SCHEMES AND CYCLES FOR OCEAN TEMPERATURE DIFFERENCES UTILIZATION

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Summary

The vertical temperature distribution in the open ocean can be simplistically described as consisting of two layers separated by an interface. The upper layer is warmed by the sun and mixed to depths of about 100 m by wave motion. The bottom layer consists of colder water formed at high latitudes. The interface or thermocline is sometimes marked by an abrupt change in temperature but more often the change is gradual. The temperature difference between the upper (warm) and bottom (cold) layers ranges from 10°C to 25°C, with the higher values found in equatorial waters. To an engineer this implies that there are two enormous reservoirs providing the heat source and the heat sink required for a heat engine. A practical application is found in a system (heat engine) designed to transform the thermal energy into electricity. This is referred to as OTEC for Ocean Thermal Energy Conversion.

Several techniques have been proposed to use this ocean thermal resource; however, at present it appears that only the closed cycle (CC-OTEC) and the open cycle (OC-OTEC) schemes have a solid foundation of theoretical as well as experimental work. In the CC-OTEC system, warm surface seawater and cold seawater are used to vaporize and condense a working fluid, such as anhydrous ammonia, which drives a turbine-generator in a closed loop producing electricity. In the OC-OTEC system seawater is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to

drive a turbine-generator. Cold seawater is used to condense the steam after it has passed through the turbine. The open-cycle can, therefore, be configured to produce desalinated water as well as electricity.

Records available from experimental plants demonstrate technical viability and provide invaluable data on the operation of OTEC plants. The economic evaluation of OTEC plants indicates that their commercial future lies in floating plants of approximately 100 MW capacity for industrialized nations and smaller plants for small-island-developing-states (SIDS). Unfortunately, the size of the experimental plants (< 0.3 MW) is about two orders of magnitude less than the size required for commercial (i.e., cost competitive) systems in industrial nations. Data extrapolation of this order is not acceptable to banking institutions or developers. The records that are available, however, are sufficient to design an OTEC plant sized at approximately 1.5 to 2 MW. This size range is appropriate for the smaller markets encountered in SIDS.

To proceed beyond experimental plants and towards commercialization in developed nations, a scaled version of a 100 MW plant must be designed and operated. The operational data is needed to earn the support required from the financial community and developers. Considering a 4-module system, a 1/5-scaled version of a 25 MW module is proposed as an appropriate size. The 5 MW pre-commercial plant is also directly applicable in some SIDS.

1. Background

It is estimated that, in an annual basis, the amount solar energy absorbed by the oceans is equivalent to at least 4000 times the amount presently consumed by humans. For an OTEC efficiency of 3 %, in converting ocean thermal energy to electricity, we would need less than 1 percent of this renewable energy to satisfy all of our desires for energy. However, even assuming that the removal of such relatively small amount of ocean solar energy does not pose an adverse environmental impact we must first identify and develop the means to transform it to a useful form and to transport it to the user.

The first documented reference to the use of ocean temperature differences to produce electricity is found in Jules Verne’s "Twenty Thousand Leagues under the Sea" published in 1870. Eleven years after Jules Verne, D'Arsonval proposed to use the relatively warm (24°C to 30°C) surface water of the tropical oceans to vaporize pressurized ammonia through a heat exchanger (i.e., evaporator) and use the resulting vapor to drive a turbine-generator. The cold ocean water transported (upwelled) to the surface from 800 m to 1000 m depths, with temperatures ranging from 8°C to 4°C, would condense the ammonia vapor through another heat exchanger (i.e., condenser). His concept is grounded in the thermodynamic Rankine cycle used to study steam (vapor) power plants. Because the ammonia circulates in a closed loop, this concept has been named closed-cycle OTEC (CC-OTEC). D’Arsonval’s concept was demonstrated in 1979, when a small plant mounted on a barge off Hawaii (Mini-OTEC) produced 50 kW of gross power, with a net output of 18 kW. Subsequently, a 100 kW gross power, land-based plant was operated in the island nation of Nauru by a consortium of Japanese companies. These plants were operated for a few months to demonstrate the concept. They were too small to be scaled to commercial size systems.

Forty years after D'Arsonval, Georges Claude, another French inventor, proposed to use the ocean water as the working fluid. In Claude's cycle the surface water is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to drive a turbine-generator and the relatively colder deep seawater is used to condense the steam after it has passed through the turbine. This cycle can, therefore, be configured to produce desalinated water as well as electricity. Claude's cycle is also referred to as open-cycle OTEC (OC-OTEC) because the working fluid flows once through the system. He demonstrated this cycle in 1930 in Cuba with a small land-based plant making use of a direct contact condenser (DCC). Therefore, desalinated water was not a by-product. The plant failed to achieve net power production because of a poor site selection (e.g., thermal resource) and a mismatch of the power and seawater systems. However, the plant did operate for several weeks. This was followed by the design of a 2.2 MW floating plant for the production of up to 2000 tons of ice (this was prior to the wide availability of household refrigerators) for the city of Rio de Janeiro. Claude housed his power plant in a ship (i.e., plantship), about 100 km offshore. Unfortunately, he failed in his numerous attempts to install the vertical long pipe required to transport the deep ocean water to the ship (the cold water pipe, CWP) and had to abandon his enterprise in 1935. His failure can be attributed to the absence of the offshore industry, and ocean engineering expertise presently available. His biggest technological challenge was the at-sea installation of a CWP. This situation is markedly different now that there is a proven record in the installation of several pipes during experimental operations.

The next step towards answering questions related to operation of OTEC plants was the installation of a small OC-OTEC land-based experimental facility in Hawaii. This plant was designed and operated by a team led by the author. The turbine-generator was designed for an output of 210 kW for 26°C warm surface water and a deep water temperature 6°C. A small fraction (10 %) of the steam produced was diverted to a surface condenser for the production of desalinated water. The experimental plant was successfully operated for six years. The highest production rates achieved were 255 kWe (gross) with a corresponding net power of 103 kW and 0.4 l s^{-1} of desalinated water. These are world records for OTEC.

A two-stage OTEC hybrid cycle, wherein electricity is produced in a first-stage (closed cycle) followed by water production in a second-stage, has been proposed by the author and his coworkers to maximize the use of the thermal resource available to produce water and electricity. In the second-stage, the temperature difference available in the seawater effluents from an OTEC plant (e.g., 12°C) is used to produce desalinated water through a system consisting of a flash evaporator and a surface condenser (basically, an open cycle without a turbine-generator). In the case of an open cycle plant, the addition of a second-stage results in doubling water production.

The use of the cold deep water as the chiller fluid in air conditioning (AC) systems has also been proposed. It has been determined that these systems would have tremendous economic potential as well as providing significant energy conservation independent of OTEC. For example, to produce 5800 tons (roughly equivalent to 5800 rooms) of air conditioning only 1 m^3 s^{-1} of 7°C deep ocean water is required. The pumping power required is 360 kW as compared to 5000 kW for a conventional AC system. The investment payback period is estimated at 3 to 4 years.

A number of possible configurations for OTEC plants have been proposed. These configurations range from floating plants to land-based plants, including shelf-mounted towers and other offshore structures. The primary candidate for commercial size plants appears to be the floating plant, positioned close to land, transmitting power to shore via a submarine power cable.

2. Technical Limitations

The performance of OTEC power generating cycles is assessed with the same elementary concepts of thermodynamics used for conventional steam power plants. The major difference arises from the large quantities of warm and cold seawater required for heat transfer processes, resulting in the consumption of 20 to 30 % of the power generated by the turbine-generator in the operation of pumps. The power required to pump seawater is determined accounting for the pipe-fluid frictional losses and in the case of the cold seawater for the density head, i.e., gravitational energy due to the differences in density between the heavier (colder) water inside the pipe and the surrounding water column. The seawater temperature rise, due to frictional losses, is negligible for the designs presented herein.

The ideal energy conversion for 26°C and 4°C warm and cold seawaters respectively is 8 %. An actual OTEC plant will transfer heat irreversibly and produce entropy at various points in the cycle yielding an energy conversion of 3 to 4 percent. These values are small compared to efficiencies obtained for conventional power plants; however, OTEC uses a resource that is constantly renewed by the sun. Considering practical sizes for the cold water pipe OTEC is presently limited to sizes of no more than about 100 MW. In the case of the open-cycle, due to the low-pressure steam, the turbine is presently limited to sizes of no more than 2.5 MW. The thermal performance of CC-OTEC and OC-OTEC is comparable. Floating vessels approaching the dimensions of supertankers, housing factories operated with OTEC-generated electricity, or transmitting the electricity to shore via submarine power cables have been conceptualized. Large diameter pipes suspended from these plantships extending to depths of 1000 m are required to transport the deep ocean water to the heat exchangers onboard. The design and operation of these cold water pipes are major issues that have been resolved by researchers and engineers in the USA.

It has been determined that approximately 4 $m^3 s^{-1}$ of warm seawater and 2 $m^3 s^{-1}$ of cold seawater (ratio of 2:1), with a nominal temperature difference of 20°C, are required per MW of exportable or net electricity (net = gross - inhouse usage). To keep the water pumping losses at about 20 to 30 % of the gross power, an average speed of less than 2 $m s^{-1}$ is considered for the seawater flowing through the pipes transporting the seawater resource to the OTEC power block. Therefore, a 100 MW plant would use 400 $m^3 s^{-1}$ of 26°C water flowing through a 16 m inside diameter pipe extending to a depth of 20 m; and 200 $m^3 s^{-1}$ of 4°C water flowing through an 11 m diameter pipe extending to depths of 1000 m. Using similar arguments, a 20 m diameter pipe is required for the mixed water return. To minimize the environmental impact due to the return of the processed water to the ocean (mostly changes in temperature), a discharge depth of 60 m is sufficient for most sites considered feasible, resulting in a pipe extending to depths of 60 m.

The amount of total world power that could be provided by OTEC must be balanced with the impact to the marine environment that might be caused by the relatively massive amounts of seawater required to operate OTEC plants. The discharge water from a 100 MW plant would be equivalent to the nominal flow of the Colorado River into the Pacific Ocean (1/10 the Danube, or 1/30 the Mississippi, or 1/5 the Nile into the Atlantic). The discharge flow from 60,000 MW (0.6 % of present world consumption) of OTEC plants would be equivalent to the combined discharge from all rivers flowing into the Atlantic and Pacific Oceans (361,000 m^3 s^{-1}). Although river runoff composition is considerably different from the OTEC discharge, providing a significant amount of power to the world with OTEC might have an impact on the environment below the oceanic mixed layer and, therefore, could have long-term significance in the marine environment. However, numerous countries throughout the world could use OTEC as a component of their energy equation with relatively minimal environmental impact. Tropical and subtropical island sites could be made independent of conventional fuels for the production of electricity and desalinated water by using plants of appropriate size. The larger question of OTEC as a significant provider of power for the world cannot be assessed, beyond the experimental plant stage, until some operational and environmental impact data is made available through the construction and operation of the pre-commercial plant mentioned above.

3. OTEC and the Environment

OTEC offers one of the most benign power production technologies, since the handling of hazardous substances is limited to the working fluid (e.g., ammonia), and no noxious by-products are generated. OTEC requires drawing seawater from the mixed layer and the deep ocean and returning it to the mixed layer, close to the thermocline, which could be accomplished with minimal environmental impact. The carbon dioxide out-gassing from the seawater used for the operation of an OC-OTEC plant is less than 1 % of the approximately 700 g kWh^{-1} released by fuel oil plants. The value is even lower in the case of a CC-OTEC plant.

A sustained flow of cold, nutrient-rich, bacteria-free deep ocean water could cause sea surface temperature anomalies and biostimulation if resident times in the mixed layer and the euphotic zone respectively are long enough (i.e., upwelling). The euphotic zone is the upper layer of the ocean in which there is sufficient light for photosynthesis. This has been taken to mean the 1 % light-penetration depth (e.g., 120 m in Hawaiian waters). This is unduly conservative, because most biological activity requires radiation levels of at least 10 % of the sea surface value. Since light intensity decreases exponentially with depth, the critical 10 % light-penetration depth corresponds to, for example, 60 m in Hawaiian waters. The analyses of specific OTEC designs indicate that mixed seawater returned at depths of 60 m results in a dilution coefficient of 4 (i.e., 1 part OTEC effluent is mixed with 3 parts of the ambient seawater) and equilibrium (neutral buoyancy) depths below the mixed layer throughout the year. This water return depth also provides the vertical separation, from the warm water intake at about 20 m, required to avoid reingestion into the plant. This value will vary as a function of ocean current conditions. It follows that the marine food web should be minimally affected and that persistent sea surface temperature anomalies should not be induced. These conclusions need to be confirmed with actual field measurements that could be performed with the pre-commercial plant described below in Section 9.

To have effective heat transfer it is necessary to protect the heat exchangers from biofouling. It has been determined that biofouling only occurs in OTEC heat exchangers exposed to surface seawater. Therefore, it is only necessary to protect the CC-OTEC evaporators. Chlorine (Cl_2) has been proposed along with several mechanical means. Depending upon the type of evaporator, both chemical and mechanical means could be used. To protect marine life, the USA Environmental Protection Agency (EPA) allows a maximum Cl_2 discharge of 0.5 mg l^{-1} and an average of 0.1 mg l^{-1}. CC-OTEC plants need to use Cl_2 at levels of less than 10 % of the EPA limits. The power plant components will release small quantities of working fluid during operations. Marine discharges will depend on the working fluid, the biocides, the depth of intake and the discharge configuration chosen.

Other potentially significant concerns are related to the construction phase. These are similar to those associated with the construction of any power plant, shipbuilding and the construction of offshore platforms. What is unique to OTEC is the movement of seawater streams with flow rates comparable to those of rivers and the effect of passing such streams through the OTEC components before returning them to the ocean. The use of biocides and ammonia are similar to other human activities. If occupational health and safety regulations like those in effect in the USA are followed, working fluid and biocide (most probably anhydrous ammonia and chlorine) emissions from a plant should be too low to detect outside the plant sites. A major release of working fluid or biocide would be hazardous to plant workers, and potentially hazardous to the populace in surrounding areas, depending on their proximity. Both ammonia and chlorine can damage the eyes, skin, and mucous membranes, and can inhibit respiration. Should an accident occur with either system, the risks are similar to those for other industrial applications involving these chemicals. Ammonia is used as a fertilizer and in ice skating rink refrigeration systems. Chlorine is used in municipal water treatment plants and in steam power plants. Chlorine can be generated *in situ;* therefore storage of large quantities of chlorine is not recommended.

Organisms impinged by an OTEC plant are caught on the screens protecting the intakes. Impingement is fatal to the organism. An entrained organism is drawn into and passes through the plant. Entrained organisms may be exposed to biocides, and temperature and pressure shock. Entrained organisms may also be exposed to working fluid and trace constituents (trace metals and oil or grease). Intakes should be designed to limit the inlet flow velocity to minimize entrainment and impingement. The inlets need to be tailored hydrodynamically so that withdrawal does not result in turbulence or recirculation zones in the immediate vicinity of the plant. Many, if not all, organisms impinged or entrained by the intake waters may be damaged or killed. Although experiments suggest that mortality rates for phytoplankton and zooplankton entrained by the warm-water intake may be less than 100 %, in fact only a fraction of the phytoplankton crops from the surface may be killed by entrainment. Prudence suggests that for the purpose of assessment, 100 % capture and 100 % mortality upon capture should be assumed unless further evidence exists to the contrary. Metallic structural elements (e.g., heat exchangers, pump impellers, metallic piping) corroded or eroded by seawater will add trace elements to the effluent. It is difficult to predict whether metals released from a plant will affect local biota. Trace elements differ in their toxicity and resistance to corrosion. Few studies have been conducted of tropical and subtropical species. Furthermore, trace metals released by OTEC plants will be quickly diluted with great volumes of water passing through the plant. However, the sheer size of an OTEC plant circulation system suggests that the aggregate of trace constituents released from the plant or redistributed from natural sources could have long-term significance for some organisms.

OTEC plant construction and operation may affect commercial and recreational fishing. Fish will be attracted to the plant, potentially increasing fishing in the area. Enhanced productivity due to redistribution of nutrients may improve fishing. However, the losses of inshore fish eggs and larvae, as well as juvenile fish, due to impingement and entrainment and to the discharge of biocides may reduce fish populations. The net effect of OTEC operation on aquatic life will depend on the balance achieved between these two effects. Through adequate planning and coordination with the local community, recreational assets near an OTEC site may be enhanced.

Other risks associated with the OTEC power system are the safety issues associated with steam electric power generation plants: electrical hazards, rotating machinery, use of compressed gases, heavy material-handling equipment, and shop and maintenance hazards. Because the CC-OTEC power plant operates as a low-temperature, low pressure Rankine cycle, it poses less hazard to operating personnel and the local population than conventional fossil-fuel plants. It is essential that all potentially significant concerns be examined and assessed for each site and design to assure that OTEC is an environmentally benign and safe alternative to conventional power generation. The consensus among researchers is that the potentially detrimental effects of OTEC plants on the environment can be avoided or mitigated by proper design.

4. Engineering Challenges

The design and installation of a cost-effective pipe to transport large quantities of cold water to the surface (i.e., cold water pipe, CWP) presented an engineering challenge of significant magnitude complicated by a lack of evolutionary experience. This challenge was met in the USA with a program relying on computer-aided analytical studies integrated with laboratory and at-sea tests. The greatest outcome achieved has been the design, fabrication, transportation, deployment and test at-sea of an instrumented 2.4 m diameter, 120 m long, fiber glass reinforced plastic (FRP) sandwich construction pipe attached to a barge. The data obtained was used to validate the design technology developed for pipes suspended from floating OTEC plants. This type of pipe is recommended for floating OTEC plants. For land-based plants there is a validated design for high-density polyethylene pipes of diameter less than 1.6 m. In the case of larger diameter pipes offshore techniques used to deploy large segmented pipes made of steel, concrete or FRP are applicable. Pressurized pipes made of reinforced elastomeric fabrics (e.g., soft pipes), with pumps located at the cold water intake, seem to offer the most innovative alternative to conventional concepts. However, the operability of pumps in 800 m to 1000 m water depths over extended periods must be verified and the inspection, maintenance and repair (IM&R) constraints established before soft pipes can be used in practical designs.

Other components for OTEC floating plants that present engineering challenges are the position keeping system and the attachment of the submarine power cable to the floating plant. Deep ocean-mooring systems, designed for water depths of more than 1000 m, or dynamic positioning thrusters developed by the offshore industry can be used for position keeping. The warm water intake and the mixed return water also provide the momentum necessary to position the surface vessel. The offshore industry also provides the engineering and technological backgrounds required to design and install the riser for the submarine power cable.

The design of OTEC CWPs, mooring systems and the submarine power cable must take into consideration survivability loads as well as fatigue induced loads. The first kind is based on extreme environmental phenomena, with a relatively long return period, that might result in ultimate strength failure while the second kind might result in fatigue-induced failure through normal operations.

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Biographical Sketch

Dr. Luis A. Vega

A naturalized citizen of the United States was born in Perú.

His university education lead to degrees in Applied Mathematics and Aerospace Engineering from the United States Naval Academy

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He taught engineering courses at the Universidad Mayor de San Marcos in Lima, Perú before beginning the first phase of his consulting engineer career working in ocean oriented projects to develop systems ranging from mining of manganese nodules to uses of ocean thermal energy. The majority of the work described in this article was performed while working for PICHTR managing OTEC projects in Hawaii.

Since 1995 he has also been working as a renewable energy consultant in projects aimed to implementing sustainable rural electrification in South Pacific island nations using solar and wind resources.

His stated goal is to work with organizations committed to the resolution of technical issues that must be addressed to follow a sustainable path towards the future.