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ABSTRACT

The Solar Energy Research Institute, under funding and program direction from the U.S. Department of Energy, has been operating a small-scale test apparatus to investigate key components of open-cycle Ocean thermal energy conversion (OC-OTEC). The apparatus started operations in October 1987 and continues to provide valuable information on heat- and mass-transfer processes in evaporators and condensers, gas sorption processes as seawater is depressurized and repressurized, and control and instrumentation characteristics of open-cycle systems. Although other test facilities have been used to study some of these interactions, this is the largest apparatus of its kind to use seawater since Georges Claude's efforts in 1926. The information obtained from experiments conducted in this apparatus is being used to design a larger scale experiment in which a positive net power production is expected to be demonstrated for the first time with OC-OTEC. This paper describes the apparatus, the major tests conducted during its first 18 months of operation, and the experience gained in OC-OTEC system operation.

BACKGROUND

Testing of Ocean Thermal Energy Conversion (OTEC) systems began in 1926 with Frenchman Georges Claude's plant in Cuba (Claude, 1930). No significant efforts in OTEC occurred after the limited success of the Claude experiments until interest in the process was revived in the 1970s. Three major experiments on closed-cycle OTEC were conducted. In the Mini-OTEC experiments, the focus was on net power production, and in the OTEC-1 experiment the focus was on improving the technology of the heat exchangers and the seawater supply system. The Japanese also demonstrated net power production with a shore-based plant in Nauru. These experiments are examples of closed-cycle OTEC systems where ammonia or R-12 refrigerant is circulated between an evaporator warmed by surface seawater and a condenser cooled by cold, deep seawater. Claude's plant used the open-cycle system where the working fluid is low-pressure steam boiled directly from the warm seawater. Closed-cycle systems found favor in the 1970s because, among other reasons, their turbines operate at significantly higher pressures and power densities than turbines found in open-cycle systems. However, closed-cycle systems also require large and potentially expensive metal heat exchangers to separate the working fluid from the seawater.

In 1978, the U.S. Department of Energy (DOE) supported investigations into the feasibility of open-cycle ocean thermal energy conversion (OC-OTEC) with a study by Westinghouse Electric Corporation of a 100-MW_e floating plant (Westinghouse, 1979). Westinghouse's study indicated that the open-cycle system offers potentially significant advantages over closed-cycle OTEC plants because it reduces the size of the heat exchangers and minimizes problems such as biofouling and corrosion of heat exchangers. OC-OTEC also produces a valuable desalinated water by-product when steam is condensed in surface condensers.

Federally funded research on OC-OTEC continued from 1978 to the present to address key uncertainties in OC-OTEC processes. Experiments on evaporators and condensers were conducted using fresh water at the Solar Energy Research Institute's (SERI) Low-Temperature Heat- and Mass-Transfer Laboratory in Golden, Colo. (Bharathan et al., 1983). Small-scale evaporators, condensers, and gas deaerators were studied at the Natural Energy Laboratory of Hawaii (NELH) using seawater. Other experiments at NELH studied surface condenser corrosion and biofouling characteristics and showed the potential for low-cost aluminum heat exchangers in OTEC applications (Larsen-Basse, 1987). Other laboratories, such as CREARE, Inc. (Sam and Patel, 1982), Oak Ridge National Laboratory (Galshani and Chen, 1981), and Alstom-Neyrtec and Ifremer in France (Fournier, 1985 and Marchand, 1986), have also contributed to improved knowledge of how key components perform under OC-OTEC conditions.

Now, a new experimental apparatus at NELH is providing researchers with valuable information on heat- and mass-transfer processes using seawater at a scale larger than previously tested. This heat- and mass transfer scoping test apparatus (HMTSTA) is the first OC-OTEC experiment to operate at thermal loads up to 1 MW using natural seawater. DOE, through SERI, and Argonne National Laboratory, constructed the apparatus at the Seacoast Test Facility (STF) at NELH on the west coast of the big island of Hawaii. After the completion of construction activities in 1987, the apparatus was operated by SERI with support from NELH. In January 1989, the Pacific International Center for High Technology Research assumed responsibility for operations. The apparatus has already provided significant data on evaporators, surface condensers, and warm seawater deaerators. At present, it is being used to study two direct-contact condenser configurations. Data obtained from these scoping tests on OC-OTEC subsystems are expected to lead directly to the design of a net

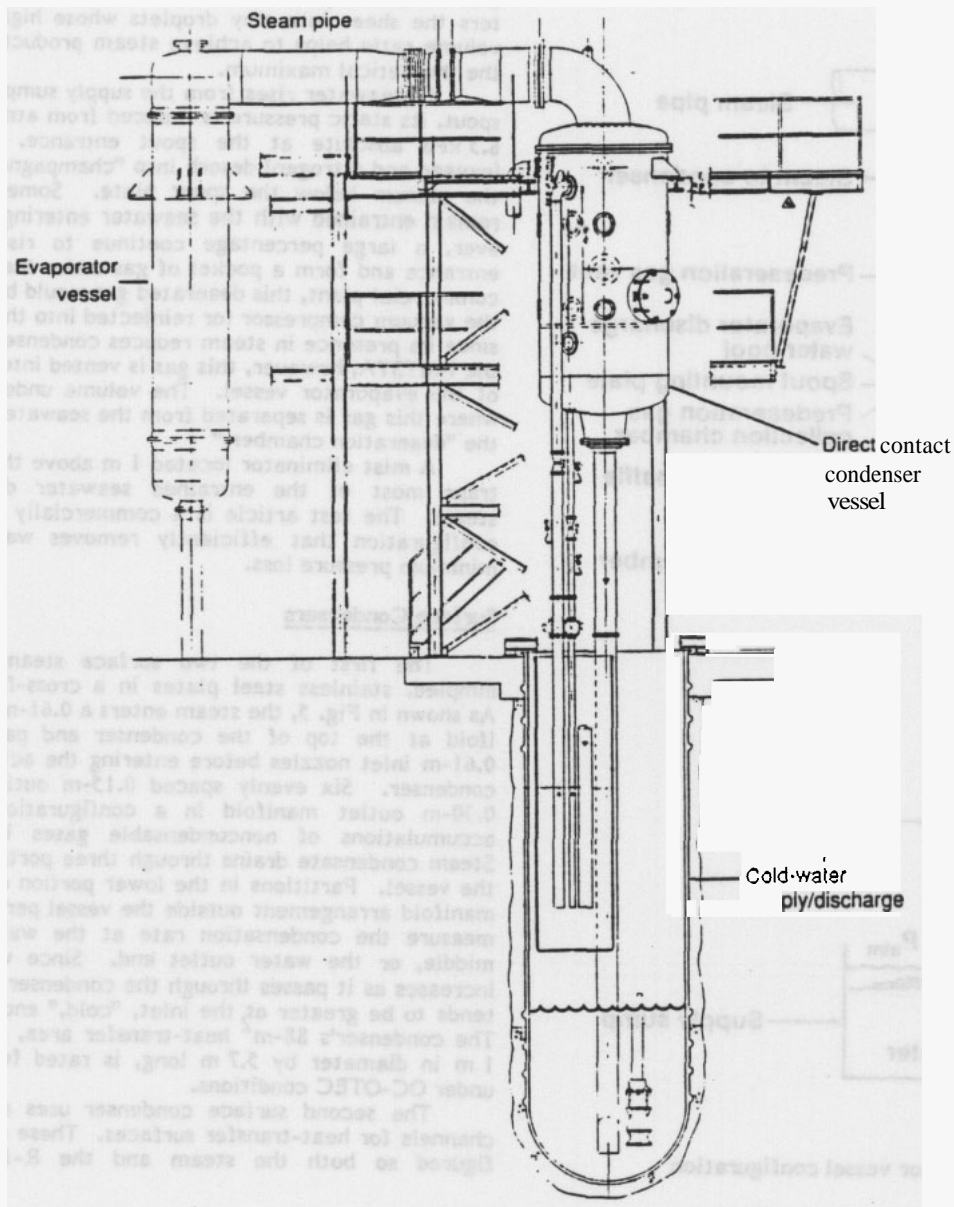


Fig. 3 Elevation view of the Phase II HMTSTA modifications

of approximately 600 m through three pipes. Capacity from the original 0.30-m cold water pipe at NELH was recently augmented by new 0.45-m and 1-m pipes (the latter was a result of a cooperative agreement between the State of Hawaii and DOE). The HMTSTA was designed to use the original capacity of the 0.30-m pipe, $0.065\text{-m}^3/\text{s}$. Delivered cold water temperature varies from about 6 deg C when the 1-m pipe is used to about 8 deg C when the 0.45-m pipe is used (due to ambient heating).

NELH also uses up to three pipes to extract warm seawater from the ocean at depths of about 15 m. Although flows up to about $0.1\text{ m}^3/\text{s}$ can be delivered using two 0.30-m pipes, a new 0.71-m pipe can supply an additional $0.630\text{ m}^3/\text{s}$. The HMTSTA was designed to use a maximum of $0.1\text{-m}^3/\text{s}$ of warm seawater. Warm seawater temperatures fall in the range of 24-28 deg C.

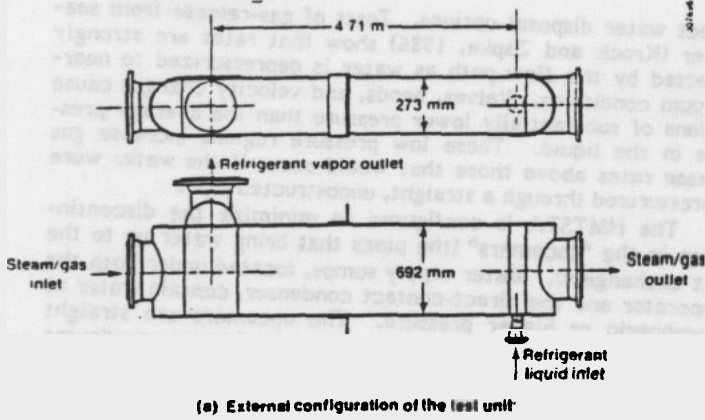
Water used in the apparatus is returned to the Ocean via the NELH disposal system where water quality checks are performed on a weekly basis.

Evaporator

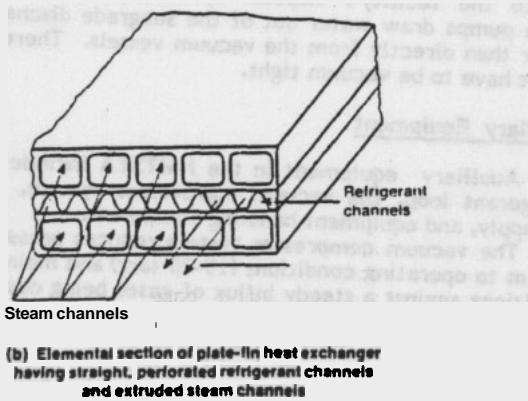
The aluminum evaporator vessel (Fig. 4) is 1.07 m in diameter by 6.9 m high. It features 0.3-m seawater supply and discharge ports, view ports, a plate suitable for mounting a variety of vertical evaporator spouts, tabs for mounting a mist eliminator, and a 0.76-m steam outlet port. Access is provided by a 0.61-m hatch just above the spout mounting plate and a removable full-diameter head.

The spout mounting plate can accommodate single spouts from 0.11 m to 0.25 m in diameter or three 0.11-m spouts equally spaced around a "bolt circle" 0.53 m in diameter. All test spouts extended 0.91 m above the spout plate and 0.82 m below the plate. The active height of the spout can be easily varied by changing the level of the discharge pool that forms above the spout plate.

Water exiting through the top of the spout forms an annular sheet until pressure is reduced to 21 kPa. At that and lower pressures, a portion of the incoming seawater flashes



(a) External configuration of the test unit



(b) Elemental section of plate-fin heat exchanger having straight, perforated refrigerant channels and extruded steam channels

Fig. 6. Second-stage surface condenser configuration

channeled through passages in a countercurrent arrangement as shown in Fig. 6. By confining steam flow through channels, the accumulation of noncondensable gas into pockets is minimized. This compact condenser has a 49-m² heat-transfer surface in a unit measuring 0.27 m high by 0.69 m wide by 5 m long. It is mounted at a slight angle so that condensate drains out the steam exhaust port.

Condensate from each surface condenser is collected in temporary holding tanks. Measurements of the level changes in these tanks add a check on heat load calculations to determine condensation rates. Since the condensate tanks are exposed to system vacuum levels, water must be pumped out. Condensate from the first stage, which can be produced at rates up to 0.0005 m³/s (7.5 gal/min) can be routed to filters and a bottling station. Laboratory analysis of the distillate indicates purity exceeding both state of Hawaii and federal drinking water standards. Bottled water samples have proven to be of great interest to government and industry representatives.

Direct-Contact Condenser

The direct-contact condenser vessel houses two condenser stages within its 1.8-m-diameter by 4.1-m-high steel walls. Since the vacuum loads are withstood by the external vessel, low-cost internal stages can be constructed out of thin-wail polycarbonate material in a variety of sizes and configurations. In Phase II, two direct-contact condenser configurations will be tested. In both configurations, the stages will be filled with a commercially available structured packing to enhance water mixing and the water-to-steam contact area.

In the first configuration, the two stages are located side by side as shown in Fig. 7, with the first stage located in the center of the vessel directly below the 0.76-m steam inlet port. Although this configuration uses a relatively small portion of the available volume in the vessel, it permits close to

ideal steam distribution in the first stage. A variable-speed, hydraulically driven water distribution nozzle in the first stage provides good water distribution under various flow rates and minimizes disturbances to the incoming steam. Since the water and steam flow in the same direction downward, it is termed a cocurrent stage.

At the bottom of the first stage, steam is free to circulate into the unused portion of the vacuum vessel. However, the steam must enter the second stage to reach the vessels exhaust port. To ensure that condensation occurs only in the two (small) condenser stages under study, the steam passage between the side-by-side stages is enclosed with a flexible sheath. This additional enclosure is required only because of the relative size between the two stages and the vessel; it would not be required in typical applications. In the second stage the steam moves upward against the falling water in a countercurrent configuration. Since little steam remains uncondensed at the top of the second stage, a simple perforated water distribution plate can be used without adversely affecting steam distribution or pressure loss.

In the second direct-contact condenser configuration, the first stage occupies an annular volume around the second stage as shown in Fig. 8. This configuration requires the steam to expand and change direction between the inlet port and the top of the packing. However, it also uses almost all of the available volume of the vessel. This configuration might well be used in a commercial OC-OTEC plant to minimize the cost of the condenser vessel.

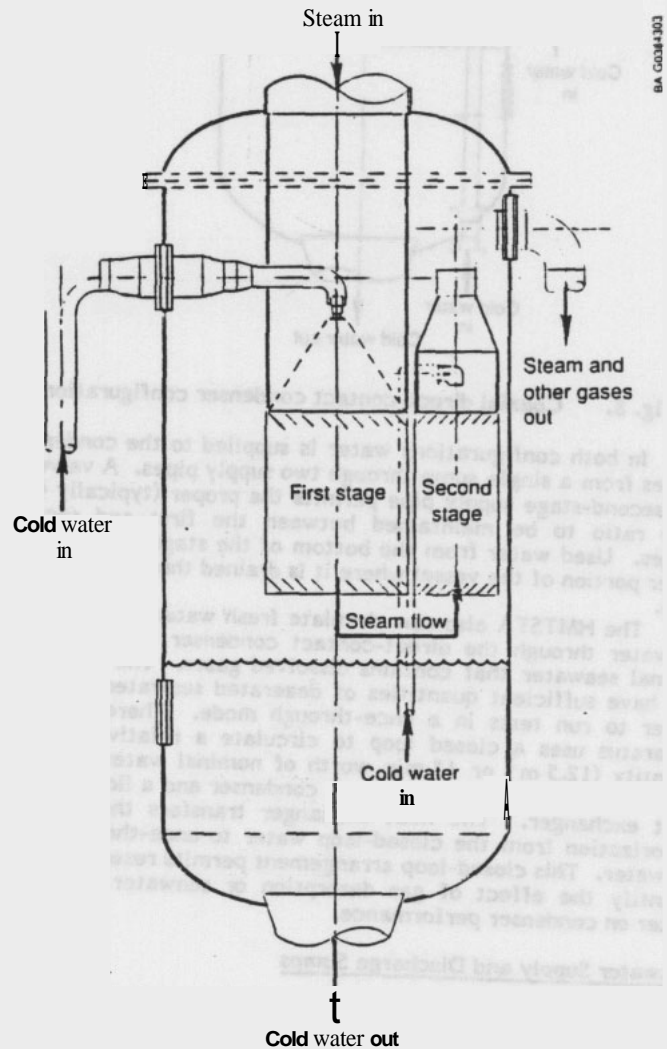


Fig. 7. Side-by-side direct-contact condenser configuration

signals from these sensors permit evaporator pressures to be maintained within 20 Pa (equivalent to 0.1 deg C change in steam saturation temperature).

Up to 64 channels of information on conditions in the apparatus are monitored and recorded using a PDP 11/23+ computer. Critical signals include water flow rates, absolute temperatures and pressures, differential temperatures and pressures, and water levels. In addition, real-time measurements are taken of dissolved oxygen and salinity levels in incoming and discharged seawater. Because of the difficulties inherent in measuring flow rate of low-density steam, researchers calculate flow rates based on heat balance measurements. Researchers from the University of Hawaii have recently installed a residual gas analyzer at the HMTSTA that promises to provide important information about noncondensable gas concentrations in the steam at various points in the system.

In addition to the main data acquisition computer, parallel signals are also recorded by a 15-channel strip chart recorder and, via an 8-channel digital voltmeter, to an IBM-compatible personal computer. These units enhance the operator's ability to ensure that steady-state conditions are achieved and that critical sensors are operating properly.

EXPERIMENTAL ACTIVITY

Experiments commenced at the HMTSTA in December 1987 and are expected to continue through the summer of 1989. This paper describes the performance parameters and test conditions expected to strongly influence performance without discussing test results. These will be documented by each test's principal investigator. However, besides obtaining information on component performance, operation of the apparatus has provided valuable information on the component interactions, controls, instrumentation, and environmental effects. These findings are discussed in this section.

Evaporator Tests

In the evaporator tests researchers sought to quantify the seawater performance of vertical spout evaporators under a variety of operating conditions. Since a substantial performance data base had been compiled using the fresh water OTEC test facility at SERI (Bharathan and Penney, 1984), these tests sought to identify the differences between fresh water and seawater performance.

The key performance characteristics for OC-OTEC evaporators are thermal effectiveness and water-side head loss. Thermal effectiveness is the ratio of the change in inlet and outlet water temperature to the temperature difference between inlet water and outlet steam. This parameter describes the evaporator's approach to the theoretical, limit where outlet steam temperature is equal to the outlet water temperature. In fresh-water tests spouts had routinely shown effectiveness levels of 90% or better with head losses of 0.30 m.

Spout thermal performance was expected to be influenced by active spout height, velocity of water in the spout, flashdown (the difference between the inlet water temperature and the outlet steam temperature), and, to a lesser extent, spout diameter and number of spouts. Scoping tests were conducted to quantify the effects of these parameters on evaporator performance. Thermal effectiveness levels of over 90% were obtained under a variety of conditions (Bharathan and Link, 1988). Two-phase flow at the spout exit increases water velocity and dynamic head loss over levels that single-phase hydraulic models would indicate. Good performance was obtained with a spout height of only 0.50 m.

Surface Condenser Tests

In surface condenser tests the primary objective was to obtain data for condensation rates under low pressure and high noncondensable gas loadings typical of OC-OTEC systems.

Since the surface condensers are not of a configuration expected to apply to larger scale systems (the first stage condenser, in particular, has a relatively short steam path and only a single-pass water path), high performance levels were not expected. However, tests provided important information on the effects of inlet steam flow, inlet noncondensable gas concentration, water flow, and the fraction of steam condensed. Performance can be quantified in terms of the overall heat-transfer coefficient and steam-side pressure loss.

The second-stage condenser is used primarily as a means to control conditions in the first-stage condenser and to reduce the total volume displacement required of the vacuum compressor. Higher flows of refrigerant through the second-stage condenser increase the amount of steam it condenses. In the first-stage condenser, this condition reduces the amount of steam condensed, increases the outlet steam velocity, and decreases the outlet percentage of noncondensable gas. Under good conditions in the second-stage condenser, the steam approaches the temperature of the refrigerant (0.5 deg C). At such cold temperatures, steam content is reduced to about 50% of the gas mixture vented from the condenser. In accounting for this condition, designers could specify a smaller displacement vacuum compressor than would otherwise be required for this apparatus.

Besides influencing system performance, the second-stage condenser provided researchers with the opportunity to study steam condensation under the special conditions of high noncondensable gas content and low densities peculiar to open-cycle OTEC. Although experiments have been conducted with direct-contact condensers under these conditions, these were the first such tests of surface condensers.

The data from these tests are presently being analyzed and compared with those of a computer model. Preliminary indications are that the data for the first-stage condenser performance appear consistent and repeatable. First-stage performance predictions made with the computer model appear to match the data reasonably well. Control problems with the refrigerant loop appear to have adversely affected the performance of the second-stage condenser.

Warm Seawater Deaeration Tests

In the warm seawater deaeration tests, the objectives were to identify the degree to which noncondensable gases desorb in a deaeration chamber and in the evaporator. This phenomenon is quantified in terms of the fraction of incoming dissolved gas released. Measuring the total rate of gas release is complicated by the difficulty of measuring dissolved nitrogen levels without expensive equipment, such as a mass spectrometer, which is not well-suited for use at this outdoor experimental facility. Therefore, for scoping test purposes, total desorption rates were based on measurements of dissolved oxygen levels only. The experimental test plan (Parsons, 1983) discusses the rationale for measurement of oxygen release as an indication of total gas release.

Deaeration rates were expected to depend on chamber pressure, water flow rate (which affects residence time), flow path geometry, and nucleation site enhancement. At lower chamber pressures, equilibrium dissolved gas levels are significantly lower than at higher pressures. In addition, bubbles of desorbed gas are larger and separate from the seawater more readily. Longer residence time increases the time for equilibrium conditions to be reached. Using a baffle plate to direct the water through a region of lower pressure before entering the spout, would be expected to enhance deaeration as would adding bubble nucleation sites through seeding techniques.

Test results are under analysis and will be reported shortly. Additional tests have been proposed to quantify the effects of warm water deaeration on condenser performance and to use recently available gas-analysis instrumentation as a check on the dissolved oxygen measurement technique.

Conclusions

The HMTSTA provided, and continues to provide, the largest, most advanced facility available for testing OC-OTEC components using natural seawater. The initial series of tests conducted in the apparatus provided valuable data that can be used to design evaporators, predeaerators, and surface condensers for larger scale OC-OTEC systems. Operational experience in the HMTSTA has helped to identify appropriate instruments and controls for OC-OTEC systems. Methods are being refined to control corrosion and leakage problems.

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