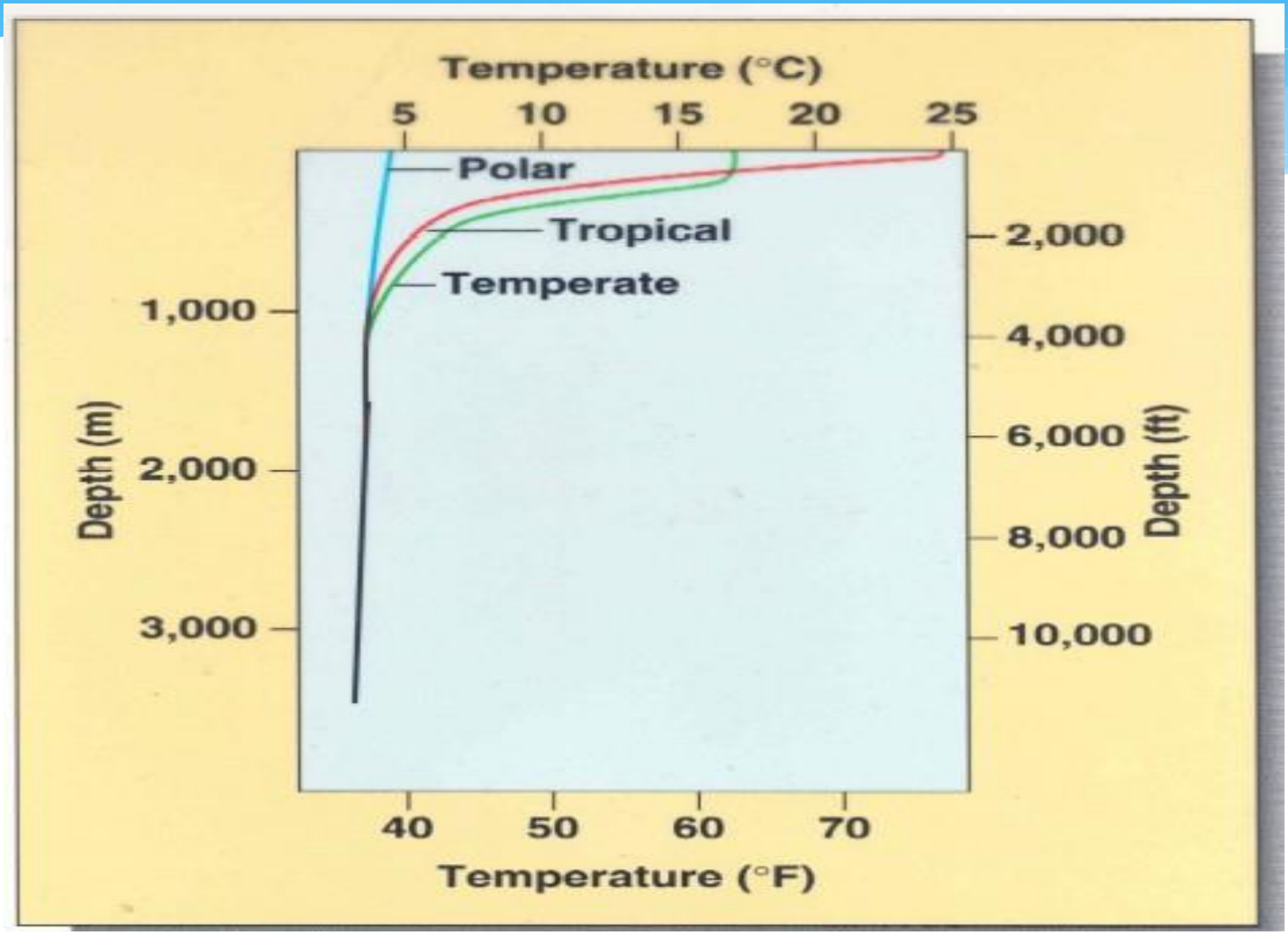
Absorption of solar radiation followed by Beer Lamberts law

$$-\frac{dI(y)}{dy} = \mu I \qquad I(y) = I_o \exp(-\mu y)$$

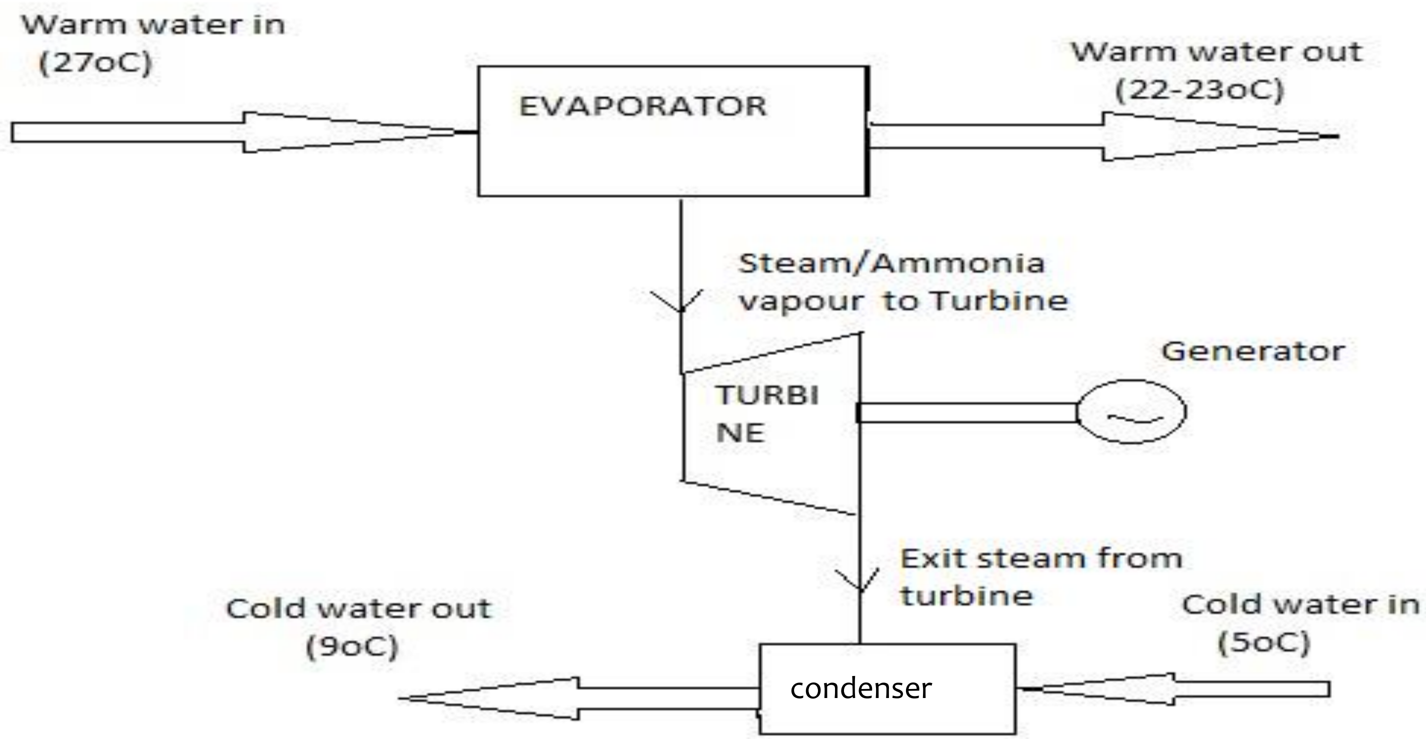
where, y = depth of water in m, I=Intensity of radiation W/m^2,
μ= Absorption coefficient

Nature of water	µ value/m
Clear fresh water	0.05
Turbid fresh water	0.27
Very salty water	0.50

TEMPERATURE VARIATION ALONG DEPTH



SCHEMATIC ARRANGEMENT OF OTEC SYSTEM



OTEC POWER GENERATION

OTEC CLASSIFICATIONS

* Based on construction

  Land based

  Shelf based

  Floating platform

* Based on working cycle
  * Open cycle OTEC
  * Closed cycle OTEC
  * Hybrid cycle

Based on construction

* Land based: Plants constructed on or near land do not require sophisticated mooring, lengthy power cables
* Shelf based: OTEC plants can be mounted to the continental shelf at depths up to 100 meters (330 ft)
* Floating: Floating OTEC facilities operate off-shore

OPEN CYCLE OTEC

COMPONENTS OPEN CYCLE OTEC

- Flash evaporator (Spout evaporator)
  (0.0317 bar)

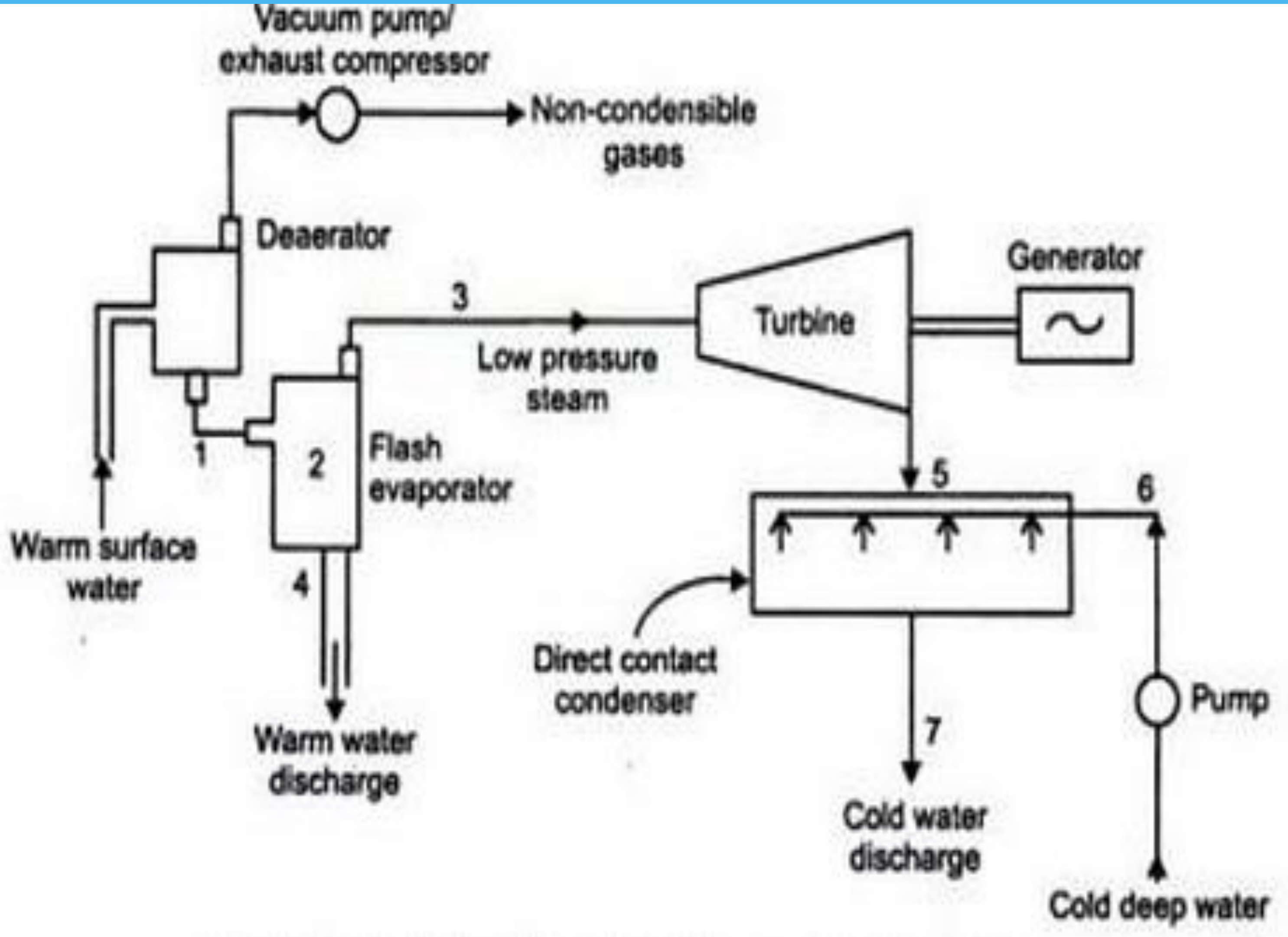
- Special low pressure Turbine (Radial inflow turbine)

- Condenser (0.017bar)

- Pumps

- Vacuum system

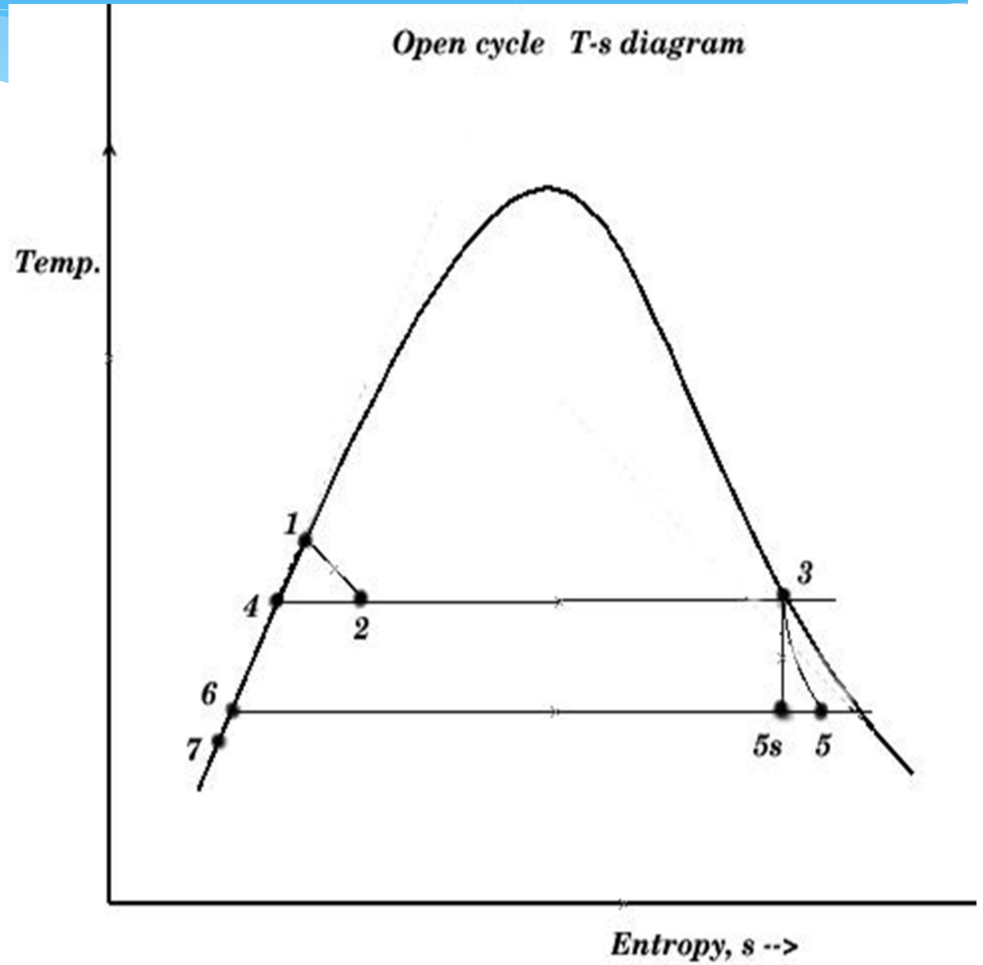
OTEC OPEN SYSTEM WORKING



- Surface sea water (27^0 C) pumped to flash evaporator
- Flash evaporator maintained at a pressure below the saturation pressure at 25^{o}C (0.0317 bar). Less than 0.5% of the mass of warm sea water entering the evaporator is converted into steam.
- Steam is dried and saturated steam is produced and warm water discharged back to ocean.
- Steam with low pressure and high specific volume is passed through a specially designed turbine (0.0317 bar, 43.4 m^3/kg)
- Exhaust steam gets condensed in a direct contact condenser (.017 bar, 10^{o}C)
- Cooling water taken from deep sea at 5^o C
- After condensation final saturation water discharged to the ocean

OTEC OPEN WORKING CYCLE (Claude cycle)

- Point 1 , 27^{o}C and saturation pressure of 0.0356 bar
- 1-2 throttling with constant enthalpy process
- Point 2 mixture of water and steam at low quality (0.0317 bar)
- 3- saturated vapour and at 4- saturated water discharged back to sea
- 5- exit of turbine contact with deep cold water at 7 and discharged at 6



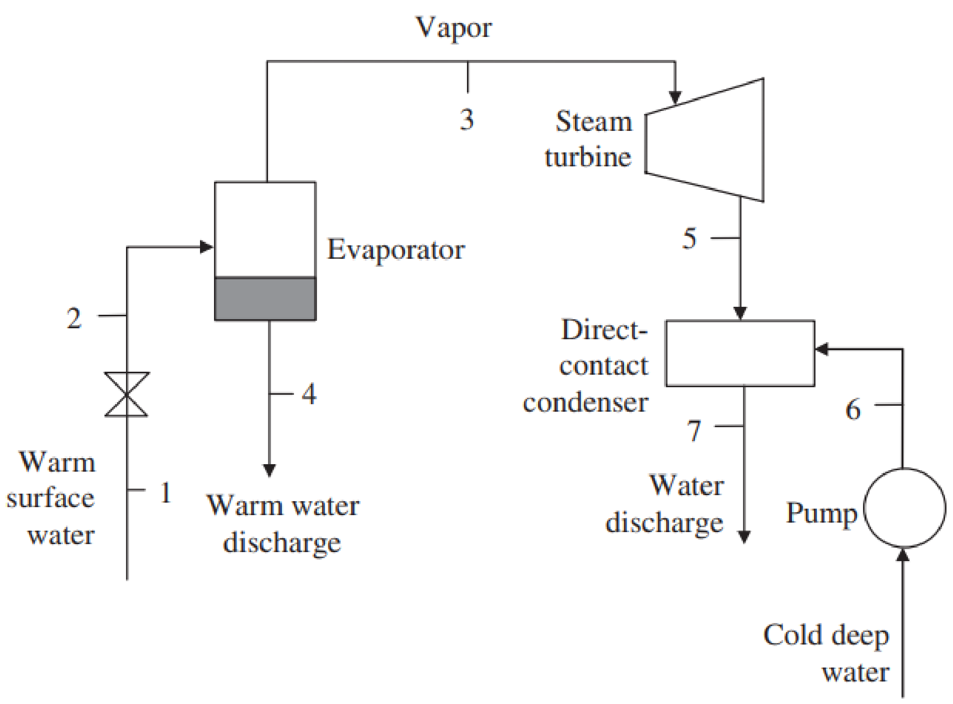
ADVANTAGES & DISADVANTAGES

- Advantages
- Open cycle OTEC eliminates expensive heat exchangers
- Bio-fouling control gets minimised
- Only working medium is water and no pollution by the leakage of binary fluid (mercury)
- Additional fresh water production is an added advantage
- CO_2 released for open cycle as 40g/kWh
- **Disadvantages**
- Turbine handle low pressure and high specific volume which leads to larger size of turbine
- Low thermal efficiency (3-4%)
- Deaerators or degasifiers used to eliminate dissolved gases , increases the input power.
- Too expensive compared to closed system by maintaining the vacuum

OPEN OTEC PROJECTS

* open-cycle OTEC system at Matanzas Bay, Cuba, in 1930. The system produced 22 kilowatts (kW)
* 1956: French researchers designed a 3-megawatt open-cycle plant for Abidjan on Africa's west coast.
* 1993: An open-cycle OTEC plant at Keayhole Point, Hawaii, produced 50,000 watts
* In 2002, India tested a 1 MW floating OTEC pilot plant near Tamil Nadu.
* In March 2013, Saga University with various Japanese industries completed the installation of a new OTEC plant.

An open-system OTEC plant operates with a surface water temperature of 30°C and a deep water temperature of 10°C. The evaporator pressure is 3 kPa and condenser pressure is 1.5 kPa. The mass flow rate of warm surface water entering the evaporator is 100 kg/s and the turbine has an isentropic efficiency of 85 percent. Determine (*a*) the mass and volume flow rates of steam at the turbine inlet, (*b*) the turbine power output and the thermal efficiency of the plant, and (*c*) the mass flow rate of the cold deep water. Neglect pumping power and other internal or auxiliary power consumptions in the plant.



SOLUTION (*a*) We neglect kinetic and potential energy changes, and use ordinary water properties for ocean water. Water properties are obtained from Tables A-3 through A-5. We refer to Fig. 9-1 for state numbers. First, the properties of water at the evaporator are

$$\left.\begin{array}{l} T_1 = 30^\circ\text{C} \\ x_1 = 0 \end{array}\right\} h_1 \cong h_{f\,@\,30^\circ\text{C}} = 125.74\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 3\ \text{kPa} \\ h_2 = h_1 = 125.74\ \text{kJ/kg} \end{array}\right\} \begin{array}{l} T_2 = 24.08^\circ\text{C} \\ h_4 = h_{f\,@\,3\,\text{kPa}} = 100.98\ \text{kJ/kg} \\ h_3 = h_{g\,@\,3\,\text{kPa}} = 2544.8\ \text{kJ/kg} \\ s_3 = s_{g\,@\,3\,\text{kPa}} = 8.5765\ \text{kJ/kg}\cdot\text{K} \\ v_3 = v_{g\,@\,3\,\text{kPa}} = 45.654\ \text{m}^3/\text{kg} \end{array}$$

The quality of water at state 2 is

$$x_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{125.74 - 100.98}{2544.8 - 100.98} = 0.010132$$

The mass flow rate of steam at the turbine inlet is

$$\dot{m}_3 = x_2 \dot{m}_1 = (0.01013)(100\ \text{kg/s}) = \mathbf{1.0132\ kg/s}$$

The volume flow rate of steam at the turbine inlet is

$$\dot{V}_3 = v_3 \dot{m}_3 = (45.654\ \text{m}^3/\text{kg})(1.0132\ \text{kg/s}) = \mathbf{46.26\ m^3/s}$$

(*b*) The enthalpy at the turbine exit for the isentropic process is

$$\left.\begin{aligned} P_5 &= 1.5\ \text{kPa} \\ s_{5s} &= s_3 = 8.5765\ \text{kJ/kg}\cdot\text{K} \end{aligned}\right\} \begin{aligned} x_{5s} &= 0.97098 \\ h_{5s} &= 2453.1\ \text{kJ/kg} \\ T_{5s} &= 13.02°\text{C} \end{aligned}$$

Using the definition of the turbine isentropic efficiency, the actual enthalpy at the turbine exit is determined as

$$\eta_{\text{turb}} = \frac{h_3 - h_5}{h_3 - h_{5s}} \longrightarrow 0.85 = \frac{2544.8 - h_5}{2544.8 - 2453.1} \longrightarrow h_5 = 2466.9\ \text{kJ/kg}$$

The specific volume at the turbine exit is

$$\left.\begin{aligned} P_5 &= 1.5\ \text{kPa} \\ h_5 &= 2466.9\ \text{kJ/kg} \end{aligned}\right\} v_5 = 85.90\ \text{m}^3/\text{kg}$$

The power output from the turbine is

$$\dot{W}_{out} = \dot{m}_3(h_3 - h_5) = (1.0132 \text{ kg/s})(2544.8 - 2466.9)\text{kJ/kg} = \mathbf{78.93\ kW}$$

The energy or heat input to the power plant can be expressed as the energy difference between the states 1 and 4. Then,

$$\begin{aligned}\dot{Q}_{in} &= \dot{m}_1 h_1 - \dot{m}_4 h_4 \\ &= (100 \text{ kg/s})(125.74 \text{ kJ/kg}) - (100 - 1.0132 \text{ kg/s})(100.98 \text{ kJ/kg}) \\ &= 2578 \text{ kW}\end{aligned}$$

The thermal efficiency of the plant is then

$$\eta_{th} = \frac{\dot{W}_{out}}{\dot{Q}_{in}} = \frac{78.93 \text{ kW}}{2578 \text{ kW}} = 0.0306 \text{ or } \mathbf{3.06\%}$$

(c) Direct-contact condenser is basically a mixing chamber. The steam leaving the turbine is mixed with cold deep water so that the water at state 7 is saturated liquid at 1.5 kPa pressure. The enthalpies of liquid water at states 6 and 7 are

$$h_6 \cong h_{f\,@10^\circ\mathrm{C}} = 42.022\ \mathrm{kJ/kg}$$

$$h_7 \cong h_{f\,@1.5\ \mathrm{kPa}} = 54.688\ \mathrm{kJ/kg}$$

Then, the mass flow rate of cold deep water is determined from an energy balance to be

$$\dot{m}_5 h_5 + \dot{m}_6 h_6 = \dot{m}_7 h_7$$

$$(1.0132\ \mathrm{kg/s})(2466.9\ \mathrm{kJ/kg}) + \dot{m}_6(42.022\ \mathrm{kJ/kg}) = (\dot{m}_6 + 1.0132\ \mathrm{kg/s})(54.688\ \mathrm{kJ/kg})$$

Solving this equation gives

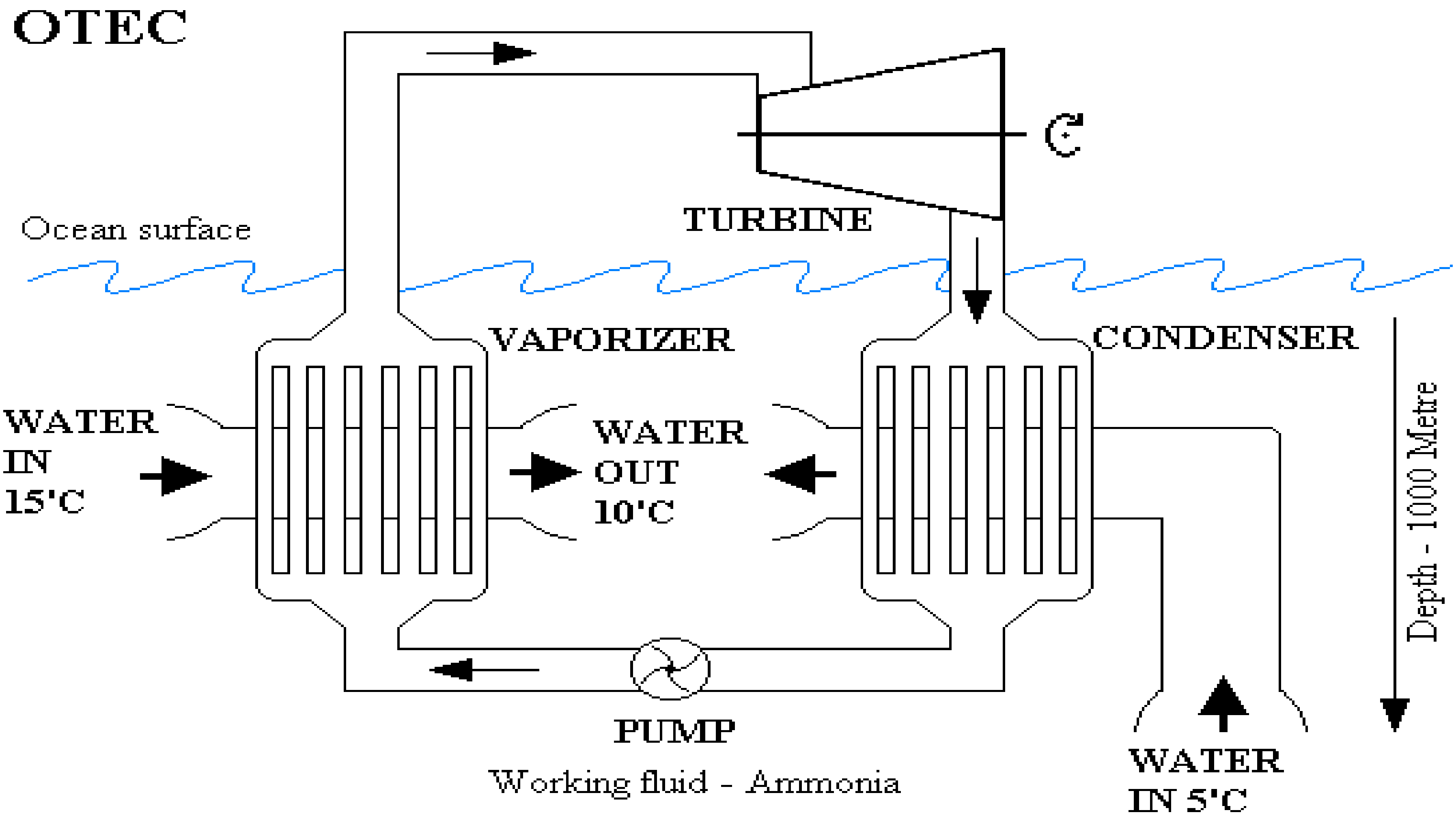
$$\dot{m}_6 = \mathbf{193\ kg/s}$$

CLOSED CYCLE

COMPONENTS

* Evaporator
* Working fluid like NH_3, Propane, R22
* Turbine
* Condenser
* Pumps

CLOSED CYCLE

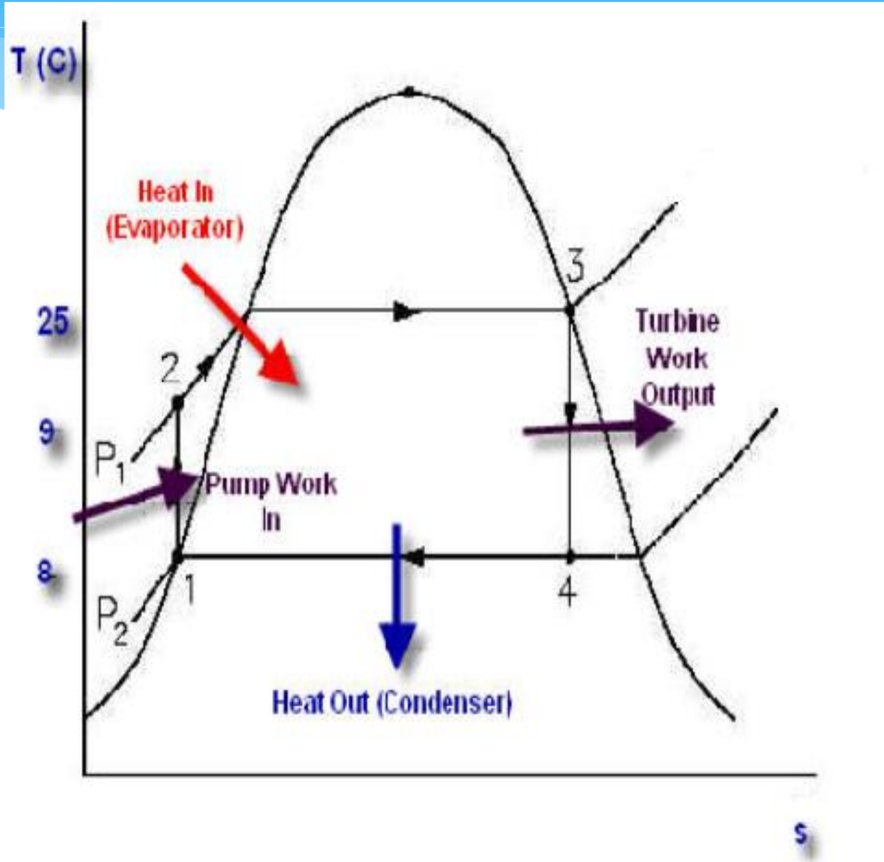


CLOSED CYCLE

* Ammonia, R22, Propane etc… low temperature boiling liquids are working fluids
* Warm surface sea water passed through evaporator with the help of pump
* In the evaporator working fluid (ammonia) gets heated at high pressure and become vapour (8.96 bar)
* The vapour drives the turbine and after expansion cooled in condenser in which cold sea water circulates
* The condensing liquid is then pumped back to evaporator thus closing the cycle

OPERATING CYCLE (Rankine cycle)

- 1-2 Pump used to pressurize liquid to higher pressure
- 2-3 Heat addition to evaporate ammonia
- 3-4 Work produced from expansion through turbine
- 4-1 Heat extraction in condenser, the ammonia become liquid.



ADVANTAGES &DISADVANTAGES

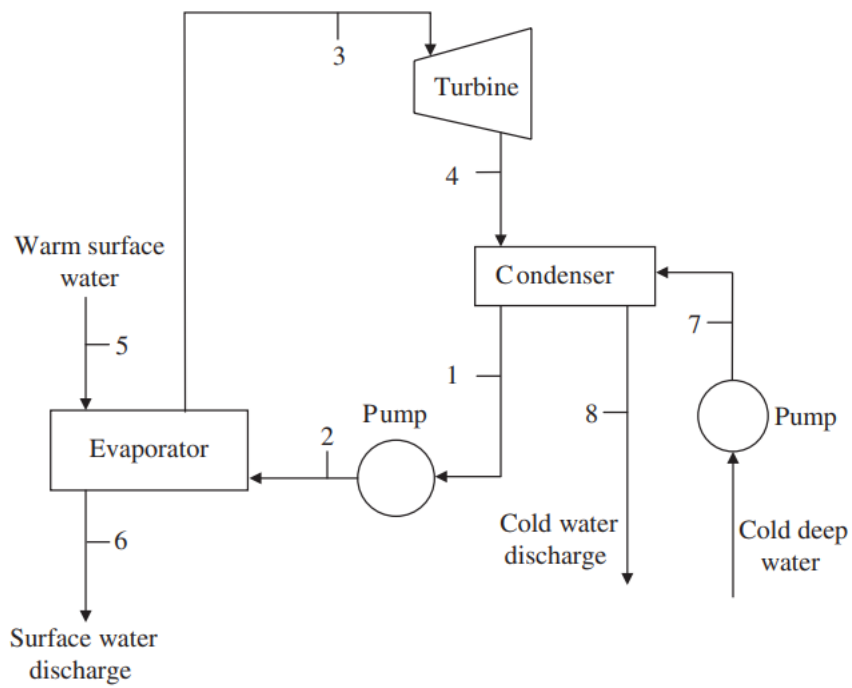
Advantages

* Closed system is compact as compared to open cycle for the same power output
* The closed-cycle can also be designed using already existing turbo machinery and heat exchanger designs.
* No need of vacuum maintenance in evaporator
* No need of deaerator or degasifier

Disadvantages

* Expensive heat exchangers are required
* Bio fouling is a majour issue which require monthly cleaning by mechanical, chemical etc..
* Leakage of working fluid causes serious environmental issues

9-13 An OTEC power plant operates on a closed-cycle with a surface water temperature of 30°C and a deep water temperature of 5°C. The working fluid is propane. Propane leaves the evaporator as a saturated vapor at 20°C and it condenses at 10°C. The surface water leaves the evaporator at 25°C and the cold water leaves the condenser at 8°C. The turbine has an isentropic efficiency of 85 percent and the power output from the turbine is 100 kW. Determine (*a*) the mass flow rates of surface water, deep water, and propane and (*b*) the thermal efficiency of the plant. Neglect pumping power and other internal or auxiliary power consumptions in the plant. The enthalpies of propane are: Pump and evaporator inlet $h_2 \cong h_1 = 223.32$ kJ/kg, evaporator outlet $h_3 = 581.85$ kJ/kg, turbine outlet $h_4 = 570.73$ kJ/kg.



H_2O

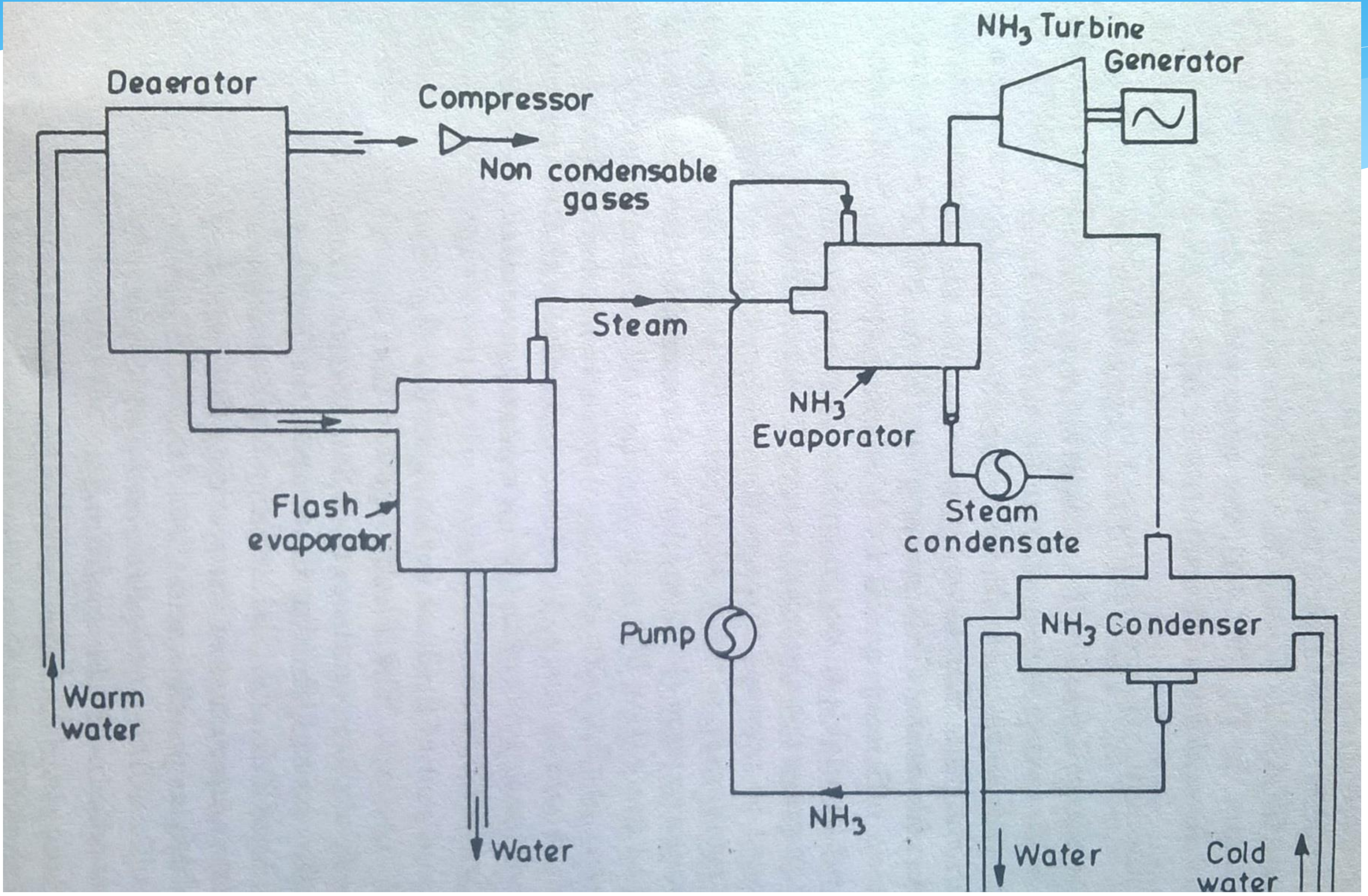
TABLE A-2 Properties of Saturated Water (Liquid–Vapor): Temperature Table

		Specific Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Temp. °C	Press. bar	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Temp. °C
.01	0.00611	1.0002	206.136	0.00	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	.01
4	0.00813	1.0001	157.232	16.77	2380.9	16.78	2491.9	2508.7	0.0610	9.0514	4
5	0.00872	1.0001	147.120	20.97	2382.3	20.98	2489.6	2510.6	0.0761	9.0257	5
6	0.00935	1.0001	137.734	25.19	2383.6	25.20	2487.2	2512.4	0.0912	9.0003	6
8	0.01072	1.0002	120.917	33.59	2386.4	33.60	2482.5	2516.1	0.1212	8.9501	8
10	0.01228	1.0004	106.379	42.00	2389.2	42.01	2477.7	2519.8	0.1510	8.9008	10
11	0.01312	1.0004	99.857	46.20	2390.5	46.20	2475.4	2521.6	0.1658	8.8765	11
12	0.01402	1.0005	93.784	50.41	2391.9	50.41	2473.0	2523.4	0.1806	8.8524	12
13	0.01497	1.0007	88.124	54.60	2393.3	54.60	2470.7	2525.3	0.1953	8.8285	13
14	0.01598	1.0008	82.848	58.79	2394.7	58.80	2468.3	2527.1	0.2099	8.8048	14
15	0.01705	1.0009	77.926	62.99	2396.1	62.99	2465.9	2528.9	0.2245	8.7814	15
16	0.01818	1.0011	73.333	67.18	2397.4	67.19	2463.6	2530.8	0.2390	8.7582	16
17	0.01938	1.0012	69.044	71.38	2398.8	71.38	2461.2	2532.6	0.2535	8.7351	17
18	0.02064	1.0014	65.038	75.57	2400.2	75.58	2458.8	2534.4	0.2679	8.7123	18
19	0.02198	1.0016	61.293	79.76	2401.6	79.77	2456.5	2536.2	0.2823	8.6897	19
20	0.02339	1.0018	57.791	83.95	2402.9	83.96	2454.1	2538.1	0.2966	8.6672	20
21	0.02487	1.0020	54.514	88.14	2404.3	88.14	2451.8	2539.9	0.3109	8.6450	21
22	0.02645	1.0022	51.447	92.32	2405.7	92.33	2449.4	2541.7	0.3251	8.6229	22
23	0.02810	1.0024	48.574	96.51	2407.0	96.52	2447.0	2543.5	0.3393	8.6011	23
24	0.02985	1.0027	45.883	100.70	2408.4	100.70	2444.7	2545.4	0.3534	8.5794	24
25	0.03169	1.0029	43.360	104.88	2409.8	104.89	2442.3	2547.2	0.3674	8.5580	25
26	0.03363	1.0032	40.994	109.06	2411.1	109.07	2439.9	2549.0	0.3814	8.5367	26
27	0.03567	1.0035	38.774	113.25	2412.5	113.25	2437.6	2550.8	0.3954	8.5156	27
28	0.03782	1.0037	36.690	117.42	2413.9	117.43	2435.2	2552.6	0.4093	8.4946	28
29	0.04008	1.0040	34.733	121.60	2415.2	121.61	2432.8	2554.5	0.4231	8.4739	29
30	0.04246	1.0043	32.894	125.78	2416.6	125.79	2430.5	2556.3	0.4369	8.4533	30

HYBRID CYCLE

- In a hybrid, warm seawater enters a vacuum chamber and is flash-evaporated.
- The steam vaporizes the ammonia working fluid of a closed-cycle loop on the other side of an ammonia vaporizer.
- The vaporized fluid then drives a turbine to produce electricity.
- The steam condenses within the heat exchanger and provides desalinated water
- Attempt to combine the best features and avoid the worst features of both open and closed cycle

Hybrid Cycle



TECHNICAL ISSUES & PRACTICAL CONSIDERATIONS

Bio fouling

- The inside of the pipe wall deposited by marine organisms forms thick layer, which will increase the resistance to heat flow and thereby reduce the performance. Such bio-fouling is one of the major problems in OTEC design.

Pumping requirements

- Work is required to move large quantities of hot water, cold water and working fluid around the system against friction. This will have to be supplied from the gross power output of the OTEC system,

PRACTICAL CONSIDERATIONS

A number of practical, engineering and environmental difficulties

1. <u>The platform</u>

The construction of the platform is a major difficulty.

2. <u>Construction of the cold water pipe</u>

The pipe is subject to many forces in addition to the stresses at the connection. These include drag by currents, oscillating forces, forces due to harmonic motion of the platform, forces due to drift of the platform and the dead weight of the pipe itself

3. <u>Link to the shore</u>

High voltage, large power, submarine cables, standard components of electrical power transmission systems, are expensive

PRACTICAL CONSIDERATIONS

- 4.The turbine
- Even though the turbine has to be large, standard designs can be used.

5. Choice of working fluid

- There are many common fluids having an appropriate boiling point, e.g. ammonia, Freon or water, but many of these are environmentally unacceptable, since leaks increase greenhouse or ozone-depleting gases

ADVANTAGES OF OTEC

* OTEC uses clean, abundant, renewable and natural resources to produce electricity.
* Reduces Carbon footprint by providing clean cost effective energy
* Produces desalinated water for industrial, agricultural and residential uses
* Enhances energy independence
* Has potential to mitigate green house gas emissions from burning fossil fuels
* Mixing of deep ocean water with shallower water brings up nutrients and makes them available to shallow water life

DISADVANTAGES

* The thermal gradient gives OTEC a typical energy conversion of 3 to 4%
* Compensate for its low thermal efficiency, OTEC has to move a tremendous amount of water.
* It takes 20 to 40% of the power generated to pump the water
* Another disadvantage of a land-based plant would be the discharging of the cold and warm seawater
* Mixing of deep ocean water with shallower water unbalance the ecological system around the power plant.
* Technical issues like dissolved gases, microbial fouling, sealing etc….