OCEAN THERMAL ENERGY CONVERSION: HEAT EXCHANGER EVALUATION AND SELECTION

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ABSTRACT

This study summarizes available data on heat exchanger requirements for closed-cycle OTEC power systems obtained during over thirty years of R&D work and technology demonstration programs, and presents how these requirements can be met using commercially-available heat exchangers used today in other applications by a variety of industries. The study focuses on the following design criteria: configuration (shell-and-tube, compact-type, and others), process performance, surface enhancement, corrosion resistance, biofouling control, manufacturability, ease of operation and maintenance, and over-all cost-effectiveness. Selection of the appropriate working fluid will also be discussed. Data evaluated include previously developed power system designs such as those completed during the 1970's and 1980's by GE, JHU/APL, ANL, and engineering reports from OTEC technology demonstration programs such as the Nauru, Mini-OTEC and OTEC-1 test projects. A critical performance assessment is made between the use of stainless-steel plate heat exchangers and aluminum-brazed plate-fin heat exchangers in the context of present day technology. Alternatives to mitigate and control the adverse effects of biofouling are discussed.

INTRODUCTION

Ocean thermal energy conversion (OTEC) is a base-load renewable energy source that uses the temperature difference between the warm surface ocean water and the cold deep ocean water to generate electricity. OTEC is applicable to most parts of the world's deep oceans between 20^o North and 20^o South latitude including the Caribbean and Gulf of Mexico, the Pacific, Atlantic and Indian Oceans, and the Arabian Sea, where the temperature difference between the warm surface ocean water and the cold deep ocean water is equal or greater than 20 ^{o}C. In essence, OTEC recovers part of the solar energy continuously absorbed by the ocean and converts it into electric power. OTEC does not utilize any fuel. The electricity generated has a fixed cost, thus, it is not susceptible to the volatility resulting from world market fluctuations that affects other energy sources such as petroleum, coal and natural gas. Moreover, environmental impacts are less than those of conventional sources of energy since no products of combustion and no solid or toxic wastes are generated during the power production process. In addition, effluents are essentially similar to receiving waters, All of these aspects have caused a revival of interest in OTEC(1).

An OTEC power system consists of a heat engine cycle that converts thermal energy into mechanical work through the temperature difference between a "heat source" and a "heat sink". Although this temperature difference is relatively small compared to a steam engine, the principle is the same (Rankine thermodynamic cycle). OTEC technology is divided into three major categories: closed, open and hybrid cycles. In the closed-cycle, the temperature difference is used to vaporize (and condense) a working fluid (e.g. ammonia) to drive a turbine-generator to produce electricity (see Figure 1). In the open-cycle, warm surface water is introduced into a vacuum chamber where it is flash-vaporized. This water vapor drives a turbine-generator to generate electricity. The remaining water vapor (essentially distilled water) is condensed using cold sea water. The condensed water can either return back to the ocean or be collected for the production of potable water. The hybrid-cycle combines the characteristics of the closed cycle and the open cycle, and has great potential for applications requiring higher efficiencies for the co-production of energy and potable water(2).

The open and hybrid cycles allow the co-production of potable water through desalination, in addition to electric power. It is possible to produce up to 2 million liters per day for each megawatt of electricity generated(1). In all of the three cycles, it is required to obtain deep cold water (normally available at depths of 1,000 meters, where the water temperature is approximately 4 ^{o}C) to condense the working fluid. An OTEC plant can be installed on-shore or off-shore depending on the resource characteristics and market conditions of the proposed location. An off-shore plant could be built with a foundation on the ocean bottom (shelf-mounted), or located on a moored platform or as a grazing plantship. The electrical energy generated by the on-board OTEC power system can be transmitted ashore via underwater power cables or stored in the form of chemical energy for periodic transfer to on-land users.

During the 1970's and 1980's R&D projects such as Mini-OTEC and OTEC-1 in Hawaii and the Japanese 100-kW land-based pilot plant at the Republic of Nauru demonstrated the technical viability of OTEC, specifically with a closed-cycle system to generate electric power. Over 40 years of cumulative experience (and more than $500 MM invested in R&D) are available to us today in the form of engineering data, equipment development, environmental studies, conceptual & preliminary designs, and technical information. The information is sufficient to build the first commercial OTEC plants, with a capacity in the range of 50 to 100 MWe(2). Although the source of OTEC energy is renewable, continuous and fuel-cost free, the OTEC net thermal efficiency of operation is approximately 3%*.

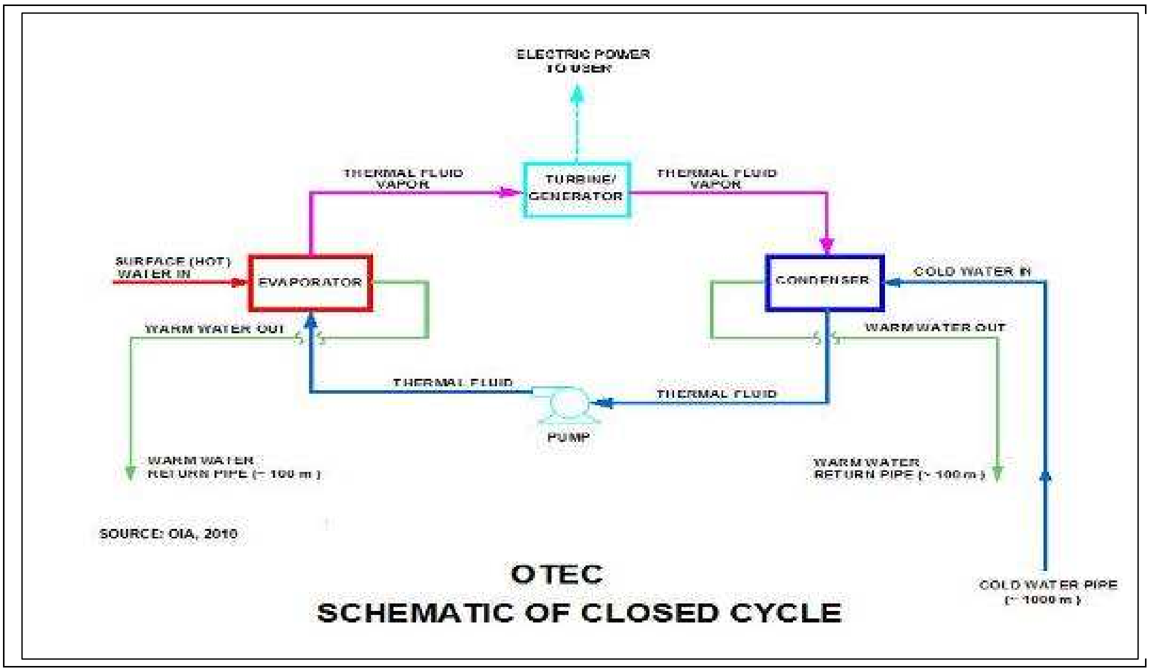


Figure 1. Schematic of an OTEC closed-cycle system with ammonia as working fluid.

Extensive research and development has been conducted to determine the optimum configuration, design basis and material of construction for the heat exchangers required for an OTEC process[2][3]. Projects such as Mini-OTEC and OTEC-1 as well as the test facilities at the Argonne National Laboratory (ANL), Keahole Seacoast in Hawaii and the experiments conducted at Punta Tuna in Puerto Rico provided the bases for the development of design methods for OTEC commercial-scale heat exchangers[2]. Lessons learned from these experiences have been applied to the development of heat exchangers which are being used for other applications today. Since large heat exchangers are required for a commercial size plant (due to the large flowrates of water required for the process), design and selection should be based on two major factors: optimum heat transfer rate and low cost. In addition, the material selection should be based on durability (resistance to corrosion and biofouling), compatibility with the working fluid and life-cycle cost.

The objective of this paper is to demonstrate that commercially available heat exchangers used today in other industries can be used for the first generation of OTEC commercial-scale facilities, while meeting cost-effectively, the criteria of heat transfer rate and 30-year life expectancy.

The heat exchanger evaluation and selection process presented in this study is based on a closed-cycle system and ammonia as the working fluid. The reason behind this decision is that the majority of the technical studies, research and development, conceptual designs and demonstration projects completed during the past four decades focused on the Rankine closed-cycle system with ammonia as the working fluid[1][2]. In addition, ammonia is the preferred working fluid over other substances such as propane and commonly-known refrigerants (R-12, R-22 and R-114) due to its cost-effectiveness, its superior thermal characteristics, proven safety record, and to the extensive operational experience with ammonia refrigeration systems in commercial and industrial applications[1][2][3].

EQUIPMENT DESIGN & CONFIGURATION

The OTEC research and development programs initially focused on shell-and-tube heat exchangers because there was more experience with this design as compared to other configurations[2][3]. Later it was realized that the use of shell-and-tube heat exchangers for OTEC commercial plants would make these equipment a major volume element in the overall plant installation.

R&D programs shifted their attention to investigate other designs and configurations with the objective of reducing heat exchanger unit size per kilowatt of power produced. Compact heat exchangers became the central focus of subsequent R&D programs and technical demonstration projects[2]. The volume of the OTEC heat exchangers and associated water and working fluid piping establishes the requirement for minimum construction and materials costs and the implementation of a systems integration strategy during the design of the power modules and its incorporation into the rest of the plant subsystems. Otherwise, the cost of the heat exchangers could become the major factor in the total OTEC plant cost.

Shell-and-tube heat exchangers are the most widely used type of heat exchangers for industrial evaporator and condenser applications (see Figure 2a). They are typically used for high pressure and high temperature applications. Shell-and-tube heat exchangers consist of an array of parallel tubes commonly referred as the core and a cylindrical vessel that encloses the tube bundle. One of the fluids in the process flows through the tubes interior while the other fluid flows over the tubes external surface (shell side) following a tortuous path while heat transfer occurs between both fluids. Configurations evaluated for OTEC include horizontal (flooded bundle and spray) and vertical (falling film and two-phase upflow) installations for both evaporator and condenser.

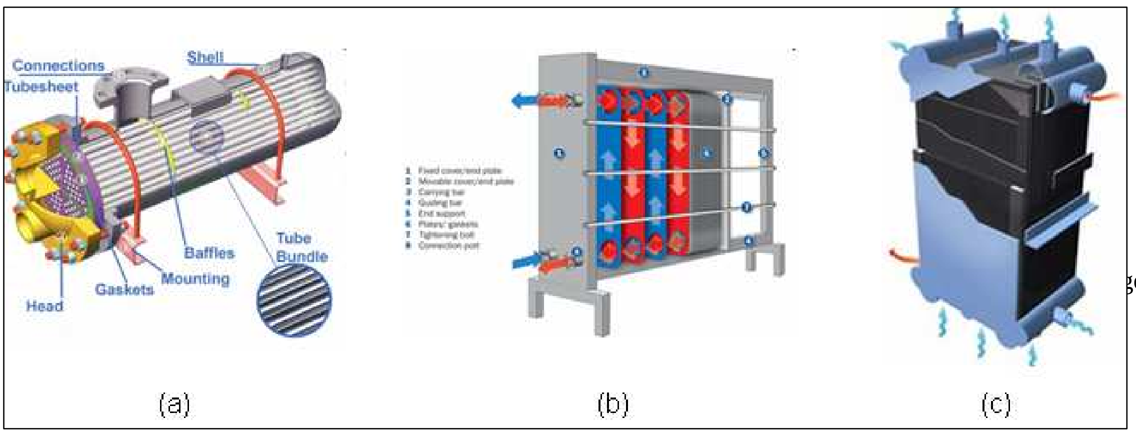
Plate heat exchangers are widely used in a variety of industries such as chemical plants, oil and gas, pulp and paper, HVAC and power generation (see Figure 2b). These are composed of multiple, thin, slightly-separated plates that are configured in a stack defining flow passages and resulting in very large surface area for heat transfer. Advances in gasket and brazing technology have made the plate-type heat exchanger increasingly practical. Configurations evaluated for OTEC include conventional design, cross-flow and plate-and-shell. Plate designs studied for OTEC include gasket sealing, weld/semi-weld sealing and nickel-brazed sealing.

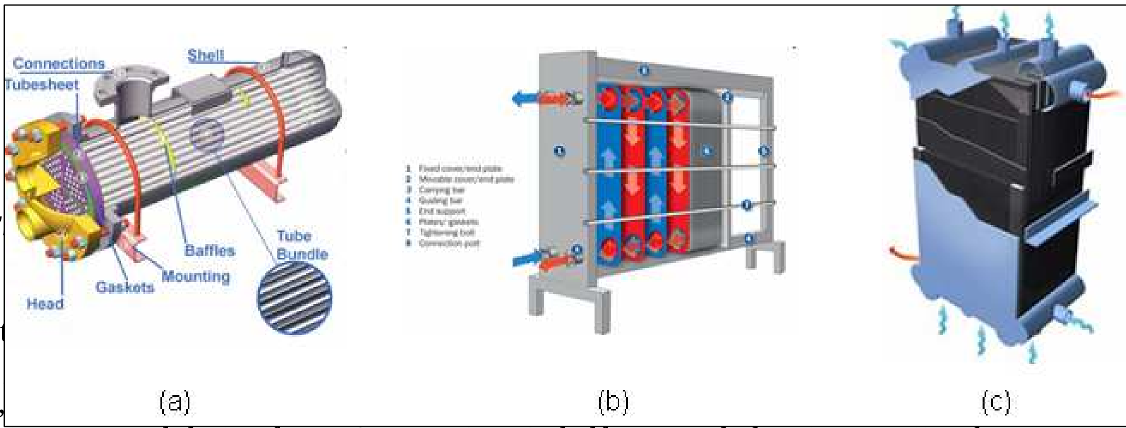
Brazed aluminum plate-fin heat exchangers have been successfully used a variety of applications (see Figure 2c). The major applications have been in the cryogenic separation and liquefaction of air, natural gas processing and liquefaction, the production of petrochemicals and offgases treatment, and large refrigeration systems. A brazed aluminum plate-fin heat exchanger consists of a core of alternating passages of corrugated fins. The stacked assembly is brazed in a vacuum furnace to produce a rigid core. Configurations evaluated for OTEC include vertical conventional design and horizontal installation (upflow and falling film).

In 1978 a heat exchanger test facility was constructed at Argonne National Laboratory (ANL) with the support from the U.S. Department of Energy. The objective was to test various OTEC heat exchanger designs at a large enough scale to provide sufficient and valid design data for demonstration-size OTEC power units[(2)]. Various designs of evaporators and condensers were tested at this facility: shell-and-tube Linde flooded-bundled evaporator, shell-and-tube Linde sprayed-bundled evaporator, shell-and-tube Linde enhanced-tube condenser, shell-and-tube Carnegie-Mellon (CMU) vertical fluted-tube evaporator, Alfa-Laval and Tranter plate heat exchangers, Saga University plate heat exchangers and Trane brazed-aluminum plate-fin heat exchangers. Another heat exchanger design, folded-tube heat exchanger, was evaluated and tested by John Hopkins University/Applied Physics Laboratory (JHU/APL), and eventually incorporated into their 1980 baseline design for a 40-MW OTEC pilot plant[(2)]. Nevertheless, neither the CMU fluted-tube or the JHU/APL folded-tube heat exchangers are commercially available today. For this reason the study will concentrate its analysis for equipment evaluation and selection on the shell-and-tube, plate and plate-fin heat exchanger designs.

PROCESS PERFORMANCE

In general, compact heat exchangers are considered to provide higher heat transfer efficiency than the traditional shell-and-tube heat exchangers in most applications. Tests results from ANL showed that the overall heat transfer coefficients for compact heat exchangers (plate and plate-fin) were 1.5-3 times[(2)] greater than the values obtained for the shell-and-tube heat exchanger designs for both evaporator and condenser[***]. This is consistent with industry experience in other applications where overall heat transfer coefficient values for compact designs are typically several times greater than shell-and-tube designs[(4)]. OTEC-1 (a converted T-2 tanker used for OTEC heat exchanger tests off the coast of Hawaii in 1980) used one shell-and-tube evaporator and one shell-and-tube condenser, each unit with a capacity of 1-MWe. Heat exchangers operation and performance were very similar to the behavior predicted by the ANL test facility for the shell-and-tube designs[(2)].





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... d other privat ... ld[2]. It used ... s[2]. In 1983, ... as part of their conceptual design for a 40-MWe OTEC shelf-mounted plant in Hawaii. The survey examined three candidates: brazed-aluminum plate-fin design by Trane, plate design by Alfa Laval and a new compact design by GE. In the category of overall thermal-hydraulic performance (heat transfer/pressure drop), both the plate and the plate-fin heat exchangers were rated "good"[4]. These ratings were based on the predicted overall heat transfer coefficient and low pressure losses, and equipment "compactness" characteristic. However, in the category of OTEC related performance (test experience), the brazed-aluminum plate-fin exchanger was rated "good" and the plate design was rated "fair"[4]. Optimized designs for brazed-aluminum plate-fin heat exchangers have improved their thermal performance when compared to the initial designs tested at ANL[5]. Cross-flow configurations for plate heat-exchangers offer great potential for further improvements in thermal and hydraulic performance[2].

SURFACE ENHANCEMENT

Heat transfer surfaces can be enhanced on both the working fluid and water sides. For the water side, enhancement is attained by the utilization of roughened/porous surfaces, internal fins, corrugations, spirals, flutes and other modifications. For the working fluid side, enhancement is attained with alterations comparable to those on the water side and other techniques such as wire wraps and flame-sprayed aluminum (Hi-Flux®). Most of these surface treatment alternatives apply to shell-and-tube heat exchangers.

The Nauru 100-kW OTEC pilot plant (a 1981 colaborative project between the Republic of Nauru, Tokyo Electric Power Company and Toshiba Corporation) employed shell-and-tube heat exchangers with enhanced surfaces. Freon was selected as the working fluid, although analysis showed that ammonia would be a better choice for commercial operation[2]. The surface treatment consisted in spraying the evaporator tubes with copper particles and installing spirally grooved tubes in the condenser sealed at intervals to separator plates. The heat exchangers performed as expected, with overall heat transfer coefficient values slightly higher than those recorded at the ANL test facility[2]. The OTEC-1 shell-and-tube evaporator included two independent sections of tube-bundles. The upper section had plain tubes and the lower section had Linde-design Hi-Flux® enhanced tubes. The condenser only contained plain tubes. These enhancements were not found cost-effective[3]. The plate heat exchangers used in the Mini-OTEC project were not provided with surface enhancement.

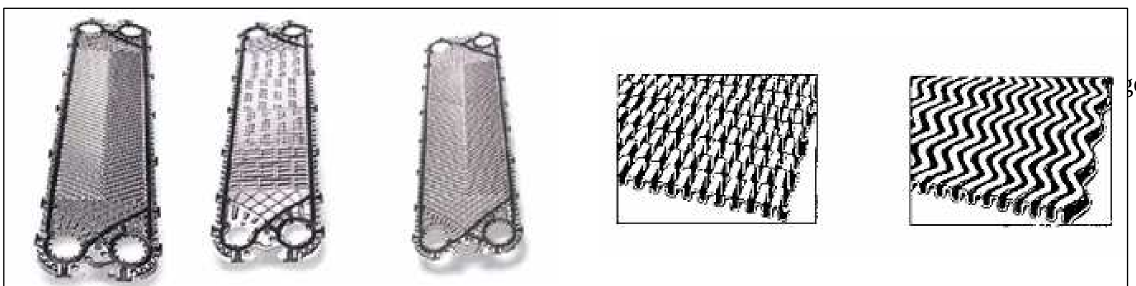

Figure 3. Integrated surface enhancements: (a) chevron pattern, (b) fin corrugations[****].

Compact heat exchangers depend on integral enhancement as part of the unit construction. Plate designs rely on a chevron pattern stamped into the plates (see Figure 3a) for the formation of the water and working fluid passages and for rigidity[(3)]. The thermal performance of these heat exchangers can be improved by employing high-flux surface on plates as demonstrated by performance tests at ANL[(2)]. However, applying a coating to the heat exchanger plates may not be cost-effective[(3)]. It will depend on the material of construction selected for the plate heat exchanger (stainless steel, titanium, etc.). The brazed-aluminum plate-fin design do not provide enhancement on the water extruded passages but aluminum fins such as straight and serrated types provide enhanced passage for the working fluid side (see Figure 3b). Integral enhancement configurations for both plate and plate-fin heat exchangers provide high heat transfer capabilities compared to shell-and-tube designs and are found to be cost-effective[(3)].

MATERIAL SELECTION

The selection of material for commercial heat exchangers has depended on tradeoffs among durability, fabrication and packaging, thermal conductivity, and cost. In the case of OTEC, the selected heat exchanger material must withstand the corrosive action of seawater. In order to maintain the operation, maintenance and repair (OM&R) costs of OTEC plants to a minimum, a service of 30 years has been established for the heat exchangers[(3)]. For this reason, the selection of materials for the heat exchangers and their biofouling controls is extremely critical to the success of the OTEC operation. To achieve maximum heat transfer, the surfaces of OTEC heat exchangers must be kept free of significant corrosion product films, calcareous deposits, biofouling and any other foreign deposits. Before the 1970’s, data on the resistance to corrosion in seawater of metals that required to be clean at all times was very scarce[(3)]. Since then, the OTEC R&D programs as well as materials research and development from other applications and industries have successfully provided the necessary technical data and commercial experience to design, construct, operate and maintain heat exchangers under OTEC process conditions and requirements[(2)(3)].

Heat exchangers for commercial use have been constructed from alloys of copper, titanium, aluminum and stainless steel. The R&D and test programs at ANL, the Naval Coastal Systems Center in Florida, the LeQue Center for Corrosion Research, the Center for Energy and Environmental Research in Puerto Rico and the Sea Coast Test Facility in Hawaii were established in the 1970’s and 1980’s to furnish data on the durability of the aforementioned candidate alloys in order to qualify OTEC heat exchangers for 30-year life.

Corrosion-Resistant Alloys

Copper-nickel was included in the OTEC test programs due to its resistance to corrosion in seawater, which is required to provide the desired 30-year life for the heat exchangers. In addition, copper-nickel has antifouling characteristics that make it even more attractive for OTEC application. However, copper-nickel is not compatible with ammonia/water solutions(3). Nevertheless, if other working fluid is selected, copper-nickel is a strong candidate for an OTEC application.

Titanium has been recognized as a material with exceptional resistance to corrosion under seawater conditions(4). This metal is available in the form of tubing and in plates (for compact heat exchangers). For many years, titanium has been successfully used in seacoast power plants and has performed "free from corrosion" in all tests conducted under OTEC process parameters(3)(4). Moreover, tests results from the LeQue Center for Corrosion Research showed that biofouling control methods such as mechanical cleaning and intermittent chlorination did not impact the material's performance on corrosion resistance(3). Titanium was also tested at Punta Tuna, Puerto Rico with warm water. No perceptible corrosion was shown(3). For these reasons, titanium was qualified very early in the OTEC R&D programs for the required 30-years life.

Stainless steel alloys have been candidates for OTEC heat exchangers based on numerous corrosion tests and vast experience in seacoast power plants. Specifically, alloys AL-6X and AL-29-4C have demonstrated to resist corrosion in seawater applications(3). These metals are also available in the form of tubing and plates. Crevice corrosion tests were conducted in the LeQue Center for Corrosion Research for both AL-6X and AL-29-4C alloy materials which yielded successful results in terms of validating its corrosion resistance characteristic. In addition, the U.S. Navy sponsored independent crevice corrosion tests on this two alloys showing similar results(3). The program concluded that the AL-6X and AL-29-4C alloys are strong candidates for the OTEC heat exchangers. Moreover, these two alloys performed very similar to titanium in that erosion-corrosion will not occur during frequent mechanical cleaning/intermittent chlorination for biofouling control. For these reasons, AL-6X and AL-29-4C alloys have been qualified for 30-year life service.

Aluminum alloys have been extensively evaluated for OTEC heat exchangers due to their potential readily extruded enhancements and shapes, and their lower cost when compared to other metals such as Titanium and stainless steel alloys. Specifically, aluminum alloys 5052, 3003, Alclad 3003 and Alclad 3004 are considered leading candidates. The OTEC R&D and test programs focused on evaluating the tendency of aluminum alloys to pitting corrosion and erosion-corrosion under seawater conditions(3). Most commercial aluminum applications in seawater are protected with paint or cathodic protection. Since OTEC requires clean heat-transfer surfaces, the erosion-corrosion effect on these aluminum alloys caused by biofouling control methods such as mechanical cleaning and chlorination were viewed as threats for their qualification.

Alclad 3003 and 5052 alloys were tested at the LeQue Center for Corrosion Research with mechanical cleaning and no chlorination. Tests showed that at a maximum cleaning cycle, erosion-corrosion caused early failure of the aluminum alloy(3). Corrosion tests were performed for several years at the Secoast Test Facility in Hawaii on alloys 5052, 3004, Alclad 3003 and Alclad 3004 using warm water (no biofouling control). No pitting was shown on any of these alloys(3). Tests conducted using cold water (no biofouling control) indicated that all alloys pitted by corrosion, but at rates lower than those acceptable for OTEC heat exchanger requirements(3).

The DOE conducted extensive tests using warm water at Punta Tuna, Puerto Rico initially on alloy 5052 and later on alloy 3003. The 5052 tests included infrequent mechanical cleaning. Tests showed that no localized attack occurred, although some general corrosion was observed. No erosion had occurred as a result of the mechanical cleaning. For the 3003 alloy, aluminum sections from a plate-fin heat exchanger designed by Trane were tested. A patented cladding method using zinc was implemented on the seawater surfaces of the alloy sections. Various samples with different zinc concentrations were tested including 0.5%, 1% and 45%. Bare alloy 3003 extrusions were tested, too. With brush cleaning, intermittent chlorination and the use of a device to monitor heat transfer, average corrosion rates recorded were below those required for OTEC application(3).

In the GE trade-off analysis for compact heat exchanger designs, the Trane aluminum-brazed plate-fin heat exchanger evaluated had a zinc coating in the water side passage. In the category of corrosion-erosion resistance/protection, the plate-fin heat exchanger was rated "fair"(4). As anticipated, the titanium plate heat exchanger was rated "excellent". The GE report concludes that 5052, Alclad 3003 and the zinc-coated 3003 alloys are candidate materials for OTEC heat exchangers. Table 1 shows a summary of test results for aluminum alloys evaluated under OTEC conditions at the aforementioned test facilities and sites.

Long-term research and development programs have proved that these aluminum alloys experience corrosion rates low enough to qualify them for at least 20-year life, and with a great potential for 30-year life for OTEC heat exchangers(2)(3).

AL Alloy	Water	Comments	Conclusions
Al-3003 drawn tube	Warm	No pitting	Acceptable
Al-3003 extrusion	Warm	No pitting	Acceptable
Al-3003 extrusion (diffused zinc)	Warm	Some pitting	Acceptable with caution
Al-5052 tube	Warm	No pitting	Acceptable
Alclad 3004 RFW	Warm	Pitting	Not acceptable
Alclad 3004 drawn tube	Warm	No pitting	Acceptable
Al-3003 drawn tube	Cold	Some pitting	Acceptable with caution
Al-5052 drawn tube	Cold	No pitting	Acceptable
Al-3002 extrusion	Cold	Some pitting	Acceptable with caution
Al-3002 extrusion (diffused zinc)	Cold	Some pitting	Acceptable with caution
Alclad 3004 RFW	Cold	Pitting	Not acceptable
Alclad 3004 drawn tube	Cold	Pitting	Not acceptable

Table 1. Summary of test results for aluminum alloys evaluated for OTEC.

BIOFOULING

Biofouling, the undesirable accumulation of microorganisms, plants, algae, and/or animals on wetted structures, has to be prevented or removed in order to achieve maximum heat transfer efficiency in the OTEC heat exchangers. This issue was considered critical at the beginning of the OTEC R&D programs due to the fact that biofouling could cause heat exchangers performance degradation. Nevertheless, as critical as it is, the extent of the potential problems were overestimated since fouling rates in tropical open-ocean waters suitable for OTEC operation are significantly lower than in coastal waters(2). The result is that biofouling control is more effective for OTEC as compared to typical marine heat exchangers. In terms of biofouling control methods, physical methods can be effective at lower intensities or longer time cycles. Chemical agents can also be used in concentrations that are environmentally safe and in compliance with applicable environmental regulations.

An important conclusion in regards to biofouling is that the fouling effect in the heat exchanger (a percentage reduction in overall heat transfer coefficient) is independent of the change in temperature(2). In other words, the low thermal efficiency of OTEC does not make its performance particularly sensitive to a heat transfer reduction caused by biofouling. If overall heat transfer coefficients are improved by design, the sensitivity of the heat exchanger performance to biofouling is expected to increase as well(2).

Another important conclusion is that the differences between the organisms that causes biofouling at sites in Puerto Rico, Gulf of Mexico and Hawaii are not significant, which provides enough assurance that the methods adopted to control biofouling for one of these sites will be applicable to the rest(2).

Microfouling

The initial OTEC R&D programs concluded that an acceptable value for the fouling factor for both the evaporator and condenser must be less than 0.000088 $m^2\ ^oC/W$(2)(3). Multiple experiments and test activities were conducted in Hawaii, the Gulf of Mexico and Puerto Rico to determine rates of biofouling under typical OTEC conditions using a heat transfer monitor (HTM) originally developed by the Carnegie-Mellon University (CMU) and later improved by ANL. Results showed that biofouling would exceed unacceptable levels in the warm water system (fouling factor > 0.000088 $m^2\ ^oC/W$) after six weeks of operation without fouling control(2)(3). To maintain the fouling factor below the acceptable level, both physical and chemical methods were explored including chlorination (continuous and intermittent), brushing, smooth or abrasive balls, slurries, ultrasonic and ultraviolet. The method found to be the most practical and cost effective is intermittent chlorination(2)(3)(4). Since continues chlorination would require more parasitic power, intermittent chlorination was the preferred choice for the majority of the tests. It has been proven that injection of 70 parts per billion of chlorine for one hour per day in the warm water system prevents biofouling formation effectively. This concentration is significantly less than the limits allowed by the Environmental Protection Agency on the discharge of chlorine from coastal power plants and similar industries(2)(3). Intermittent ozonation should be at least as effective as chlorination, and may be an alternative for actual plants.

In the case of the cold water system, there was no indication of biofouling formation in all the tests conducted at the above sites. This is consistent with the operational data from the NELHA open-cycle OTEC test facility at Keahole Point in Hawaii, where no biofouling was ever found in the cold water system during the project’s five-year operation(2).

The GE trade-off analysis rated the Trane aluminum-brazed plate-fin heat exchanger “good” in the category of biofouling control category due to its ease of chlorination and the smooth, defined water passages(4). The report states that the Alfa-Laval plate heat exchanger design will require a closed-cycle clean-in-place (CIP) system based on slow circulation of a cleaning solution (e.g. 3% NaOH) through the heat exchanger. Due to this added complexity, the plate heat exchangers were rated “fair”(4) in this category. These recommendations were based on the tests results from the Seacoast Test Facility in Hawaii and the tests conducted in Puerto Rico.

Macrofouling

The biofouling control program described above also included macrofouling, the accumulation of coarse matter of either biological or inorganic origin. This can be material suspended in water, and tends to adhere to surfaces and impede flow, as well as the growth of algae and marine organisms that feed on the bacterial film or slime that forms on surfaces exposed to seawater. In addition to the OTEC heat exchangers, other surfaces such as screens, sumps, piping, pumps and valves require macrofouling control or prevention. The degree of macrofouling development was specifically identified during the biofouling and corrosion tests conducted in Puerto Rico in the early 80's. Nevertheless, the power industry has available various macrofouling control and prevention measures for service in seawater such as anti-fouling paint systems and mechanical cleaning. The selection for macrofouling control should be based on reliability and cost-effectiveness. Suitable effective low-cost methods are commercially available today and are applied at coastal power plants and comparable industries to address this issue, which represents a critical factor to achieve the long service life needed for OTEC power systems(1)(2).

ECONOMICS & OVERALL COST-EFFECTIVENESS

As mentioned before, the selection of commercially available heat exchangers for the first generation of OTEC power plants should be based on the equipment's capability to meet the following design criteria: maximum thermal and hydraulic performance, 30-year life cycle and low unit cost per net power produced. Establishing the cost-effectiveness of OTEC heat exchangers is not an easy task. Since the beginning of the OTEC R&D and test programs, heat exchangers provided the largest targets for potential cost reductions in order to make OTEC commercially attractive(2)(5). Ample data is available today that can be used for cost comparison between shell-and-tube heat exchangers and compact heat exchangers, and between plate heat exchangers and plate-fin heat exchangers with variations in the material selected for the equipment construction.

Compact heat exchangers, when compared to shell-and-tube design, are more likely to have the lowest cost and meet the scalability requirements to successfully commercialize OTEC(4). The reduction in labor costs is considerable in going from shell-and-tube heat exchangers to compact design such as plate and plate-fin heat exchangers(3). ANL predicted potential cost reductions of approximately 40% of total hardware costs if brazed-aluminum plate-fin heat exchangers were used instead of titanium shell-and-tube heat exchangers for their 10-MWe shore-based OTEC plant conceptual design(5). These design evaluations are based on comparisons between cores only (tubing versus plates versus plate fins) since cost and weight of the other steel components (tube sheets, baffles, shells, waterbox, etc.) are significantly small compared with the cost and weight of the cores(3). For example, titanium plate heat exchangers reflect approximately 35% in core weight savings when compared with titanium shell-and-tube heat exchangers(3).

In terms of material selection, metal savings of approximately 54% can be expected when selecting plate-fin heat exchangers versus shell-and-tube designs using Alclad 3004; 39% when selecting plate heat exchangers versus shell-and-tube designs using 29-4C stainless steel alloy; 37% when selecting plate heat exchangers versus shell-and-tube designs using Al-6X stainless steel alloy; and 29% savings when selecting plate heat exchangers versus shell-and-tube designs using titanium grade I(3). Based on these data and due to the volatility and high costs of titanium over the past decades, emphasis has been made on commercially available compact heat exchangers using stainless steel and aluminum alloys, specifically, the alloys extensively evaluated and tested for corrosion resistance and biofouling control as discussed in previous sections. This is supported by the conceptual and preliminary design reports completed by JHU/APL, ANL and GE. Particularly, in their trade-off analysis, GE rated the Trane brazed-aluminum plate-fin heat exchanger design as “excellent” in the category of commercial plant capital cost; the Alfa-Laval titanium plate heat exchanger was rated “fair” in this category[4].

In recent years, ANL has favored commercially available compact heat exchangers such as plate heat exchangers using Al-6X or 29-4C stainless steel alloys and plate-fin heat exchangers using aluminum alloys such as 3003, 3004, 5052 and 6061 to be used in the first generation of OTEC commercial plants[2][5].

Maturity of Design & Manufacturing

The stainless steel plate heat exchangers and the brazed-aluminum plate-fin heat exchangers are both the result of long commercial application. The plate heat exchanger has many years of industrial and commercial application. The present configuration evolved in the 1920’s and 1930’s with application in the chemical industry, in the power industry in the 1940’s and in marine service in the 1950’s and 1960’s. Continues development in plate design and sealing methods have yielded significant improved performance and cost reductions. Stainless steel plate heat exchangers manufactured by Alfa-Laval (T-50M) and Tranter (Superchanger), with small design modifications, are considered strong candidates for the first generation of commercial OTEC plants. This configuration is widely used today in commercial-scale ammonia refrigeration systems. However, special attention must be given to the potential significant pressure drops that have characterized the plate heat exchangers design in other applications.

Brazed-aluminum plate-fin heat exchangers have over 35 years of accumulated industrial experience, primarily in the cryogenic field for hydrocarbon gas separation, natural gas processing, petrochemical offgases treatment and large refrigeration systems. The Standards of the Brazed Aluminum Plate-Fin Heat Exchanger Manufacturers' Association (ALPEMA) was created in the 1990’s to promote the quality and safe use of this type of heat exchanger. This standard contains all relevant information for the specification, procurement, and use of brazed-aluminum plate-fin heat exchangers[6]. Alternate extrusion methods and furnace-brazed fabrication capabilities are being introduced to further improve the product for other commercial applications.

ANL concluded in 1981 that the facilities needed to manufacture the stainless steel plate and the brazed-aluminum heat plate-fin heat exchangers were in place and only modest extension of current technology were required for their use in OTEC power plants[2]. This conclusion was supported by the GE trade-off analysis, where both the Alfa-Laval and the Trane compact heat exchangers were rated “good” in the category of maturity of design[4]. This conclusion remains true today, where manufacturing facilities are available to manufacture the appropriate size compact heat exchangers (plate and plate-fin) that can be used in the first generation of commercial OTEC plants.

Installation & Space Requirements

As mentioned in previous sections, from the beginning of the OTEC R&D and test programs it was realized that the selection of shell-and-tube heat exchangers for OTEC commercial plants would make the heat exchangers a major volume element in the OTEC total plant capital cost. Compact designs reduce the heat exchanger volume requirements by 55-70% in comparison with the shell-and-tube units, with a potential reduction of 45-60% in total module space requirements[2]. Moreover, the active total heat exchanger volume, which is indicative of the complexity of the equipment installation and arrangement, is approximately 10 times greater for the shell-and-tube design than the brazed-aluminum plate-fin heat exchangers. The volume for a shell-and-tube heat exchanger is approximately 4 times greater than the plate heat exchangers[(4)]. The heat exchangers volume is more critical in floating OTEC plants since the equipment space requirement affects directly the design and final cost of the selected platform configuration (shelf-mounted, moored platform or grazing plantship). For instance, the total equipment footprint for a floating platform with plate-fin heat exchangers could be approximately 20-30% less than the area required using plate heat exchangers[(2)(5)].

The piping requirements for plate and plate-fin heat exchangers diverge in terms of arrangement complexity. For the brazed-aluminum heat exchangers, its design simplifies the piping configuration. However, in the case of the plate heat exchangers, although they are simple in principle, manifolding and ducting requirements may require special attention[(2)]. In both cases, pipe distribution arrangement need to be optimized in order to minimize friction losses, which leads to an increase in total parasitic power.

Operation, Maintenance & Repair

The cost of heat exchangers must consider its original cost plus the replacement cost if the material selected does not results in an equipment life of 30 years. As indicated previously, titanium and stainless steel alloys Al-6X and 29-4C have been qualified for 30 years without replacement. By comparison, the extruded aluminum alloy Alclad 3003 would need to last at least 20 years to be competitive with titanium and at least 25 years to compete with stainless steel 29-4C[(3)]. In the case of welded aluminum Alclad 3004, it would need to last at least 15 years to compete with titanium and 20 years to compete with 29-4C[(3)]. Plate heat exchangers based on Al-6X and 29-4C can perform as designed over a period of 30 years with biofouling control. In the case of the brazed-aluminum plate-fin heat exchangers, long-term R&D has qualified this design for at least 15 years[(3)]. Some reports even suggest that these heat exchangers can be qualified for 30-years service life[(2)]. Regardless of this potential discrepancy, results from all the associated R&D programs indicate that the life-cycle cost of aluminum heat exchangers will be lower than the costs of other alternatives, specifically, when compared with titanium heat exchangers[(2)].

The impact of cleaning systems and their ability to preserve an acceptable level of fouling resistance is vital for OTEC heat exchangers cost-effectiveness. Biofouling formation reduces the heat exchanger's capability to transfer heat efficiently. Some of the consequences of not controlling or preventing biofouling formation in heat exchangers are: reduction of output, additional requirement of chemicals, an increase in parasitic power, unscheduled maintenance and cleaning, additional downtime due to leakages and repairs and overall reduction of system's life. All of these potential scenarios translate into higher operational costs and profit loss. Mechanical cleaning diminishes the life of aluminum heat transfer surfaces but is not a key problem with titanium or the stainless steel alloys. Thus, for brazed-aluminum plate-fin heat exchangers it is important to establish a biofouling control method based on periodic mechanical cleaning and intermittent chlorination in order to reduce the risk of surface erosion-corrosion. In the case of plate heat exchangers, the cost and implementation problems, such as management of spent cleaning solutions, associated with chemical usage for biofouling prevention need to be closely evaluated, specifically, if a closed-cycle clean-in-place (CIP) system is to be used in an offshore OTEC plant.

CONCLUSION

For a closed-cycle system using ammonia as the working fluid, it is concluded that commercially available compact heat exchangers can be adapted without major difficulty to be used as heat exchangers for the first generation of commercial-scale OTEC power plants. Both the plate heat exchanger and the plate-fin heat exchanger offer high thermal and hydraulic performance and surface enhancement can be integrated into the equipment design to improve the overall heat transfer coefficient. Stainless steel alloys such as Al-6X and 29-4C are qualified for 30-year service without replacement. Plate-fin heat exchangers based on aluminum alloys such as Alclad 3003 and 3004 can be qualified for at least 15 years service, which offer great potential for a competitive life-cycle cost. Biofouling control can be achieved successfully with intermittent chlorination and periodic mechanical cleaning under OTEC process conditions. Final selection between plate heat exchangers and brazed-aluminum heat exchangers should be determined by a trade-off analysis between material costs, design requirements, manufacturability, installation and space requirements, ease of operation and maintenance, and overall equipment cost-effectiveness.

FOOTNOTES

[*] This low net efficiency is due to the available temperature gradient for an OTEC plant (20-24 ^{o}C), the plant's parasitic power and the expected thermal and hydraulic losses across the system.

[**] Schematic sources: (a) SEC Heat Exchangers web site, (b) Trelleborg web site, (c) Chart Industries web site.

[***] This comparison considers plain and enhanced surfaces for both shell-and-tube and compact heat exchangers.

[****] Schematic sources: (a) Brandex Directory Co. web site, (b) ALPEMA Standards 2nd Edition.

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