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Study on the Cost Effective Ocean Thermal Energy Conversion Power Plant

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Abstract

Ocean Thermal Energy Conversion (OTEC) is a promising renewable energy resource from the ocean near equator that had been neglected for decades due to its enormous capital cost. The technologies that are developed for oil and gas industry for deep water applications could be adopted into OTEC power plant and the capital cost could be reduced by fifty percent than the estimation using conventional OTEC technology. This paper addresses a new OTEC technology for the OTEC power plant. Design and workability of the individual components of the new OTEC engine is shown. The global architecture of the power plant is illustrated. The engineering analyses studied show that the new OTEC power plant is feasible to construct and the cost analysis studied shows that the new OTEC power plant is viable for applications.

Introduction

Clean renewable energy is a necessity of today that more and more people are aware of. Countries all over the world support this effort, considering that there is no carbon dioxide emission and no environmental impact. Ocean Thermal Energy Conversion (OTEC), as one of the renewable energy source, is very attractive because no fossil fuel needed and is available with unlimited large quantity. USA is now spending several billion dollars for various renewable energy source projects. The operating cost of most of the renewable energy is very low but the capital cost is enormous. Because of the environmental nature, OTEC is very stable and reliable energy resource for tropical islands like Hawaii. The main challenge is to make the OTEC electric power generation cost-effective and comparable to the nuclear energy source.

OTEC

OTEC is a method for generating electricity utilizing the source of stored solar energy available in the ocean near the equator, where the surface water temperature is about 25 degree C or more due to heat from sunlight and at 3000 ft depth the water temperature is about 4 degree C. A thermodynamic heat transfer method is used to convert the thermal energy to run the gas turbine. Ammonia gas is used as working fluid for the OTEC engine. Heat transfer is the major engineering task to be involved on the success of any efficient OTEC power plant. Conventional OTEC does the heat transfer effort on the top of the platform deck. The amount of water needed to cool the working fluid, ammonia, is enormous. There is a cold water pipe in the conventional OTEC that is used to bring the cold water from 3000 ft down to the free surface. Similarly the gas heating process, where the surface warm water is used in the evaporator, faces the similar problem. Enormous amount of heavy equipment for handling large volumes of water on the surface of floating vessel has increased the vessel size and consequently the capital cost was very high in the conventional OTEC. This technology is addressed in Reference 1.

New OTEC

This paper addresses an OTEC engine that uses new technologies like sub-sea condenser, sub-sea pump, submerged evaporator and independent floating-pipe buoy platform to transport working fluid from turbine outlet to the subsea condenser. Oil and gas field has offered innovative and cost effective solutions for deepwater applications. The technologies developed for deepwater are well proven and are working in water depth over 6,000 ft. OTEC water depth is only 1,500 ft, which is much smaller than the depth capabilities of today oil and gas field operations. The new OTEC design uses subsea solutions for the heat conduction problem. The condenser is located subsea area where the enormous cold water is available without the need of storage. The condenser is directly exposed to the underwater environment with 4 degree C. The condenser is designed for 1,500 psi water depth pressure for its structural strength integrity. Subsea condenser is tested for flow simulation and heat conduction problem for workability by using modern ANSYS Computational Flow Dynamic (CFD) engineering software. The equipments and the piping are tested for 1,500 psi water pressure to work at 3,000 ft depth.

An innovative subsea pump is also designed for the new OTEC. A supporting vessel is designed such that the evaporator could be placed submerged in the telescopic keel-tank. The keel-tank is a part of the supporting vessel thus it does not cost extra for the support of the submerged evaporator of the new OTEC. The problems resulted with subsea condenser are solved cost effectively in this paper with different innovative OTEC equipments. The paper aims at coming up with the first 100 mega watt output power plant that could be operated in the State of Hawaii deep water. The new OTEC technology drastically removed the massive cold water pipe from the conventional OTEC technology and reduces the cost significantly. This new OTEC technology is explained in Reference 2, emphasizing with various floating support vessel possibilities.

New OTEC-Engine

For the purpose of demonstration, a simplified OTEC cycle is used with the following assumptions. Sea bed is 3000 ft below sea level; evaporator and expander are located at sea level; condenser and condensed ammonia pump are located at seabed; turbine operating condition is matched closely to the inlet and outlet conditions of an available General Electric (GE) turbine; power produced from the turbine is fixed at 20,000 kW. A pipe length equivalent of 3500 ft is used for turbine exhaust and condensed ammonia is used for pump hydraulic calculations. An 84” ID for turbine exhaust and 24” ID for pump discharge are used as specified by GE for their turbine specification. However, actual piping design could be made of several smaller pipelines running in parallel. Those details are studied in the flow simulation problems in another section of this paper. Both turbine exhaust line and condensed ammonia pump discharge line are also assumed to have heat losses. Both lines’ outlet and inlet temperature differences are to be 0.5^{o}C to approach “isothermal”. It is assumed that the condensed ammonia pump discharge control valve has 15 psi pressure drop. The new OTEC cycle is shown in Figure 1 and the Heat balance obtained in the thermodynamics are show in Table 1. The heat energy balance is obtained as given in Table 2. The turbine inlet and outlet conditions are obtained for 20 MW power output capacities.

An OTEC engine with subsea condenser located at 3000 ft seabed situation is compared with conventional OTEC, as shown in Table 3. The power consumption on the condensed ammonia pump is about 33.5% of power generated from the turbine expander. In order to minimize this power loss, two pumps are used one underwater and a second one above water. The submerged pump adequately transports the condensed working fluid to the evaporator at the top. Another axial pump is placed above water to suck the ammonia gas from the evaporator and send that to the turbine for the required input condition. This method reduces the total power consumption needed for the submerged pump. A new innovative displacement type pump is designed for this subsea application of the new OTEC power plant. The second pump located above water could be conventional pump available from standard vendors with large volumetric flow. In order to improve the performance of the turbine power output, a direct Sun heat chamber is used before the turbine inlet and the new thermodynamic cycle with these changes is named DeSI-OTEC as shown in Figure 2.

Description	**101-Expander-Inlet**	**102-Expander - Outlet**	**104-Condenser-Outlet**	**108-Evaporator-Outlet**	**106-Evaporator - Inlet**
Vapor Fraction	1	0.99	0	1	0
Temperature [F]	84	56	39	84	43
Pressure [psig]	128	85	72	128	954
Molar Flow [lbmole/hr]	237,632	237,632	237,632	237,632	237,632
Mass Flow [lb/hr]	4,046,865	4,046,865	4,046,865	4,046,865	4,046,865
Heat Flow [Btu/hr]	**- 4,715,261,097**	**- 4,783,561,097**	**- 7,011,238,524**	**- 4,715,261,097**	**- 6,988,362,991**

Table 1 HEAT AND MATERIAL BALANCE

Description	**Q-Expander**	**Q-Condenser**	**Q-Pump**	**Q-Evaporator**	**Q-P 100**	**Q-P 101**
Heat Flow [MMBtu/hr]	68	2,258	23	2,278	-46	-11
Power (kW)	19,998	661,270	6,698	667,007	-13,574	-3,125

Table 2 ENERGY STREAMS

Inlet Conditions	**Sub-Sea Condenser OTEC**	**Conventional OTEC**
Mass flow (kg/hr)	1,836,000	1,835,646
Pressure (barG)	9.848	9
Temperature (^{o}C)	29	29
Inlet Volume (Am3/hr)	251,993	247,626
Discharge Conditions		
Pressure (barG)	6.874	6
Temperature (^{o}C)	13.56	14.2
Adiabatic/Polytrophic Efficiency (%)	83.225 / 82.926	84%
Outlet Volume (Am3/hr)	344,503	338,153
Power generated (kW)	20,020	20,000

Table 3 TURBINE INLET AND OUTLET CONDITIONS

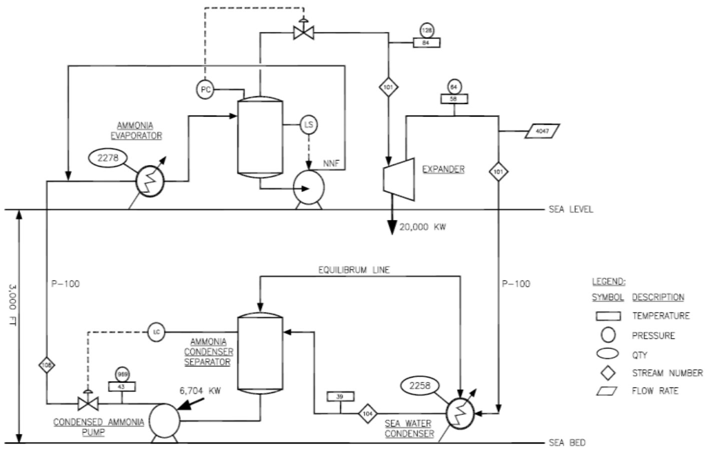

Figure 1: Simplified OTEC Engine with Subsea Condenser

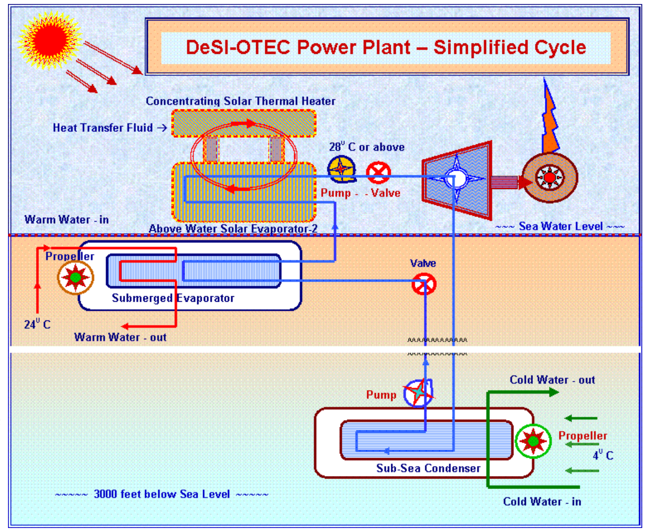

Figure 2: A New OTEC Engine with Subsea Condenser

Subsea Pump

A dedicated subsea pump is designed for the new OTEC engine. A 3 dimensional view, a cross section at discharge stroke and a detail drawing with labels of parts of the subsea pump are shown in Figure 3 (a, b & c) as a group. The subsea pump is designed innovatively with two chambers, one with large size ammonia tank for transporting the condensed working fluid from the subsea condenser to the evaporator and another with small size water tank for driving the piston hydraulically. The ammonia chemical tank is designed larger in size with 4.5 ft diameter bore for more volumetric flow and the water tank is designed smaller with 2.5 ft diameter bore for smaller volumetric displacement. The piston in the chemical chamber (ammonia) and the piston in the water chamber are welded at both ends to a hollow cylinder that rides over a circular solid rod inside. The solid rod is welded on both ends to the two chambers' edge walls. The chamber end walls are designed convex outside to take external water pressure load of 1500 psi. A stronger spring is placed in the chemical side of the chamber and a weaker spring is placed in the water side of the chamber for operational stability. The piston in the water chamber is driven by the high pressure water pump placed on top of the platform deck and is connected to the water chamber by an inlet pipe as shown in Figure 3. The maximum piston stroke distance is 12 inches and equal for both the chambers.

The water is pumped inside the water chamber with fluctuating pressure to drive the subsea pump. When water is supplied with pressure into the water chamber, it moves the piston from left to right side. Correspondingly the piston on the chemical side is moved in the same direction. The check valves provided radially on the surface of the larger chamber open-up and the condensed ammonia is sucked into the discharge side (right side) of the larger chamber. During the suction stroke, the spring on the larger ammonia chamber is compressed to maximum. When the pressure on the water inlet pipe is reduced to normal, then the piston is designed to slide back from right to left by the reaction of the larger spring force.

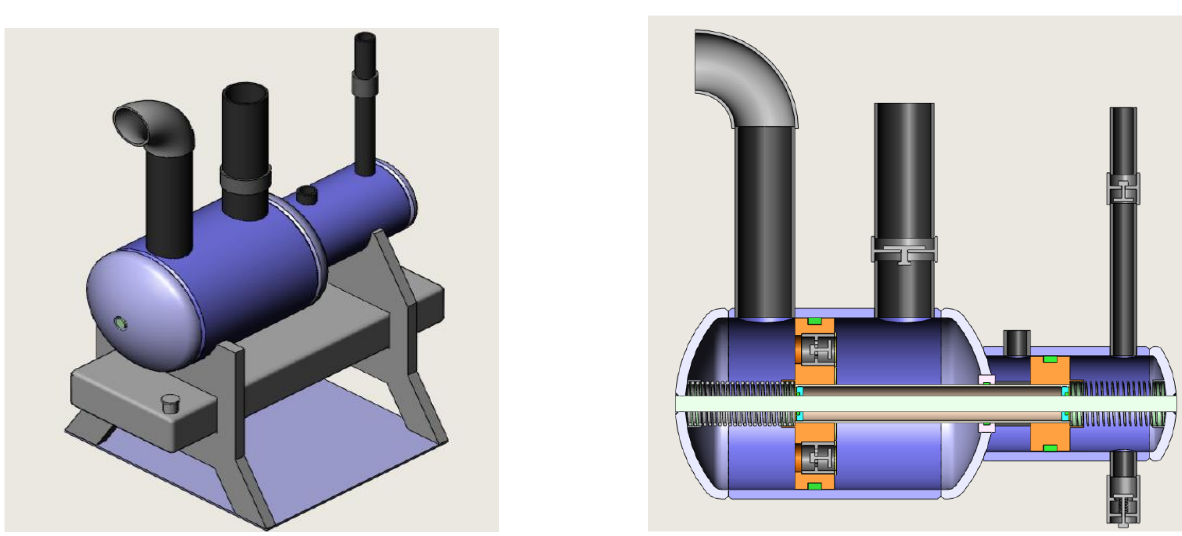

Figure 3 (a & b): Subsea Displacement Pump - shown in Three Different 3D and 2D Views

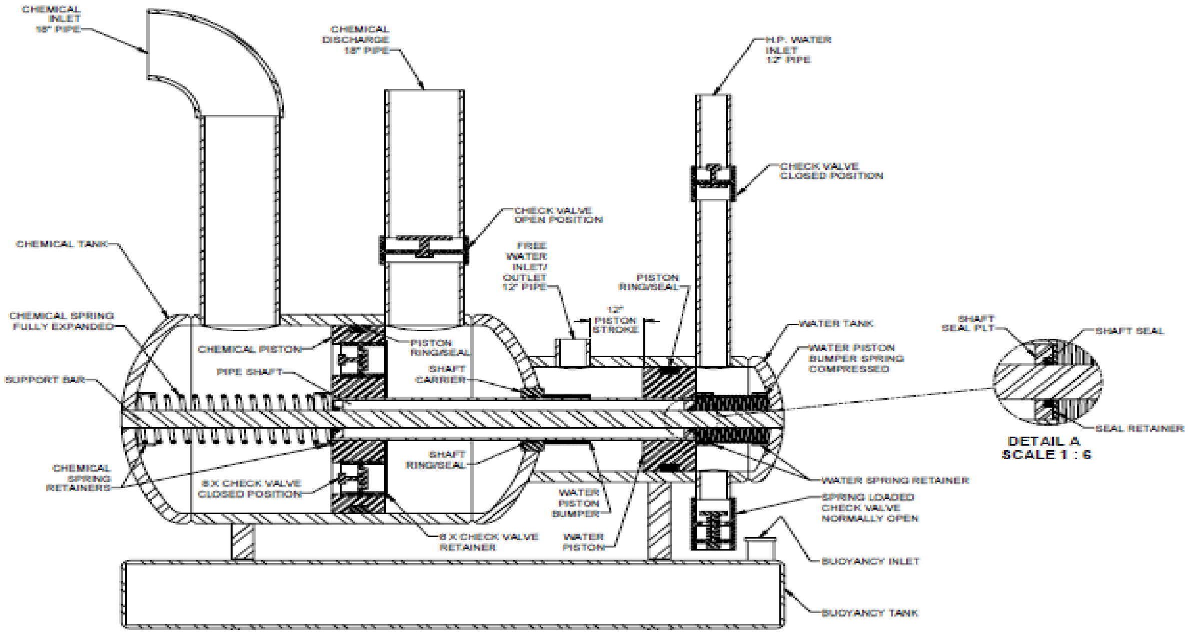

Figure 3 (c): Subsea Displacement Pump - shown in Three Different 3D and 2D Views

Several required check valves are used for the operation of appropriate pumping mechanism. The chemical chamber is designed for 1500 psi external hydraulic pressure at 3000 ft water depth with zero internal pressure. The water chamber is filled with water such that the internal and the external pressures are equal. A spring loaded check valve is used on the driving side of the water chamber for applicability. When the internal pressure exceeds the external pressure, then the valve closes and the piston drives. As the piston in the ammonia chemical chamber moves back and forth, the condensed ammonia is being sucked from the subsea condenser and moved to the other side with the help of the check valves provided on the piston surface. The discharge stroke is shown in the 3D cross-section view and the suction stroke is shown in the 2D-detail drawing. The mass flow of the working fluid from turbine output is 4046885 lb/hr. The gallons per minute (gpm) of the liquid ammonia fluid required to be pumped up by the subsea pump is 11852.52. The specific gravity of liquid ammonia multiplied by the gpm volume flow rate and height in feet, divided by 3960 would give the Horsepower required for the ammonia liquid to be pumped. A minimum of 4.6 MW power is required for the operation of this pump. In order to reduce the water volumetric flow, inner bore diameter of the water chamber is reduced. The pump could be designed for a rate of 14 strokes per minute with 2200 psi water pressure at the water inlet at the top of the deck. Thus the control of the operation of the subsea pump is feasible from the deck. The water chamber is designed for 2300 psi additional internal pressure.

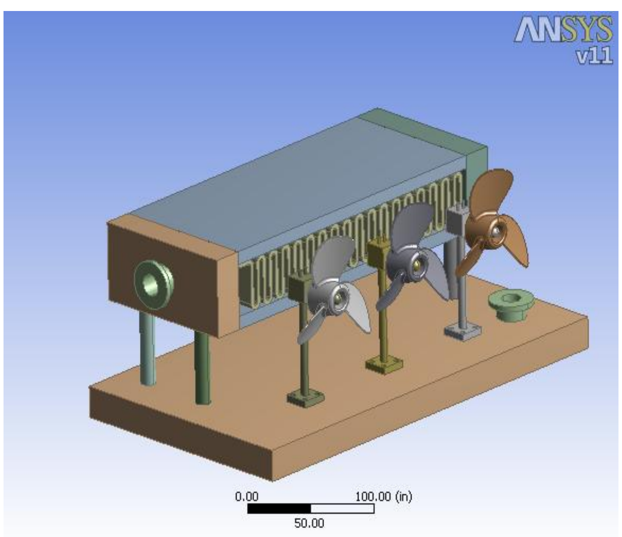

Figure 4: Subsea Condenser with Propellers

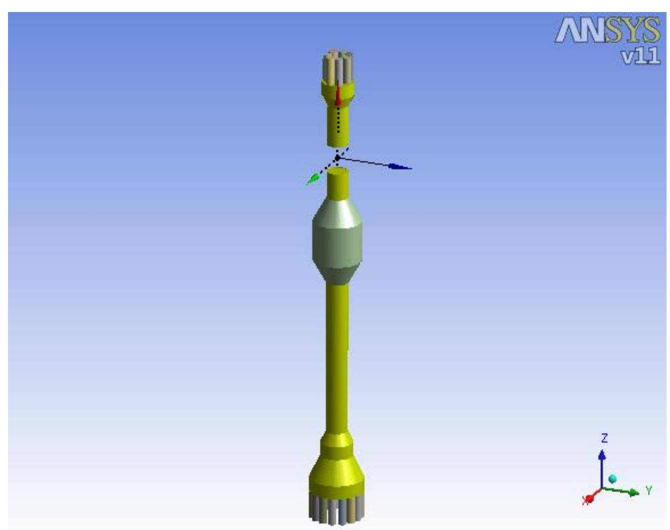

Figure 5: Independent Vertical Float Buoy

Subsea Condenser

A dedicated sub sea condenser is designed for the new OTEC engine. The condenser has inlet and outlet tanks. For efficient condensation of ammonia by cooling, a shell type condenser is used underwater and is shown in the Figure 4. Thin rectangular tubes are bent and placed between the inlet and the outlet tanks. The rectangular tube is designed with a narrow gap of 3 inch width. The tube is internally supported with vertical plates to withstand hydrostatic outside water pressure of 1500 psi. The spacing between the tube's bend is designed adequate for the surrounding sea water to flow naturally in between without resistances. Several electric propellers (Figure 4) are mounted on the other side of the condenser such that a stream of cold water flow is induced from one side to the other of the condenser through the designed spacing between the tube bends. These sub sea propellers that will induce the flow are operated hydraulically from the platform deck top through flexible hoses.

The structural integrity of the subsea condenser is verified for 3000 ft water depth external pressure application. For efficient heat conduction, aluminum is used as the material for the subsea condenser tubes. The mass flow and the heat conduction problems are solved with the ANSYS Computational Flow Dynamic (CFD) program. The results of the analysis are illustrated in the following section of this paper. Similar design concept is applied for the submerged evaporator situated closer to the free surface. The CFD and the heat conduction studies are carried out for the evaporator.

Simulation of Ammonia Flow and Heat Conduction

This section of the paper presents the results of CFD and heat transfer analyses for the subsea condenser and submerged evaporator using ammonia as the working fluid and the surrounding sea water as the cooling or heating media fluid. First CFD modeling was performed to study the flow behavior of the ammonia gas from the turbine to the top of the vertical pipe-buoy though smaller size pipes with the use of a manifold at the turbine outlet and at the top of the vertical pipe buoy. ANSYS FLUENT software was used for this CFD simulation. The results were used to obtain the optimum geometry of the inlet pipes. Ammonia vapor exits from the turbine through a pipe of 7ft diameter outlet at about 25 m/s. A manifold is required to split the ammonia flow into several smaller pipes which can be fed into the vertical pipe-buoy [Figure 5] at the top through a similar size manifold. Another manifold is designed at the bottom of the vertical pipe-buoy to distribute the ammonia gas into several smaller subsea condensers located on the seabed. The purpose of this second manifold is to reduce the velocity of the hot gas ammonia which is supplied to the condenser inlet for effective cooling. Both of these manifolds were modeled and geometries of these manifolds are shown in Figure 6 and in Figure 8.

A diffuser on the turbine side is used which expands from a 7ft diameter to a 12ft diameter outlet which is then branched out to six 3ft diameter pipes. The diffuser at bottom of the vertical pipe-buoy expands from the 8ft diameter to 12ft diameter and then to 20ft diameter outlet, where nineteen 3ft pipes are branched out to the several sub sea condensers. Isothermal CFD simulation was performed for these manifolds design to obtain flow pattern and pressure field. Figure 7 shows contours of velocity magnitude for the turbine side diffuser. Ammonia flow was uniformly divided into all the outlet pipes and the averaged velocity in each pipe was about 25 m/s. Figure 9 shows contours of velocity magnitude for the bottom diffuser where the average velocity in each outlet pipe is about 7.5 m/s. Pressure drop for these two manifolds design are insignificant (~0.018 – 0.04 bar). A simplified analysis of the heat transfer problem was performed with straight tubes for the subsea condenser to study its efficiency with the assumption of $4^{o}C$ constant outside temperature condition. It was discovered that straight tubes will not provide enough residence time and surface area for heat transfer to ammonia vapor. To increase the surface area as well as residence time, U-bends were introduced in the design of these heat transfer tubes. 2D simulation of the cross-section of single tube was performed to optimize the inside gap of the flow and the spacing of U-bends in the tube. The objective was to obtain a target temperature around 4 to $5^{o}C$ at the outlet of the sub sea condenser with surrounding cold sea water.

A sensitivity analysis was performed to determine effect of the inlet gas velocity on performance of the heat transfer on the condenser tubes. Two different gaps, 3 and 4 inches, for the flow inside the tube and three different u-bend spacing for the tube were used for this study. The effect of three configurations of condenser tube on the temperature of the outlet working fluid is shown in Figure 10 as contour plots. By introducing more u-bends on each tube, the overall flow-path for the ammonia vapor and the total contact area of tube increases. This leads to more heat transfer and hence lowered the temperature at outlet. Figure 11 shows plot of outlet temperature for these different configurations of condenser tubes against the inlet velocity. It clearly shows that with higher inlet velocity, outlet temperature is higher as less heat transfer occurred. Also as spacing between u-bends is decreased, while keeping the total height same, there are more u-bends and more surface area for heat transfer and hence lower temperature at outlet. 3D simulation of one typical condenser tube was performed. The surrounding cold sea water stream perpendicular to the direction of the ammonia working fluid was included in this CFD heat conduction model. In previous 2D simulation, for simplicity, a constant $4^{o}C$ temperature was assumed at the outer surface of the condenser tube. By including the surrounding water flow in the 3D model, accurate calculation of convective heat transfer from water to condenser tube is achieved. Figure 12 shows the geometry of the 3D model for this simulation.

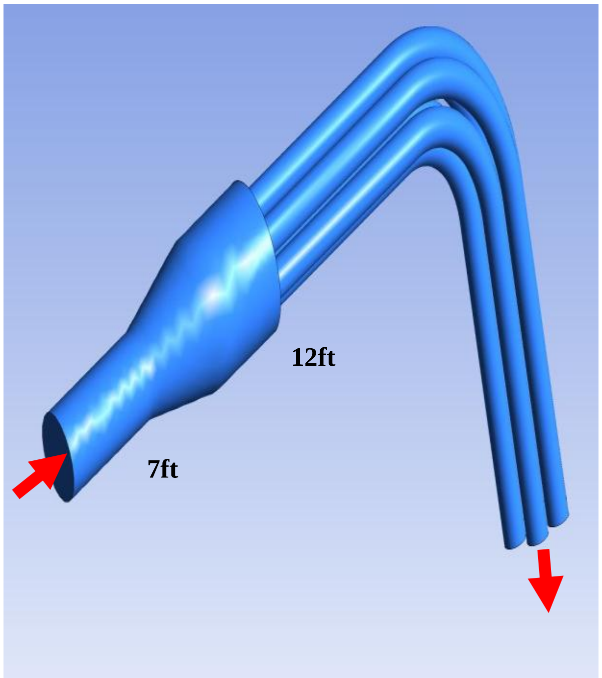

Figure 6: Turbine Side Manifold

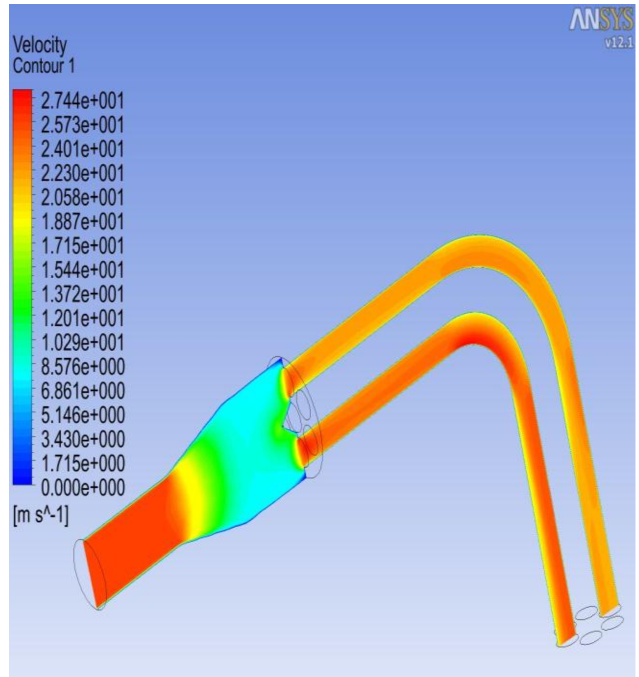

Figure 7: CFD Simulation of Turbine side Manifold - Contours of Velocity Magnitude

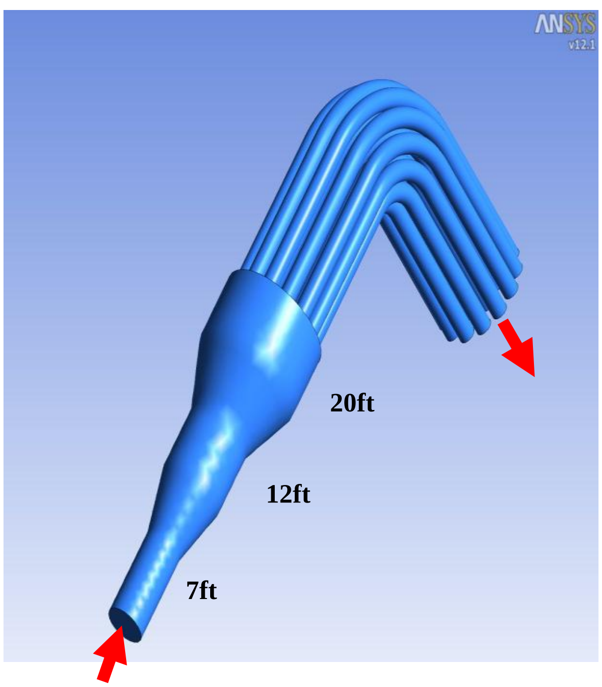

Figure 8: The manifold at Bottom of Vertical Pipe-Buoy

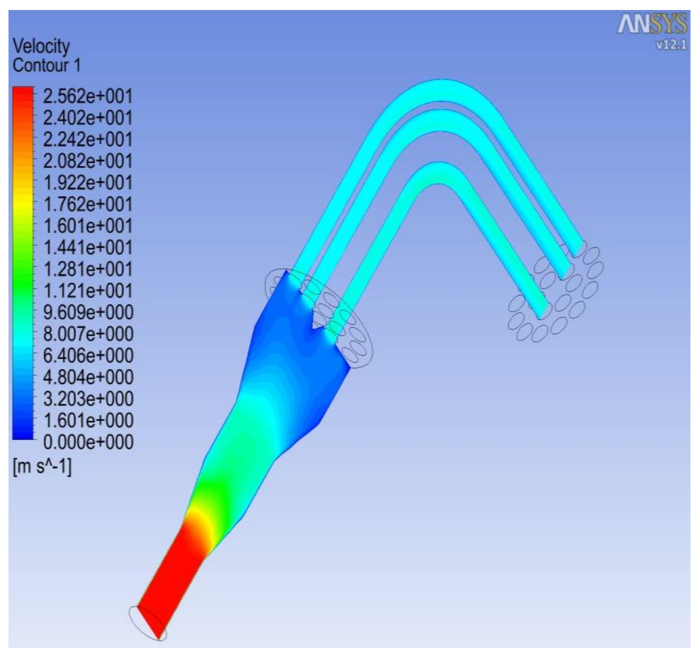

Figure 9: Vertical Pipe-Buoy Manifold – Contours of Velocity Magnitude

The ammonia gas is flowing inside the tube from top to down while water flow is outside of the tube from left to right. Figures 13 and 14 show temperature contours on middle vertical planes. Temperature of ammonia vapor decreases as it flows down. Figure 15 shows the temperature on the outer surface of the tube, which ranges from 4^{o}C to 5^{o}C. Assumption of constant 4^{o}C in previous 2D simulations was on lower side which has slightly over predicted the heat transfer. However, temperature at the outlet of the tube is sufficiently lower to ensure complete condensation of ammonia vapor.

Similar study was performed to obtain the behavior of the evaporator with the same tube arrangement. In this case ammonia liquid at 4^{o}C is entering from the bottom of the tube and the surrounding water flow is at 24^{o}C, as shown in Figure 16. Figure 17-18 shows temperature field for this evaporation simulation. Temperature is increasing from bottom to top as the heat transfer occurs from hot water. As shown in Figure 19, the temperature on the outer surface of evaporator tube is ranging from 19^{o}C to 24^{o}C. Temperature at the outlet of the tubes is sufficiently high to evaporate all liquid. The effect of water flow rate was also investigated in the above 3D simulation of the condenser and the evaporator. Water flow rate was varied from 0.1 m/s to 2 m/s and ammonia temperature at the exit of plates was compared. Temperature change for water flow was also compared. Figure 20, shows x-y plot of exit temperature vs. water flow rates for the condenser system. In the same Figure 20, similar plot for the evaporator system is shown. It is observed from these plots that water flow rate of around 1 m/s should be desired to provide required heat transfer for the condenser and the evaporator heat transfer problems. A second evoprator is placed on the platform top which uses further heated warm water by the concentric solar panels as shown in Figure 2 before. The 3D-simulation for heating of ammonia gas from 22 to 30 ^{o}C temperature is performed. It used 30 ^{o}C water temperature at .1m/s to 0.5 m/s range and ammonia gas is 22 ^{o}C with 10 m/s at the inlet. The outlet temperature of ammonia gas was about 28.132 ^{o}C to 29.05 ^{o}C.

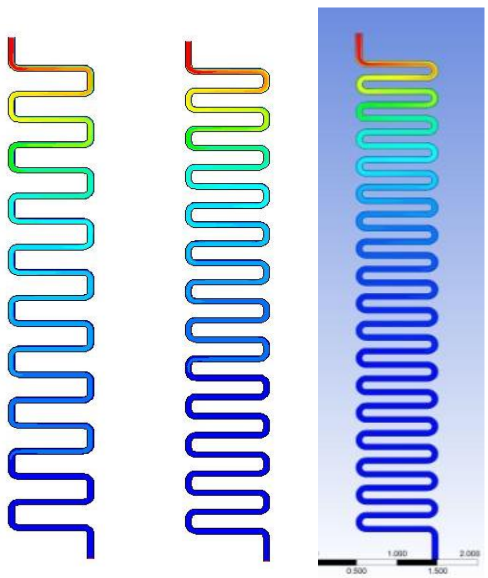

Figure 10: Contours of Static Temperature

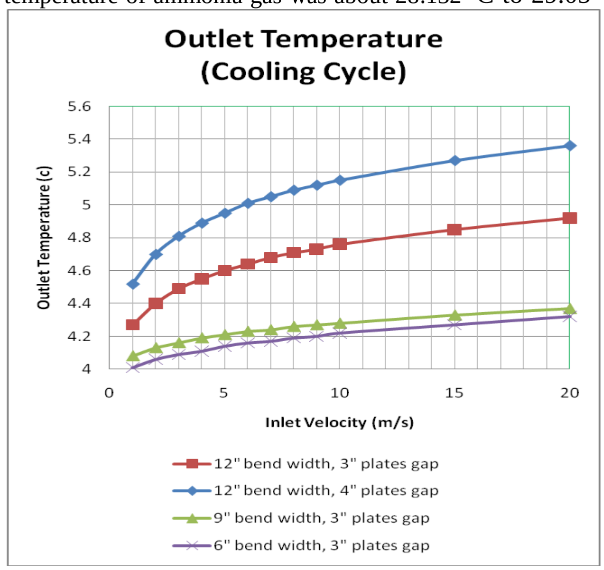

Figure 11: - Study of Outlet temperature Vs. Inlet Velocity

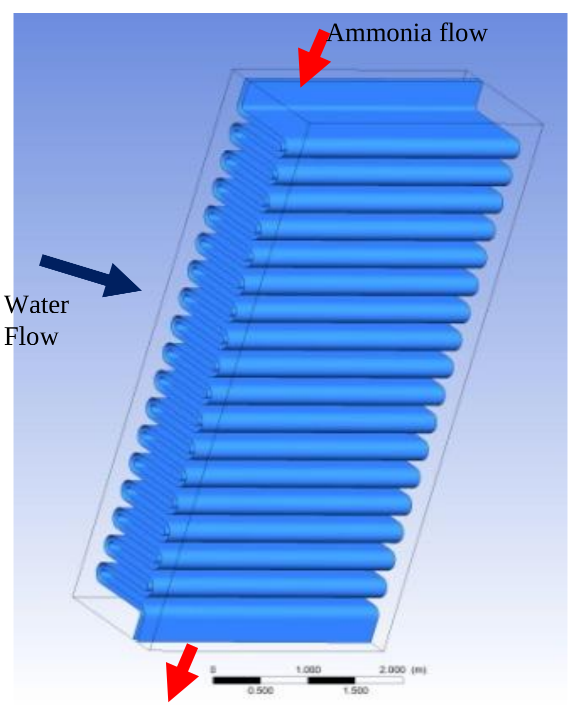

Figure 12: 3D of Single Channel for Condenser

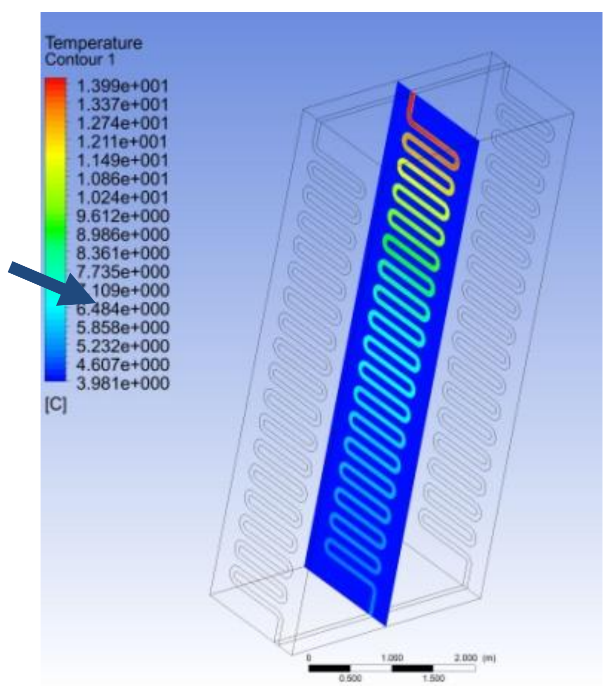

Figure 13: Temperature Contours on Middle c/s Plane

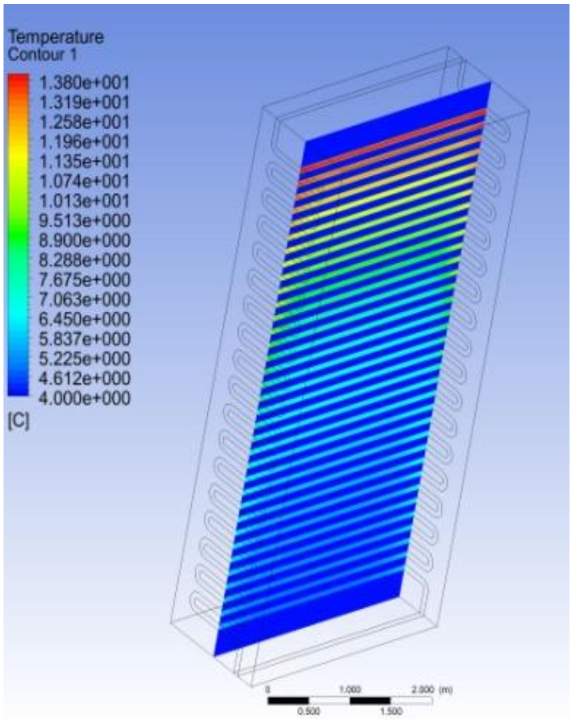

Figure 14: Temperature contours on vertical plane

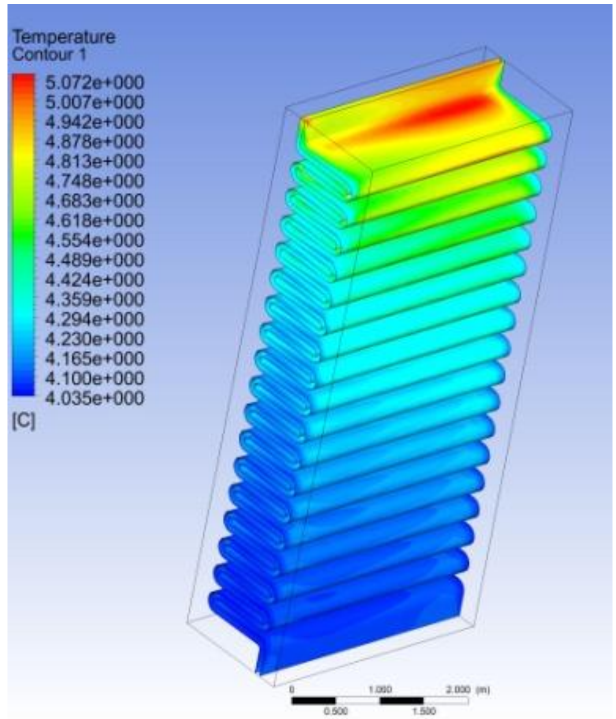

Figure 15: Temperature on outer surface of plates

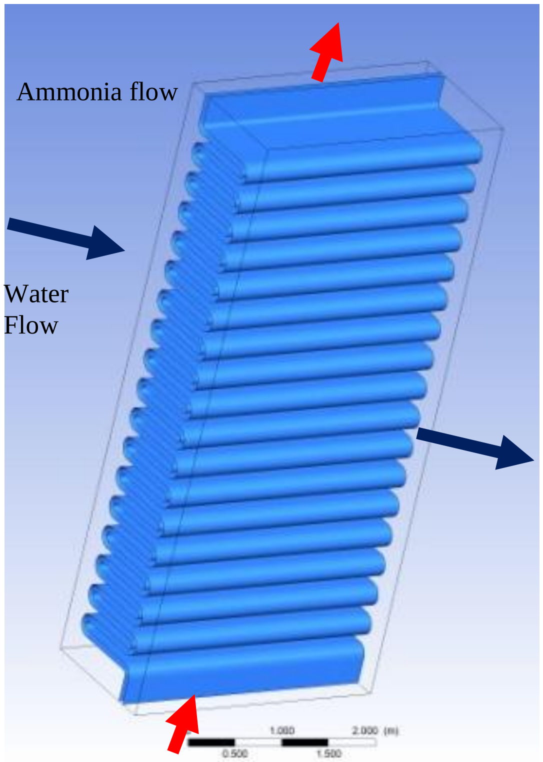

Figure 16: 3D of Single Channel of Evaporator

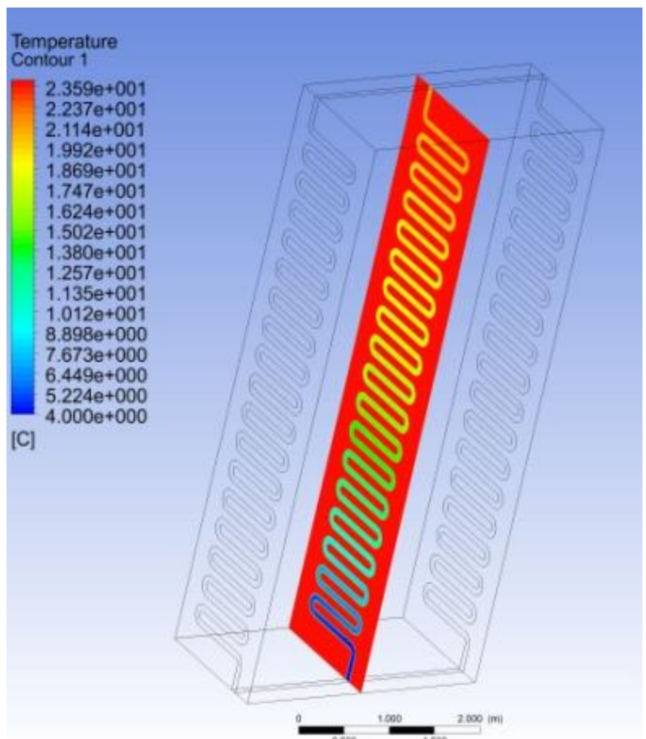

Figure 17: Temperature Contours on Middle c/s Plane

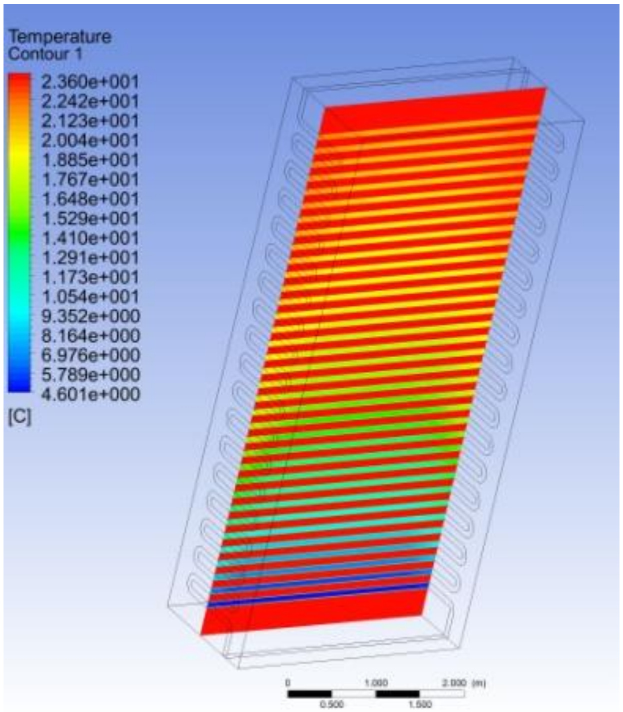

Figure 18: Temperature Contours on Vertical Plane

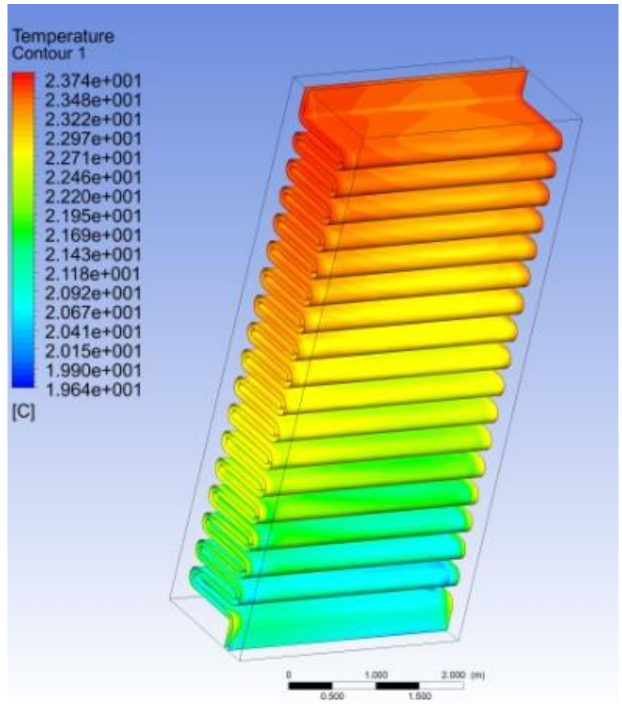

Figure 19: Temperature on Outer Surface of Plates

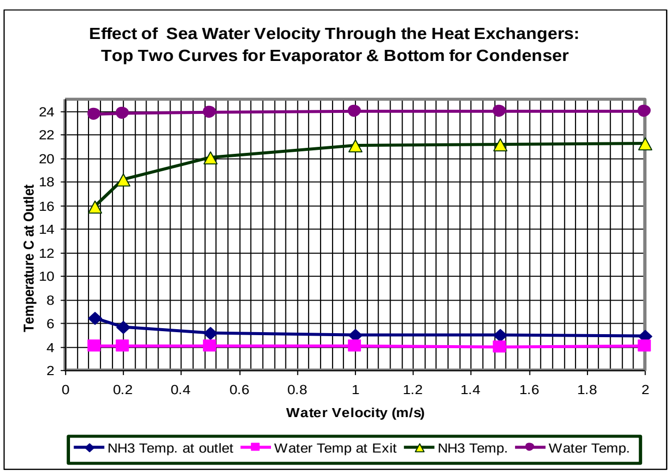

Figure 20: Water Velocity vs. Ammonia Temperature and Water Temperature at Exit

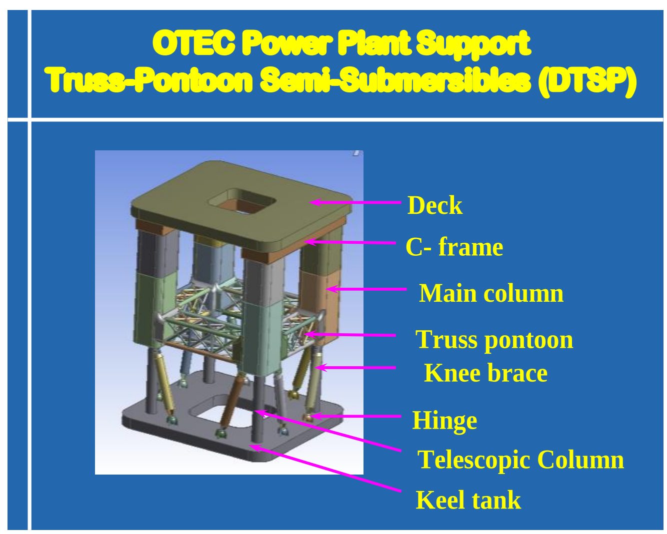

Figure 21: OTEC Supporting Vessel Concept

Supporting Vessel

Six GE turbines will be used, each with 20 MW (see Table 3). Out of these, five turbines will be used to bring the total output of 100 MW and the other one will be used for the subsea pump and other power supply requirement on the platform deck. A supporting vessel is designed for the new OTEC engine. The vessel carries some ammonia storage, the turbines, pumps, solar heat chamber, living quarters with heli-deck on top. The vessel is designed for harsh environment application of the ocean. A detailed technical merit of this vessel is given in Reference 3. It is a self-installing mobile offshore floating platform and is shown in Figure 21. The platform is sized for a topside deck payload of 2500 metric tones (5,500 kilo pounds) for supporting the new OTEC system. The platform consists of four 25 ft square columns placed at a distance of 105 ft center to center with 75 ft submerged depth and with 50 ft of free board. The platform keel tank is 130 ft by 130 ft square with 30 ft by 30 ft open at the middle and is 10 ft deep. It has the telescopic feature to 70 ft down further. Thus the total draft of the semi-submersible during operation is 155 ft. The estimated hull weight without the deck pay load is 11,700 kilo pounds.

The naval architecture stability engineering and motion behavior are studied for this vessel and is shown in Table 5. The vessel is highly stable and behaves well for the harsh environment of the ocean. The vessel heave natural period is 27 s. The heave Response Amplitude Operator (RAO) of the vessel is shown in Table 5 as an insert within the table. The telescopic keel-tank accommodates the submerged evaporator and is exposed to the open sea at 140 ft below free surface. Propellers would be mounted to simulate the water flow inside the evaporator, similar to the subsea condenser design. Six independent vertical floating-pipe buoys are used to transport the ammonia from each turbine outlet to the subsea condensers as shown before in Figure 5.

Independent Floating Vertical Pipe-Buoy

The vertical floating buoy is an 8 ft outer diameter pipe with 1 inch wall thickness for about 750 ft and rest 750 ft as 2 inch wall thickness. It is designed for external water pressure with internal stiffeners. The pipe buoy has a 12 ft diffuser at the top and 20 ft diffuser at the bottom. The top diffuser receives six 3 ft diameter pipes from the turbine outlet. The bottom diffuser supplies the hot gas to the subsea condenser through nineteen 3 ft diameter pipes. Thus the inlet velocity of the flow to the condenser is controlled below 10 m/s. The independent vertical pipe-buoy is moored at the bottom to the seabed and free floats vertically up. The center of gravity of the pipe-buoy is set below the center of buoyancy for stability requirement like SAPR vessel. Because of the 3000 ft deep pipe buoy, the vertical natural period is over 60 sec, which is above the wave exciting periods of the ocean. The diffuser at the bottom provides additional added mass. A flex joint or a universal mechanical joint could be used at the top to eliminate bending of the pipes. Special large diameter flexible hoses also could be used for this purpose. The vortex shedding behind the pipe is small because of the high Reynolds number in the order of 10e5 to 10e6. The flow around the pipe is predominantly turbulent. The vertical float buoy pipe of 8 ft diameter could be designed for tension with additional ballast load at the bottom and additional buoyancy chamber near free surface (not shown in the Figure 5 illustration).

The independent floating buoy is a feasible design concept from the structural, naval architectural and hydrodynamic point of view. This concept eliminates the need for supporting the six 8ft outlet pipes all the way to 3000ft by integrating with the platform unit. The platform is located at the middle of the six vertical floating buoys. The global architectural view of the central OTEC supporting vessel with the six independent floating buoys is shown in Figure 22. The independent vertical pipe buoy could act as the mooring for the central vessel which carries the major equipment. The independent vertical floating-pipe buoy will be locally manufactured and installed on the site. It would be installed by ballasting at the keel tank to make it upright. The pipe also could be installed vertically with the help of the platform through the moon pool by making threaded connections. In that case, a derrick is placed on top of the platform deck to lower the pipe buoy by section by section.

The entire operation could be self installed with platform cranes. The independent floating buoy itself could be used for to support the turbine and the evaporator at the top with help of a smaller platform. The cost of such power plant for 20MW output is very small compared to the plan of using a larger support vessel for 100 MW unit power output. It is wise to use this single vertical pipe buoy for the purpose of the pilot plant before the large 100 MW power plant is being built**.**

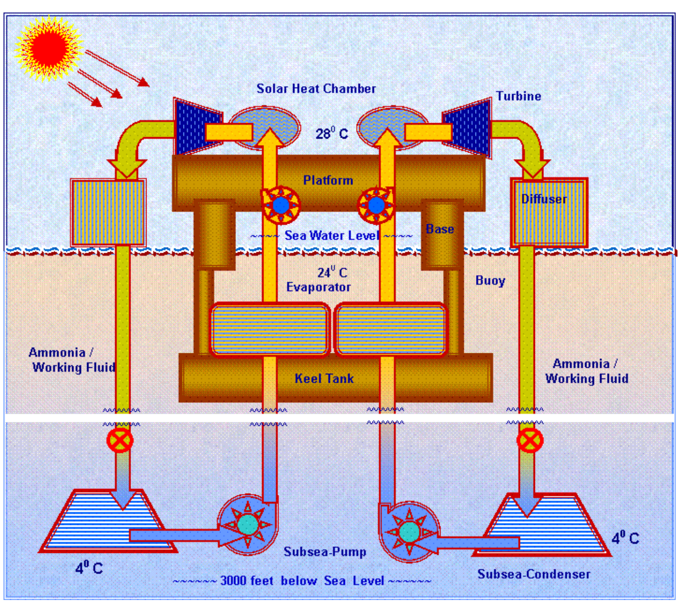

Figure 22: Global Architecture of the 100 MW OTEC: With its Independent Vertical-Pipe Floats

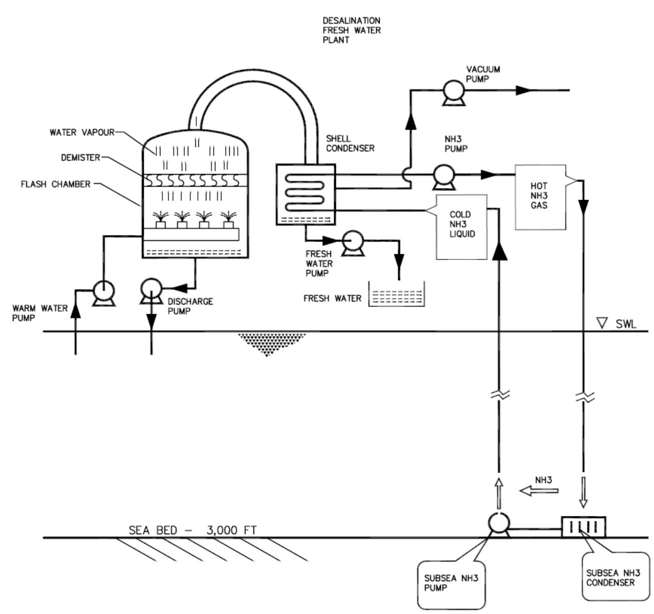

Figure 23 DeSI Desalination Plant Concept Diagram

Sub sea Cables

OTEC power plant needs subsea cables for transporting the electrical power to shore for feeding into the high voltage network. Several large cable suppliers are available in the world market (Examples are ABB, Prysmian, Nexus and Draka). A few of the manufacturers have over 25 years of subsea cable experiences. Power cable umbilical is used in offshore deepwater platforms to deliver electrical power to subsea. Duco manufactures different materials for umbilical from Aluminum, Copper, and light weight nano Umbilical with different sizes from 118 mm to 77 mm. Their dry weight varies from 23.3 kg/m to 11.6 kg/m. The submerged weight varies from 12.9 kg/m to 7.3 kg/m. The operating voltage is 11 kV and their electric performance for 10 miles is 3.0 MW power transmissions. Research is on going in Rice university of Houston, Texas, on the reduced size and weight of the power cable umbilicals with higher capacity. The research objective is to design, build and test an engineering prototype of a working ultrahigh conductivity “wire” that could in later stages be incorporated into an umbilical exceeding 100 miles in length and called upon to deliver up to 10 MW at up to 36 kV with an operating envelop ranging from -1 to 121ºC (~ 30 – 250ºF) and pressure from 0 to 4500 psi. This would benefit OTEC power plant.

Desalination a by-Product

Desalination could be a by-product of OTEC power plant or it could be independent too. Subsea condenser and subsea pump are used as similar to DeSI-OTEC power plant. The ammonia used as working fluid is cooled underwater at 3000 ft or less depth (5 to 12 degree C) and pumped up to the surface in a closed cycle with the help of a subsea pump. The warm water available near free surface (25 to 28 degree C) is flashed into a vacum chamber. The water is steamed at low temperature and then passes through the evoprator placed on the platform. The water vapour is condensed in the evoprator chamber where the cooled ammonia is used as a coolent. The ammonia is recyled back to the underwater condenser. This technology eliminated the need of large cold water pipe and uses ammonia as the working fluid. Since ammonia is condensed, the pipe sizes are small compared to the cold water pipe. The size of the water condender described above is very small. Efficiency of Ammonia for heat transfer is much faster than the cold water to condense the water vapour to produce potable water. The over all cost is reduced signifincantly and the effeciency is increased with this DeSI Desalination Plant. Figure 23 schematically illustrates the desalination plant with subsea condenser and subsea pump concept.

Cost Analysis

Capital cost is the major objective of the OTEC for its success. A cost analysis is needed to illustrate the advantage of the alternate OTEC over the conventional solution. The platform and the subcomponents of the OTEC engine as designed in this paper have shown significant cost reduction from 40 to 60% compared to the conventional OTEC. Table 6 below shows the estimated cost of the 100 MW OTEC power plant with its subsea equipment and the supporting vessel. The total estimate of the capital cost is $400 million USD. Table 7 shows the cost analysis for the OTEC project from commercialization feasibility point of view. It uses 95% reliability factor with 30 year life span for the 100 MW. The interest payments are rolled into the loan until the start of the production. The electricity cost is assumed as $0.14 per KWh which is cost effective and could be further reduced depending on the type of loan. Significant profit is seen in the Table 7. This shows OTEC with sub sea solution is attractive for real world applications.

Conclusion

Clean energy and clean water are the fundamental needs. Many islands and main lands near equator could benefit if these two could be produced cost effectively. This paper tried to achieve this goal with the knowledge that is gained from the deepwater oil and gas. The paper addressed an alternate solution for the OTEC with a subsea condenser. The thermodynamics, turbine, heat conduction, flow problems of working fluid and the supporting vessels are studied for the feasibility of the alternate solution of the new OTEC. It is concluded that the new OTEC is a promising renewable energy power source for a significant part of the world near equator. Further improvements to this new OTEC could be possible with the oil and gas deepwater technology. The new OTEC is definitely a good renewable energy source to be considered by the industry seriously. A joint industry effort is needed with support of the Federal Government for this new OTEC as a source of pollution free, renewable, alternate source of energy for many countries of the world.

Acknowledgement

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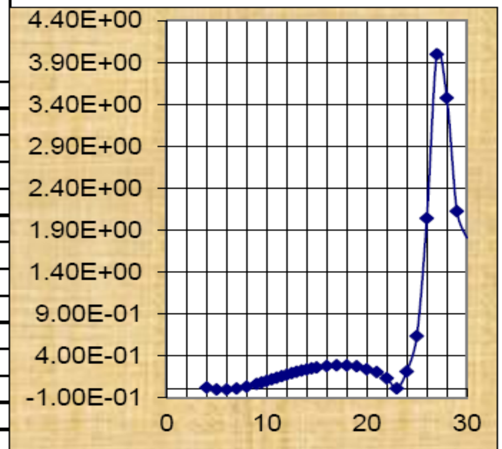
References

1. Robert Cohen, Consultant, An Overview of Ocean Thermal Energy Technology, Potential Market Applications, and Technical Challenges, OTC20176, 2009.
2. Srinivasan, Nagan, et.al. A New Improved Ocean Thermal Energy Conversion System with Suitable Floating Vessel Design, OMAE2009-80092, May 31 – June 5, 2009, Honolulu, Hawaii, USA.
3. Srinivasan, Nagan, et.al. Innovative Harsh Environment Dry-Tree Support Semi-Submersible for Ultra-deepwater Applications, OMAE2009-80085, May 31 – June 5, 2009, Honolulu, Hawaii, USA.

CENTER OF GRAVITY OF STRUCTURE				
Description	Weight (Tonns)	C.G of weights from Kell		Moment (Ton-m)
		Ft	m	
Deck PayLoad	2,500	220.00	67.06	167640.00
Deck Structure	1000	210.00	64.01	64008.00
C-frame	0	300.00	91.44	0.00
Colmn Ballast	100	100.00	30.48	3048.00
4- Main Column	1800	125.00	38.10	68580.00
Mooring Pretension	100	80.00	24.38	2438.40
4-Telescopic Column	600	45.00	13.72	8229.60
4-Truss	400	90.00	27.43	10972.80
8- Diag	300	45.00	13.72	4114.80
DP	0	160.00	48.77	0.00
KeelEvoprator	500	20.00	6.10	3048.00
KeelTank	1200	5.00	1.52	1828.80
Keel Ballast	4500	5.00	1.52	6858.00
Total	13,000			340766.40
	KG (m)			26.21



CENTER OF BUOYANCY — HEAVE RAO OF THE VESSEL WITH ADDED MASS = 27 SEC

Description	Number	length (m)	Breadth (m)	Diameter (m)	height (m)	Volume (m^3)	Lever arm (m)	Moment of Volume(m4)
Keel tank	1	40.00	40.00		3.0480	4876.8	1.52400	7432.24
Telescopic Column	4			3.06	30.4800	894.1	13.71600	12262.80
Main column	4	7.62	7.62		24.3840	5663.4	38.10000	215774.37
Deduction-Moonpool	1	12.20	12.20		3.0480	-453.7	1.52400	-691.38
Deduction for Telescopic opening in main column	4			3.06	21.3360	-625.8	13.71600	-8583.96
Truss						300.0	27.43200	8229.60
					Total	10654.7		234423.67
							KB (m)	22.00

GM					
M.I for Pitch (m^4)	M.I for Roll (m^4)	BM pitch	BM roll	GM pitch	GM roll
60596.63586	60596.64	5.69	5.69	1.48	1.48

NATURAL PERIOD OF MOTIONS						
Type of Motion	Specific Weight of water (Ton/m^3)	Acceleration Due to Gravity (m/s^2)	A_{wp} (m^2)	Volume (m^3)	Natural Frequency (rad/s)	Natural Period (s)
Heave Natural Period W/O ADDED MASS	1.025	9.81	232.26	10654.72	0.46	13.59
Pitch Natural Period (sec)					0.15	43.30
Roll Natural Period (sec)					0.15	43.30

Table 5: Supporting Vessel Stability & Motion Studies

Floating Vessel Hull +Deck Platform + Hull Equipment + Pipes+ Quarters	85,000,000
Deck Equipment: Turbine + Deck Pumps + etc	100,000,000
Independent Vertical Pipe Flotare, Sub-sea Condensar, Evoprator & Pumps	95,000,000
Sub-sea cabling and Land Power Substation System	50,000,000
Transport and Installation	30,000,000
Commissioning, Testing and Start-up	20,000,000
Contingency	20,000,000
TOTAL (USD)	**$ 400,000,000**

Table 6: Capital Cost for new OTEC Power Plant

Power Plant Capacity for Export to Land in Mega Watts	**100 MW**
Annual Revenue Calculation	
Annual Gross Capacity in kWh	**875,974,450**
Projected Reliability Factor	**95%**
Total annual kWh	**832,175,728**
Electricity Net Selling Price per kWh	**$ 0.14**
Annual Revenue from above Selling of Electricity	**$116,175,728**
Loan Calculation	
Total Capital Cost from Table 4 – 100 MW DeSI-OTEC	**$400,000,000**
Total Loan Amount that included 18 months of Loan Payment	**$500,000,000**
Annual Payment with Interest to Lender – 18 months (7.5% @ 10 years loan)	**$106,831,584**
Annual Payment @ 7.5% - for the Rest of the 8 Years	**$71,221,056**
Annual Power Plant Expense Calculation	
Annual Operating Expense per kWh	**$ 0.032**
Total annual Operating Expense	**$26,629,623**
Annual Sinking Fund	**$ 8,600,000**
Total Annual Expense	**$35,229,623**
Each Year Income and Expense Analysis After Electricity Production	
Total Annual Revenue	**$116,504,602**
Total Annual Payment for Loan for first 10 years	**$71,221,056**
Total Annual Expense	**$35,229,623**
Net Profit for Each Year After First 18 months of Loan	**$10,053,923**
Power Plant Life Time Profit Analysis	
Total – Interest plus Capital Cost of 400 million to pay-off debt in 10 years	**$712,210,615**
Total Operating Expense for the 30 years life of project	**$798,888,698**
Total sinking fund for the 30 years life of project	**$258,000,000**
Total Capital Cost + Total Operating Cost for 30 years Life of Project	**$1,769,099,313**
Total Revenue for life of project	**$3,495,138,056**
Total Profit for life of project (Before Tax)	**$1,726,038,742**

Table 7: Cost Analysis for 100 MW OTEC Power plant