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Operational Experience of the OC-OTEC Experiments at NELH

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OPERATIONAL EXPERIENCE OF THE OC-OTEC EXPERIMENTS AT NELH

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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 Alsthom-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

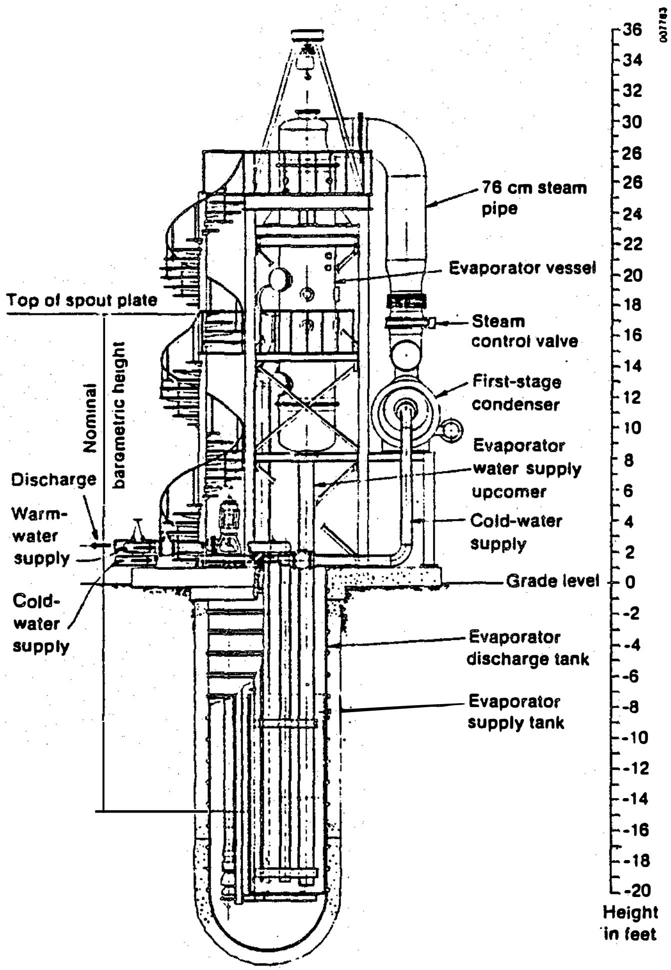


Fig. 1. Elevation view of the Phase I HMTSTA

power-producing experiment (NPPE) employing OC-OTEC technology by 1992.

DESCRIPTION OF APPARATUS

HMTSTA has been operated in two configurations. In Phase I, steam generated in a 1-m-diameter evaporator vessel was condensed in two staged surface condensers. For Phase II, a direct-contact condenser was installed in place of the first-stage surface condenser. Major features of the apparatus include

- An evaporator vessel suitable for conducting tests of evaporator spouts, warm seawater deaeration, and mist removal (Phases I and II)
- A two-stage surface condenser system, the second stage of which uses R-12 refrigerant to augment condensation capacity (Phase I configuration only)
- A direct-contact condenser vessel suitable for two internal condenser stages (Phase II configuration only)
- A closed water circulation loop to permit testing of the direct-contact condenser with deaerated seawater and fresh water (Phase II configuration only)
- Supply and discharge sumps located directly under the evaporator and direct-contact condenser vessels (Phases I and II)
- A vacuum compressor system to produce and maintain the subatmospheric pressures required for steam production (Phases I and II)
- Instruments and controls to monitor and adjust test conditions (Phases I and II).

Figures 1 and 2 show the apparatus in its Phase I configuration. Figure 3 shows how the the Phase II direct-contact condenser was integrated into the existing structure.

The following is a brief description of the major components of the apparatus.

Seawater System

Water is delivered to the HMTSTA by the NELH seawater supply system. This system draws cold seawater from depths

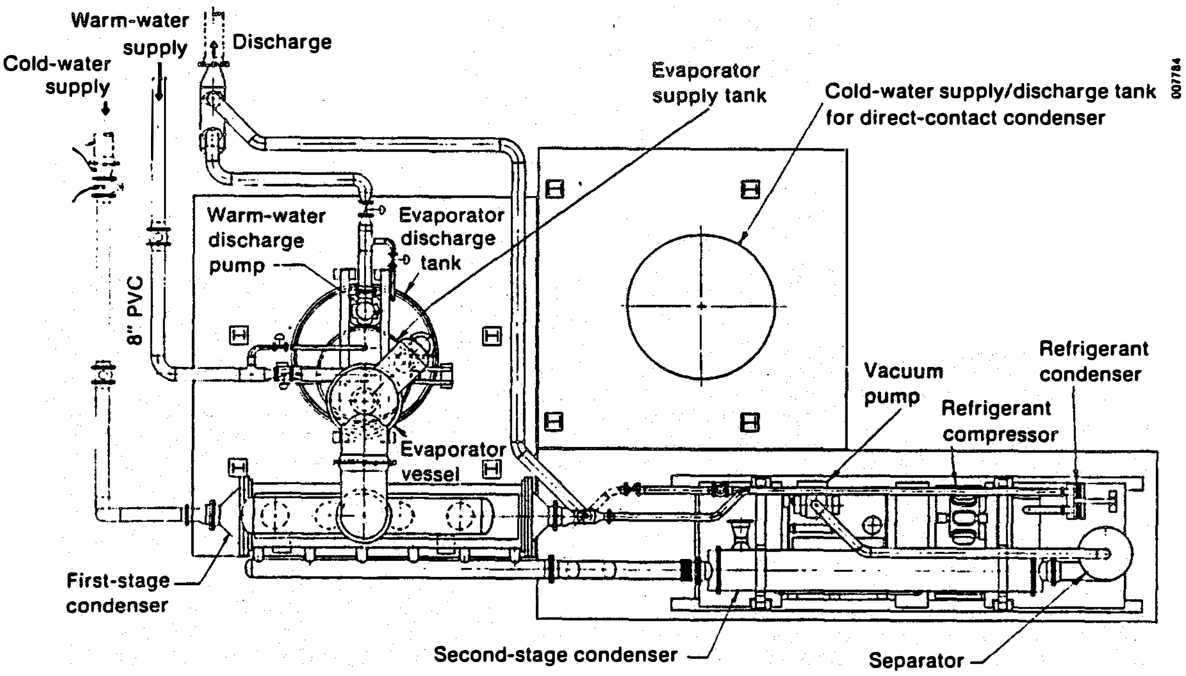


Fig. 2. Plan view of the Phase I HMTSTA

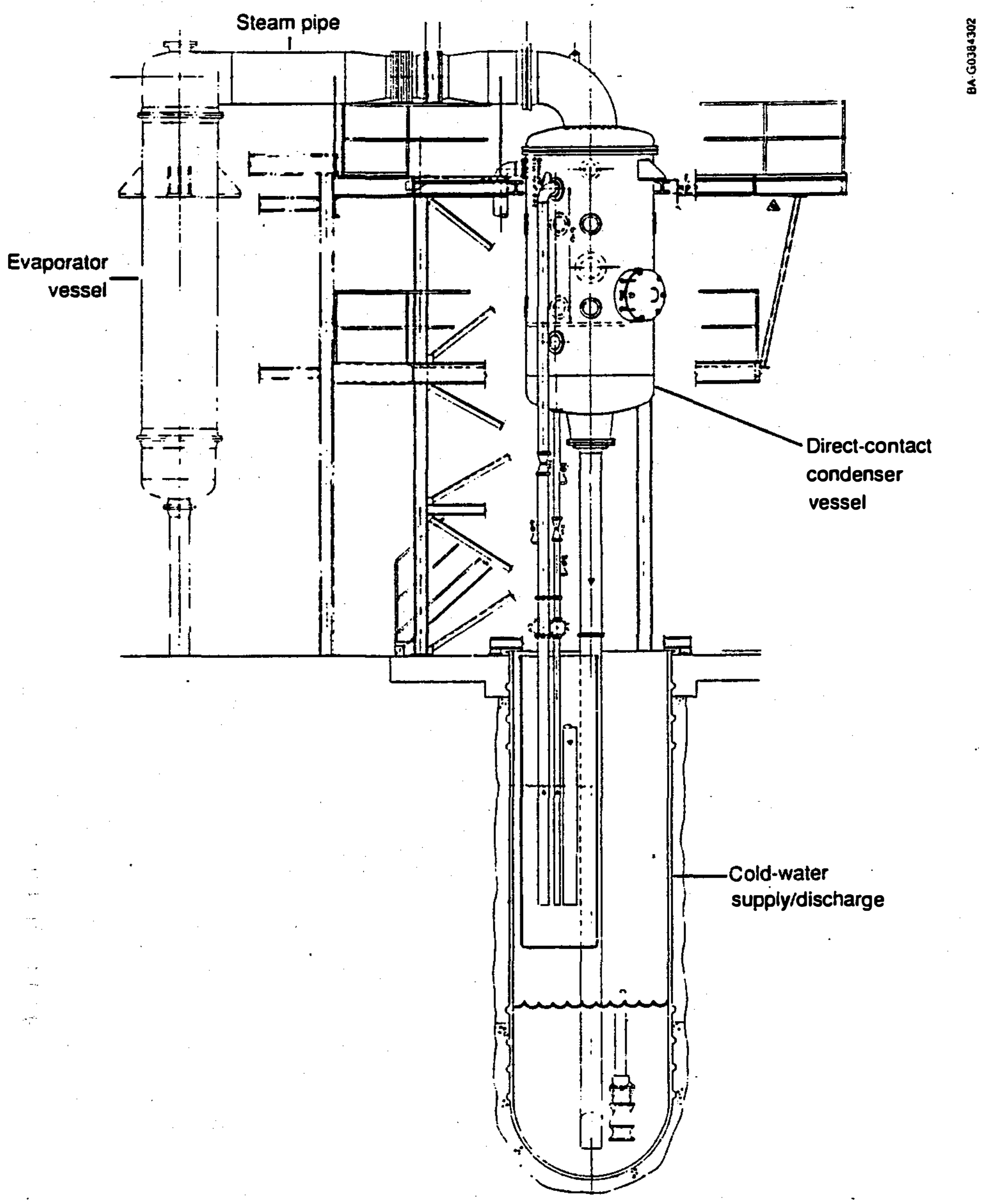


Fig. 3. Elevation view of the Phase II HMTSTA modifications

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-m^3/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 m^3/s can be delivered using two 0.30-m pipes, a new 0.71-m pipe can supply an additional 0.630 m^3/s. The HMTSTA was designed to use a maximum of 0.1-m^3/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

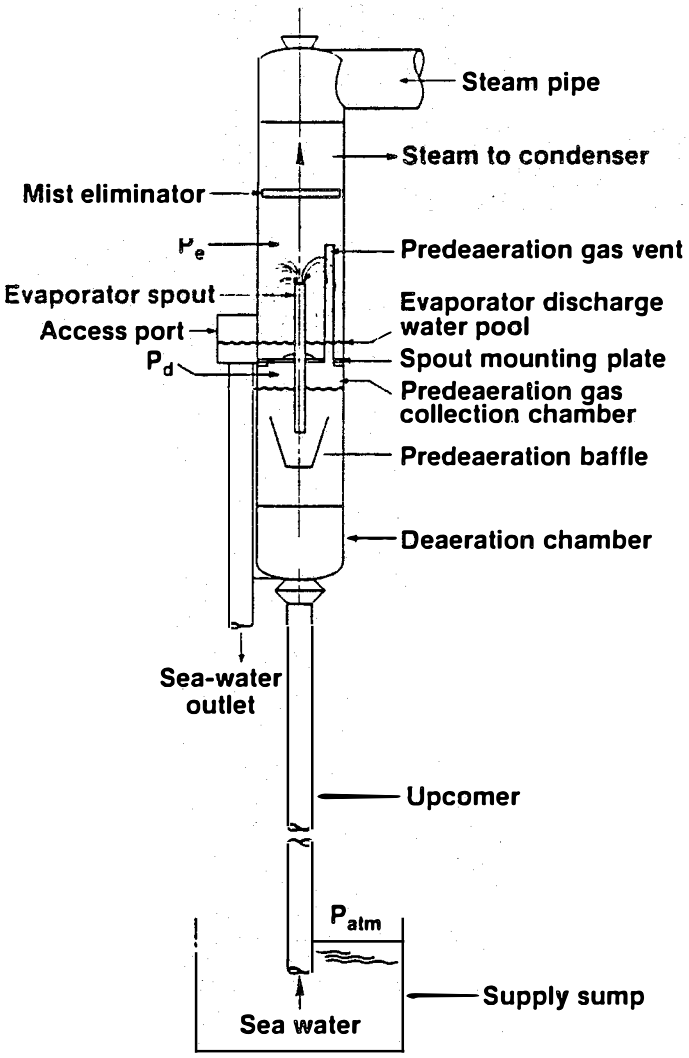


Fig. 4. Evaporator vessel configuration

into steam. Expansion of this steam at the spout's outlet shatters the sheet into tiny droplets whose high surface-area-to-volume ratio helps to achieve steam production rates close to the theoretical maximum.

As seawater rises from the supply sump to the evaporator spout, its static pressure is reduced from atmospheric to about 6.5 kPa absolute at the spout entrance. Dissolved gases (oxygen and nitrogen) desorb into "champagne" bubbles that fill the plenum below the spout plate. Some of these bubbles remain entrained with the seawater entering the spout. However, a large percentage continue to rise past the spout entrance and form a pocket of gas under the spout plate. In a commercial plant, this deaerated gas would be piped directly to the vacuum compressor (or reinjected into the discharge water) since its presence in steam reduces condenser performance. In the HMTSTA, however, this gas is vented into the upper portion of the evaporator vessel. The volume under the spout plate, where this gas is separated from the seawater, is referred to as the "deaeration chamber."

A mist eliminator located 1 m above the top of the spout traps most of the entrained seawater droplets from the steam. The test article is a commercially available, chevron configuration that efficiently removes water droplets with minimum pressure loss.

Surface Condensers

The first of the two surface steam condensers uses dimpled, stainless steel plates in a cross-flow configuration. As shown in Fig. 5, the steam enters a 0.61-m distribution manifold at the top of the condenser and passes through four 0.61-m inlet nozzles before entering the active portion of the condenser. Six evenly spaced 0.15-m outlet nozzles feed a 0.30-m outlet manifold in a configuration that minimizes accumulations of noncondensable gases in the condenser. Steam condensate drains through three ports on the bottom of the vessel. Partitions in the lower portion of the vessel and a manifold arrangement outside the vessel permit researchers to measure the condensation rate at the water inlet end, the middle, or the water outlet end. Since water temperature increases as it passes through the condenser, condensation rate tends to be greater at the inlet, "cold," end of the condenser. The condenser's 88-m^2 heat-transfer area, located in a vessel 1 m in diameter by 5.7 m long, is rated for 1.1 MW thermal under OC-OTEC conditions.

The second surface condenser uses extruded aluminum channels for heat-transfer surfaces. These extrusions are configured so both the steam and the R-12 refrigerant are

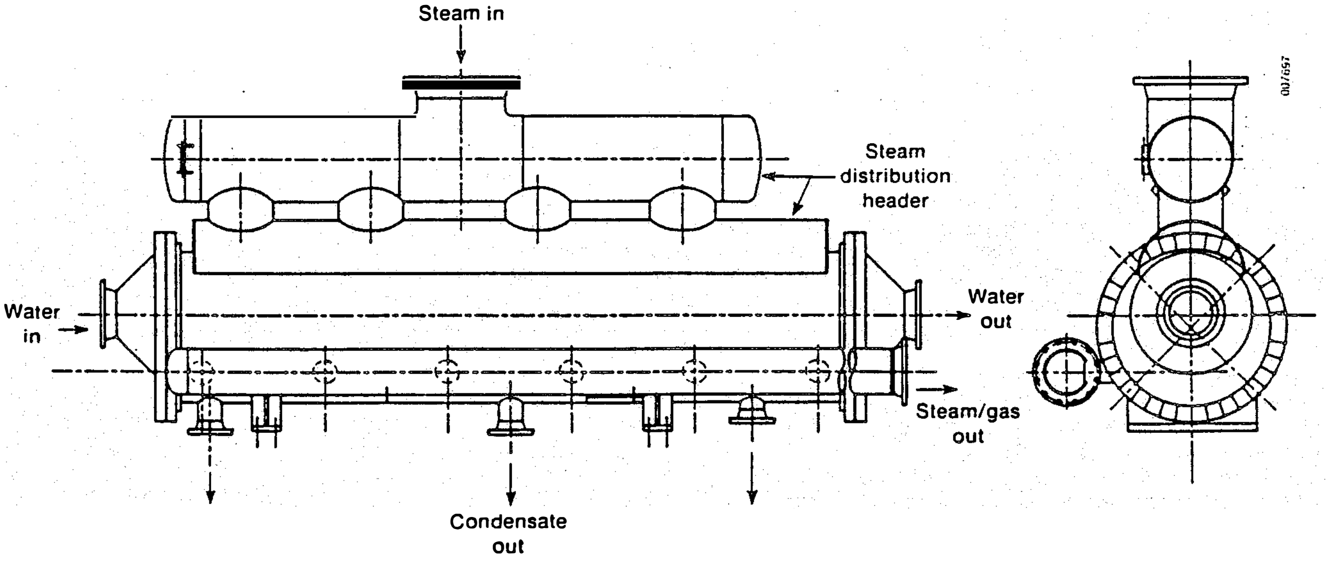
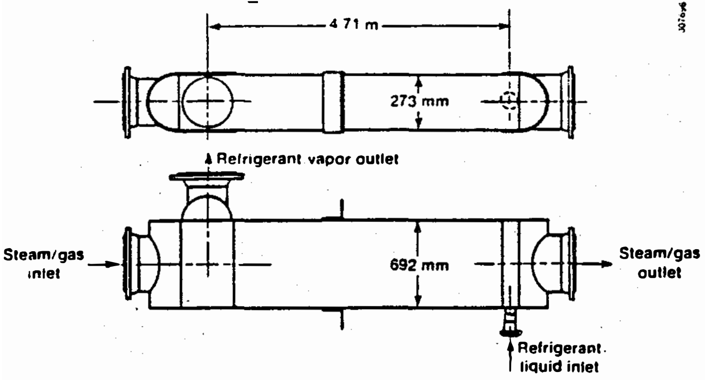
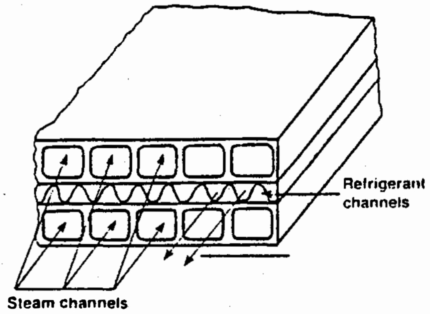


Fig. 5. First-stage surface condenser configuration



(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-m^2 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 adds 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 m^3/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-wall 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.

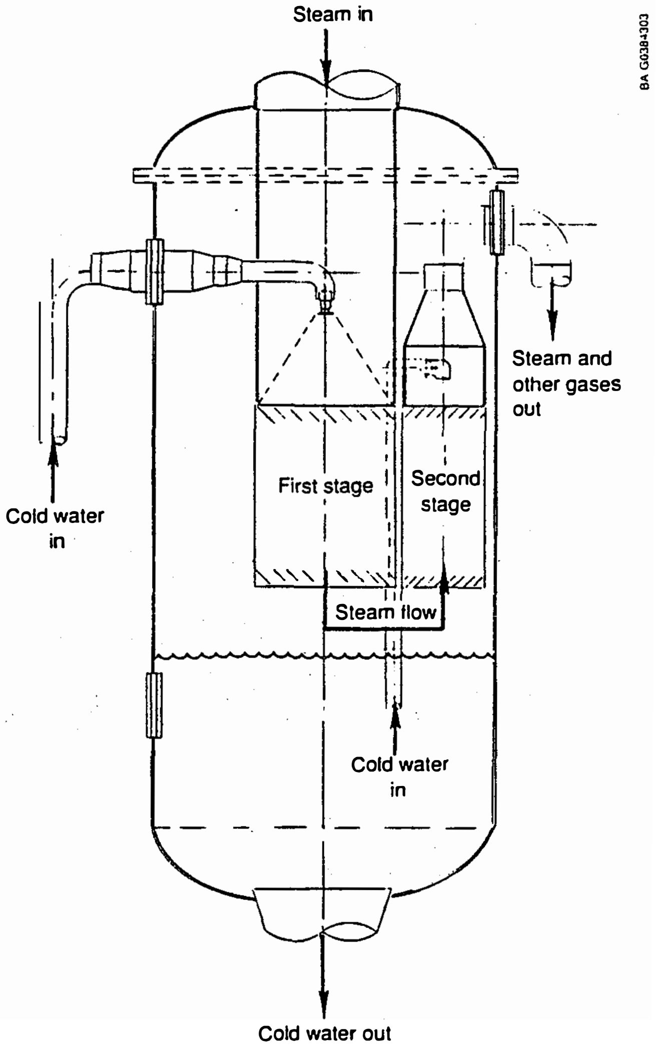


Fig. 7. Side-by-side direct-contact condenser configuration

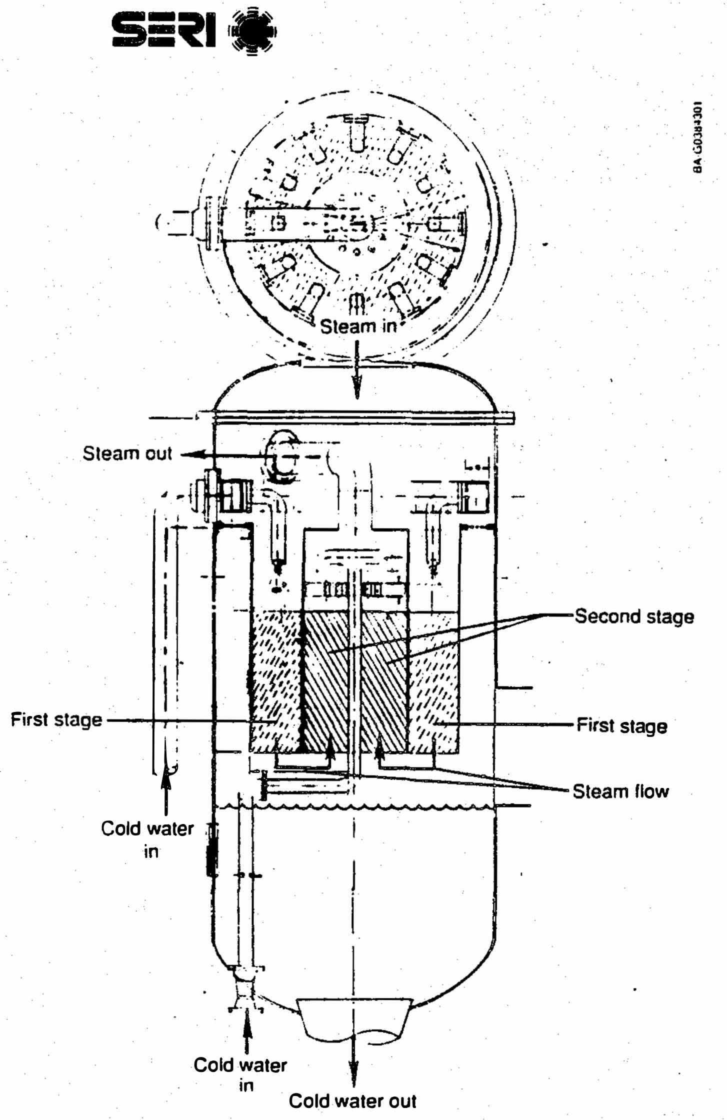


Fig. 8. Coaxial direct-contact condenser configuration

In both configurations water is supplied to the condenser stages from a single sump through two supply pipes. A valve in the second-stage supply pipe permits the proper (typically 4:1) flow ratio to be maintained between the first and second stages. Used water from the bottom of the stages falls to the lower portion of the vessel where it is drained through a 0.30-m pipe.

The HMTSTA also can circulate fresh water or deaerated seawater through the direct-contact condenser in addition to normal seawater that contains dissolved gases. The STF does not have sufficient quantities of deaerated seawater or fresh water to run tests in a once-through mode. Therefore, the apparatus uses a closed loop to circulate a relatively small quantity (12.5 m^3 or 13 min worth of nominal water flow) of water between the direct-contact condenser and a liquid-liquid heat exchanger. The heat exchanger transfers the heat of vaporization from the closed-loop water to once-through cold seawater. This closed-loop arrangement permits researchers to quantify the effect of gas desorption or seawater vs. fresh water on condenser performance.

Seawater Supply and Discharge Sumps

One area of concern with OC-OTEC is the release of dissolved gases when seawater is exposed to subatmospheric pressures in the heat exchangers. These desorbed gases increase the size and parasitic power requirements of the vacuum compressor, decrease condenser performance, and affect water disposal options. Tests of gas-release from seawater (Krock and Zapka, 1986) show that rates are strongly affected by the flow path as water is depressurized to near-vacuum conditions. Valves, bends, and velocity changes cause regions of substantially lower pressure than the average pressure in the liquid. These low pressure regions increase gas release rates above those that would occur if the water were depressurized through a straight, unobstructed pipe.

The HMTSTA is configured to minimize the discontinuities in the "upcomers" (the pipes that bring water up to the heat exchangers). Water supply sumps, located under both the evaporator and the direct-contact condenser, contain water at atmospheric or higher pressure. The upcomers are straight and, except for one valve in the second-stage condenser upcomer, free of obstructions. Thus, deaeration rates are expected to be minimized in the normal configuration.

Discharge sumps are also used in the apparatus even though they are not critical for deaeration studies. Since the heat exchangers are located lower than required for free drainage to the facility's disposal system, pumps are required. These pumps draw water out of the subgrade discharge sumps rather than directly from the vacuum vessels. Therefore, they do not have to be vacuum tight.

Auxiliary Equipment

Auxiliary equipment in the HMTSTA includes the R-12 refrigerant loop, the vacuum compressor system, instrument air supply, and equipment handling equipment.

The vacuum compressor system reduces pressures in the system to operating conditions (10-20 torr) and maintains these conditions against a steady influx of gases being desorbed from seawater and leaking into the vessels. The three-stage system uses a mechanical, blower-type first stage that achieves a compression ratio between 3 and 4 to 1. A two-stage liquid ring pump completes the work of compression to atmospheric pressure. To maintain its relatively high compression ratio, the water sealant for the liquid-ring pump must be maintained below 20 deg C at the inlet to the pump. A small, R-12-cooled, shell-and-tube heat exchanger removes the heat from the sealant water.

The refrigerant loop provides low-temperature liquid R-12 refrigerant to the second-stage surface condenser and to the small heat exchanger for the liquid-ring pump. Heat absorbed by the refrigerant in these two heat exchangers is rejected to cold seawater in a multiple-plate, counterflow heat exchanger.

Controls and Instrumentation

The HMTSTA operator obtains and maintains desired test conditions using a variety of manual and automatic controls. Primary controls include warm and cold seawater flow rates, water levels in the evaporator and direct-contact condenser vessels, and evaporator steam pressure. The typical seawater valving arrangement includes a 0.15- or 0.20 m manually controlled "roughing" valve in parallel with a 0.10-m, remotely operated, "fine-tuning" valve. Water level in the condenser vessel is controlled by varying the rotational speed of the cold water discharge pump using a variable-frequency drive. Desired evaporator pressure is maintained by adjusting a 0.61-m butterfly valve located between the evaporator and the condenser.

Since seawater is supplied to the apparatus from header tanks at a constant pressure, consistent flow rates can be achieved without automatic feedback loops. Signals for feedback loops to maintain water levels in the vacuum vessels can be provided by either level sensors in the vessels themselves or level sensors in the subgrade discharge sumps. Although pressure sensors are available to control evaporator pressure automatically, a more sensitive signal is obtained from differential temperature sensors. These sensors relate the difference in temperature between the evaporator's inlet and discharge water streams. With a full-scale range from 0 to 7.5 deg C, 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 0.80 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, 1988) 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.

Direct-Contact Condenser Tests

Tests of the direct-contact condenser had not begun as of the writing of this paper, although preliminary results may be available by the time of the conference.

Planned tests will investigate the effects on performance of inlet gas flow rate, pressure, noncondensable gas content, water flow rate and type (normal, deaerated, or desalinated), and packing height. Performance will be characterized primarily as thermal effectiveness and percentage of steam condensed. Tests conducted with fresh water at SERI's OTEC laboratory indicated that two-stage direct-contact condensers can condense 96-99% of the incoming steam at a thermal effectiveness of over 90%. Although thermal effectiveness may drop to about 86% due to the difference in physical properties between fresh water and seawater, performance levels in this range would improve confidence in selecting this condenser configuration for larger scale experiments.

General Operational Experience

System stability. In addition to results pertaining to component performance, the HMTSTA has yielded information important to integrating components into a working OC-OTEC system. Of primary importance in system integration is the stability of operation. Experience shows that little active control is required to maintain stable conditions in systems using surface condensers. Note that the HMTSTA uses a throttling valve rather than a turbine to cause a pressure drop between the evaporator and the condenser. A turbine/generator's response to transient electrical loads or steam conditions will be different. However, even without adjusting the throttling valve position, the evaporator and condenser maintained quite steady operating conditions. If, for example, warm water flow increases slightly, the temperature change in the warm water tends to decrease correspondingly to maintain a constant steam flow rate through the throttling valve. Condenser conditions do not change significantly. Although an automatic feedback loop can be used to adjust the throttling valve position as a function of evaporator pressure (or temperature change), the system operator found that good steady-state conditions can be achieved without this feedback loop.

Similarly, changes in evaporator operating pressure over the range of interest has essentially no effect on warm water flow rate and require no readjustment of supply valve settings. This lack of interaction might be expected when one considers that changing the steam temperature 5 deg C will change the evaporator pressure by less than 1 kPa. Thus, the total head loss in the warm water delivery system is changed less than 0.1 m or 0.1% of the total head available. Cold water flow rate through the surface condenser is completely independent of vacuum system conditions.

Discharge water level for the evaporator does require active control measures. However, since evaporator performance is not strongly affected by slight changes in active spout height, it was not crucial to maintain levels within tight tolerances. Thus, controls were not difficult to adjust and maintain. Experience thus far with the variable-frequency controller for the cold water discharge pump indicates that water levels in the direct-contact condenser vessel can be maintained within a few centimeters of the desired setting even though the response time to change pump speed is significantly slower than the equivalent change in valve position.

A potentially significant cost item in large-scale systems is a control valve at the inlet of the turbine. Because of the size of the turbine and the need to minimize steam pressure loss in OC-OTEC, this valve would be quite large. Experience with the HMTSTA, however, indicates that steam flow rate through the system can be quickly lowered by either venting atmospheric air into the condenser or by throttling gas at the inlet to the vacuum compressor. In the first case, venting enough air to increase system pressure by only 500 Pa immediately stops production of steam in the evaporator. A 0.05-m solenoid valve permits this pressure increase to occur in less than 1 s. In the second case, a pneumatically operated, 0.20-m butterfly valve just upstream of the vacuum compressor can be closed in 3 s. Under typical operating conditions this closure increases system pressure at a rate of 200 Pa/s and effectively terminates steam production in less than 5 s total. Although response time is slower, the system can be restored to normal conditions much faster than when air is vented into the system.

Instrumentation

One of the more difficult aspects of operating this apparatus is the maintenance of accurate measurement systems. Although the accuracy required for experimental purposes exceeds that required for commercial plant operation, even a commercial system would require monitoring very small temperature changes. For example, a 0.5 deg C temperature change in the evaporator outlet steam would result in a 16% change in steam flow rate. To date, two configurations of RTDs have been installed: absolute temperature and temperature differential.

Pretest analysis and early evaporator test results (Bharathan, 1988) indicated that the differential temperature probes could achieve accuracies of better than 0.06 deg C. However, in long-term operation, accuracies of the differential sensor have degraded such that, at present, they may error as much as 0.2 deg C--about the same accuracy as the absolute temperature probes provide. Investigations are now being made into the use of thermistors to provide long-term, accurate measurements for OC-OTEC systems.

After the premature failure of eight pressure sensors in the HMTSTA, good reliability was demonstrated by industrial-type pressure transducers used to monitor system vacuum levels. Although these sensors provide essential data to researchers, the system can be operated with very few pressure sensors. The most important pressure sensor for operation provides a coarse indication of system pressure during startup, shut down, and leak checks. Other important pressure sensors are those that indicate liquid levels. High reliability was achieved with "bubble-tube" level sensors where instrument air is slowly bled into the bottom of each water tank. The pressure required to maintain this air flow is proportional to the liquid level, and the pressure sensor is exposed to clean air rather than seawater.

One of the unexpected lessons learned from operating the HMTSTA was that external corrosion from salt-ladened sea breezes is as important as internal corrosion from the seawater flows or droplet carry-over. Instruments, vacuum vessels and their support structures, and mechanical equipment all are susceptible to corrosion and degradation. In particular, electrical connections to the temperature probes require careful protection to ensure current leakage between conductors does not affect measurements.

Vacuum Integrity

OC-OTEC systems require stringent procedures to maintain low vacuum leak rates. Air leaking into the system increases vacuum compressor power and decreases condenser performance. In the HMTSTA, vacuum leaks are often caused by changes to the apparatus required as part of experimentation procedures. Originally the system demonstrated a leak rate of only 2.5 mg/s, less than 0.5% of the gas normally released from warm seawater in the evaporator. Just before the change to the direct-contact condenser, leak rates were measured between 30 and 50 mg/s. Although these leak rates are still a relatively small fraction of gas desorbed from seawater, a continual effort is made to find and eliminate leaks throughout the system.

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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