Experiments on Oxygen Desorption from Surface Warm Seawater under Open-Cycle Ocean Thermal Energy Conversion (OC-OTEC) Conditions

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NOTICE

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ABSTRACT

This paper reports the results of scoping deaeration experiments conducted with warm surface seawater under open-cycle ocean thermal energy conversion (OC-OTEC). Concentrations of dissolved oxygen in seawater at three locations (in the supply water, water leaving a predeaerator, and discharge water from an evaporator) were measured and used to estimate oxygen desorption levels.

The results suggest that 7% to 60% of dissolved oxygen in the supply water was desorbed from seawater in the predeaerator for pressures ranging from 9 to 35 kPa. Bubble injection in the upcomer increased the oxygen desorption rate by 20% to 60%. The dependence of oxygen desorption with flow rate could not be determined. The data also indicated that at typical OC-OTEC evaporator pressures when flashing occurred, 75% to 95% of dissolved oxygen was desorbed overall from the warm seawater.

The uncertainty in results is larger than one would desire. These uncertainties are attributed to the uncertainties and difficulties in the dissolved oxygen measurements. Methods to improve the measurements for future gas desorption studies for warm surface and cold deep seawater under OC-OTEC conditions are recommended.

NOMENCLATURE

C_{eq}	= equilibrium dissolved oxygen concentration of water (mg/L)
C_{in}	= dissolved oxygen concentration of water in the supply pipe (mg/L)
C_{spout}	= dissolved oxygen concentration of water at the spout inlet leaving the predeaerator (mg/L)
C_{out}	= dissolved oxygen concentration of evaporator discharge water (mg/L)
D.O.	= dissolved oxygen
F_{eq}	= fraction of gas desorbed when water is at equilibrium conditions
F_{pd}	= fraction of gas desorbed in the predeaeration chamber
F_{ev}	= fraction of gas desorbed in the evaporator chamber
F_t	= total fraction of gas desorbed from the surface seawater
E_{pd}	= deaeration effectiveness
P_{pd}	= predeaerator pressure (kPa)

INTRODUCTION

The temperature difference between warm surface water and the deep cold water in the ocean can be used in OC-OTEC plants to generate electricity by operating a Rankine cycle system. Warm surface seawater at about 25°C is fed into an evaporator maintained at pressures below the vapor pressure of the incoming water (about 2.7 kPa). Flash evaporation occurs, generating steam. The steam is expanded through a low-pressure turbine coupled to a generator that produces electricity. The steam exits the turbine at about 1.2 kPa pressure and is condensed using cold seawater (at about 5°C) pumped from deep ocean layers in condensers, either direct contact, surface, or a combination of the two.

Seawater contains dissolved gases (oxygen, nitrogen, and carbon dioxide), bubbles, and suspended particles. As the seawater moves into the low-pressure OC-OTEC system environment, it becomes supersaturated. Therefore, dissolved gases are evolved from the water stream, especially in the presence of nucleation sites (bubbles and suspended particles). Desorption of these noncondensable gases in the evaporator and condensers degrades the condensers' performance [1]. More importantly, to maintain the vacuum levels in the exchangers, additional pumping power is required to remove the noncondensable gases. These effects are estimated to decrease the net power production of an OC-OTEC power plant by 10% [2,3]. Part of the noncondensable gases can be removed from seawater before they enter the evaporator or condensers by a predeaeration scheme, possibly with low parasitic power losses. Experimental data are required to determine how much gas desorbs at various stages of an OC-OTEC system and to validate prediction methods.

It should be noted that deaeration is defined as release of dissolved gases from the seawater in the OTEC evaporator and condensers. Predeaeration is defined as release and removal of dissolved gases from the seawater before it enters the evaporator and condensers. Both deaeration and predeaeration consist of two essential steps. First, the dissolved gases leave the liquid phase and enter bubbles. Second, the bubbles are separated from the bulk of liquid.

Because of difficulties in measuring nitrogen concentrations, previous OTEC deaeration experiments were typically conducted by monitoring levels of oxygen release and inferring overall gas release from this measurement. Oxygen release level is defined as

1

$$\frac{\text{(initial concentration - final concentration)}}{\text{initial concentration}}.$$

Lindenmuth et al. [4] investigated gas desorption in a barometric upcomer (with internal diameter of 0.1 m) using fresh water (with flow rates of about 2.8 to 13.7 kg/s). They found a small dissolved oxygen (D.O.) release (less than 8%) using filtered tap water and an increase of deaeration levels with decreasing water flow rates. Golshani and Chen [5] investigated deaeration of fresh water in a barometric upcomer (with internal diameter of 0.05 m) and a packed column (with flow rates of 1.5 to 3.5 kg/s). They found less than a 20% D.O. release in the upcomer and an increase in percent oxygen release with an increase in water flow rate. The dependency of gas release on water flow rate differed in the two experiments, possibly because of differences in experimental set-ups and water sampling techniques.

Krock and Zapka [6] studied the deaeration of fresh water and seawater in a packed column, an upcomer (with internal diameter of 0.05 m), and a debubbler (with water flow rates of 1.2 to 5 kg/s). In most of their experiments D.O. measurements were used to estimate the level of deaeration. Dissolved nitrogen was measured only in a limited number of experiments using a gas chromatograph. They found that up to 80% of dissolved gases in warm seawater can be desorbed at pressure as low as 5 kPa. They also found that deaeration levels are higher in surface seawater than in deep seawater, possibly because of the presence of a larger number of nucleation sites in the surface seawater. There were only small differences between deaeration levels of deep seawater and fresh water. Deaeration levels were found to be practically insensitive to water velocity. They recommended oxygen as a good indicator for total gas exchange for surface seawater but not for deep seawater.

Later, Zapka [7] studied deaeration of fresh and recirculated seawater (with flow rates of 0.5 to 1.3 kg/s) in a packed column, a barometric upcomer (with internal diameter of 0.075 m) and a debubbler. He also studied reinjection of air in a downcomer. He found that the D.O. release level in seawater was between 10% and 20% in the deaerator. In his experiments oxygen release level increased with the decrease of flow rate. The oxygen release level was increased to 80%-90% upon injection of air bubbles.

Figure 1 shows typical results of these experiments [4-7]. In all these studies the level of oxygen release increased as the pressure decreased.
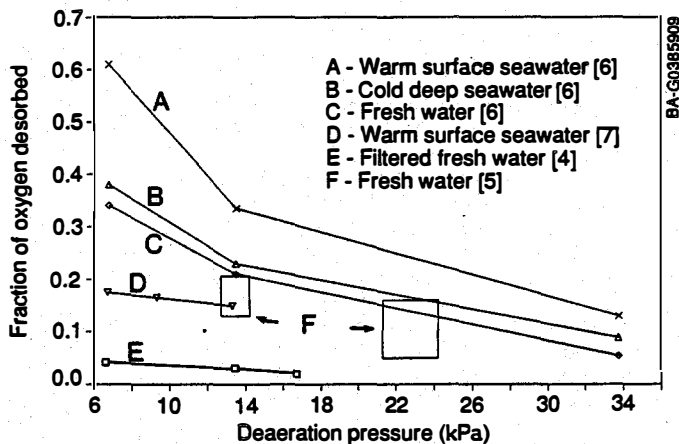

Fig. 1. Typical deaeration results of different experiments available with estimated error band with fresh water and seawater

Ghiaasiaan et al. [8] mathematically modeled the desorption process of dissolved oxygen, nitrogen, and carbon dioxide in the barometric upcomers of an OTEC plant. Their model considered the growth of bubbles due to gas mass transfer, evaporation, and decrease of hydrostatic pressure in the upcomers. Growth of bubbles, originated in ocean surface layers and/or formed in the upcomers, was considered. Heterogeneous nucleation at pipe wall crevices and on suspended particles, as well as bubble coalescence, was considered.

Previous experimental and analytical studies on gas desorption in OTEC upcomers agree on two things: (1) gas desorption rate increases with decrease of pressure and (2) presence of nucleation sites enhances the gas desorption rates. However, these studies show conflicting trends on dependency of gas release rate on the water flow rate and flow path geometry. Most of these experiments were performed in small-scale test loops, not prototypical of OTEC test facilities. Recently, deaeration tests were conducted in a heat- and mass-transfer scoping test apparatus (HMTSTA) located at the Natural Energy Laboratory of Hawaii (NELH) on Keahole Point, Hawaii.

The objectives of this study, gas desorption tests with warm water in the HMTSTA, were to determine (1) how much gas was desorbed in a large-scale OTEC experiment with typical OC-OTEC operating conditions, (2) the dependency of gas desorption on water flow rate, and (3) the effect of bubble injection on gas desorption. This paper presents the results of gas desorption tests conducted with warm surface seawater in the evaporator and predeaerator during the summer of 1988.

DESCRIPTION OF EXPERIMENT

Apparatus

The HMTSTA was configured primarily to permit testing of OC-OTEC components. The apparatus uses warm surface seawater, cold deep seawater, and electrical power supplies available at the NELH. The major features of the apparatus are

- An evaporator vessel suitable for conducting tests of warm seawater evaporation and predeaeration
- An evaporator water supply/discharge tank located directly under the evaporator vessel and associated upcomer and downcomer pipes
- Surface and direct-contact condenser systems
- A vacuum compressor system to mechanically produce and maintain the subatmospheric pressures required for seawater evaporation
- Instruments and controls to adjust, monitor, and record test conditions.

Table 1 provides the general specification of the apparatus. A more detailed description of each component of the facility is given by Parsons et al. [2].

Table 1. General Specifications for the HMTSTA

Parameter	Value
Maximum warm water flow	103 L/s
Warm water temperature	25°-27°C
Maximum cold water flow	65 L/s
Cold water temperature	6°-8.5°C
Steam flow rate	0.02-0.5 kg/s
Evaporator pressure	2.34 kPa
Condenser pressure	1.4 kPa

Figure 2 shows a schematic of the apparatus for warm seawater predeaeration experiments. The evaporator vessel, which also was used to perform deaeration tests, is 1.07 m in diameter, about 6.9 m high, and made of aluminum. Warm surface seawater enters the vessel from a supply tank through a 0.3 m upcomer. About 1.5 m of the upcomer, just below the

bottom of the vessel, is made of transparent acrylic to allow flow visualization. The rest of the upcomer is made of PVC pipe. A spout mounting plate is installed at the height of 2.7 m from the bottom of the vessel. The water from the top of the spout plate is discharged via a 0.3 m. PVC pipe to the warm water discharge tank. The water from the discharge tank is drained via a sump pump into the NELH water disposal system.
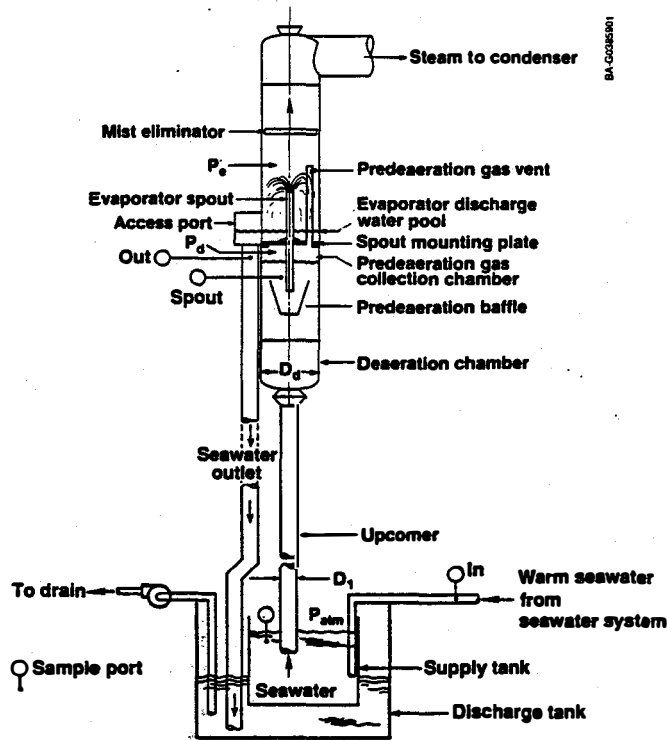

Fig. 2.   Schematic of deaeration experiment

The partitioned supply/discharge tank is provided under the evaporator as a means to control flow rates, establish barometric legs, and facilitate predeaeration studies. The water level in the supply tank is about 10 m below the evaporator spout plate. The noncondensable gases released due to low pressures are trapped beneath the spout plate. In the HMTSTA a vent line allows trapped gases to be vented into the evaporator chamber or to the vent compressor. Here, the volume under the spout plate is referred to as the "predeaeration chamber."

Spouts with a 0.25 m diameter and heights of 0.5 and 0.25 m above the spout plate were used. The length of both spouts was 0.64 m below the spout plate. A tap on the spout plate was connected to the evaporator chamber with a vent tube and a regulating valve. Because the configuration of an OC-OTEC plant may differ from that of the HMTSTA, the flow dynamics of the apparatus may not be prototypical of an OC-OTEC system.

To investigate the impact of gas bubble injection on gas desorption level, nitrogen gas bubbles were injected in the middle of the evaporator supply pipe (upcomer) via four porous tubes. An increase in the number of nucleation sites can increase the fraction of gas desorbed [7,8].

Instrumentation

To characterize the deaeration process, the following major measurements were made:

- Warm water flow rate
- Water temperatures inlet to and outlet from the evaporation/deaeration vessel
- Pressure in the predeaeration and evaporator chambers
- Water levels in the predeaeration and evaporator chambers
- Dissolved oxygen concentrations of water at three locations:
  - at the inlet to the upcomer
  - at the entrance to the spout (exit of the predeaeration chamber)
  - at the outlet from the evaporator discharge pipe.

All the temperatures were measured with resistance temperature devices (RTD). Strain gauge and capacitance transducers were used for pressure measurements. Vortex-shedding flow meters were used for measuring seawater flow rates. Strain gauge sensors and metered sight glasses were used to measure liquid levels. The D.O. concentrations were measured with Clark-type membrane-covered polarographic sensors. A minicomputer-based data acquisition system was used to sample sensor outputs, carry out necessary calculations, and record all test data. The computer sampled the data automatically at a rate specified and kept running averages of the measured values. The average values were stored on a disk for later analysis.

Oxygen Measurement

More than 98% of the dissolved gases in warm surface seawater is oxygen and nitrogen; the other 2% is mainly free (i.e., molecular) carbon dioxide [9] with minute amounts of other inert gases [10]. Measurements near the experiment site, Keahole Point in Hawaii, have shown that the D.O. concentration in warm surface seawater is about 6.8 ± 0.3 mg/L; the nitrogen concentration, about 11.2 ± 0.8 mg/L; and free carbon dioxide concentration, about 0.34 mg/L [9]. Because the amount of carbon dioxide release was expected to be small, about 2% of oxygen and nitrogen, the carbon dioxide release was assumed to be negligible and was not measured. Recent tests [11] showed that the level of carbon dioxide release was less than 4% of oxygen and nitrogen content.

Of the two major remaining gases, oxygen was selected over nitrogen to be measured as an estimate of deaeration level from warm surface seawater. The reasons were the following:

- Relatively accurate and on-line sensors were available for measuring D.O.; no such sensors exist for dissolved nitrogen measurements.
- The dissolved nitrogen content can be measured only with gas analyzers (gas chromatographs/mass spectrometers), which were not available on site at the time of the experiments.
- Measuring the overall dissolved gas content using aerometers, which measure the total amount of dissolved gases in a solution, proved to be time consuming and inaccurate [6].
- Previous experiments [6] showed that the fraction of nitrogen released from surface seawater was within 20% of the fraction of oxygen released.

It should be noted that at the time of the experiments, the capacity of the vacuum pump could not be determined with enough accuracy to do an overall mass balance.

Because of their ruggedness, precision, and on-line measurement capability, Clark-type membrane-covered polarographic sensors were used to measure the D.O. content of seawater. Because both temperature and salinity affect the D.O. content [12], sensors (YSI model 5739) and meters (YSI model 58) were selected to have circuitry for temperature and salinity compensation.

All available commercial flow-through Clark-type oxygen sensors are designed for atmospheric and high-pressure applications. Golshani and Chens [5] found that under vacuum conditions, such as in OTEC, the Clark-type sensors gave

3

erroneous results. To use D.O. sensors, the water had to be brought to atmospheric conditions by extraction using batch sampling techniques [5,6] or continuous sampling methods [7].

Batch sampling techniques are susceptible to contamination with atmospheric oxygen [7]. Therefore, a continuous sampling method similar to the one recommended by Zapka [7] was adopted for on-line measurement of seawater D.O. content for this study.

In these tests, to bring sample water to the D.O. sensors at atmospheric pressure, water samples were withdrawn from the desired locations in the vacuum vessel using sampling tubes and pumps. The sensors were located at ground level so that the water head in the tubes reduced the work required by the pump and also reduced the possibility of cavitation. This sampling methodology provided on-line measurement capability. The samples were drawn from the inlet seawater supply pipe, referred to here as "In"; the inlet water to the spout just before the water leaves the predeaeration chamber, referred to here as "Spout"; and the outlet water from the evaporator vessel, referred to here as "Out." Figure 2 shows the location of the sampling ports.

At the beginning of the tests, the three D.O. sensors were calibrated according to the manufacturer's recommendations [13]. Then the performance and accuracy of the sensors and meters were checked with oxygen-depleted fresh water and a humid mixture of oxygen and nitrogen containing 4.99% or 11.5% oxygen. It was found that under these controlled conditions, measurements of the D.O. instruments were found to be satisfactory within the manufacturer's specifications, and the variation from one sensor to another was less than 0.2 mg/L as expected (i.e., about a 1% full-scale error or 3%-8% error in the measured values). The oxygen content of seawater of atmospheric pressure measured by D.O. sensors was within the expected range.

The accuracy of the sensor measurements was also checked with the standard chemical analysis technique, the Winkler titration method. The same seawater was passed through the sensor holders connected in series, and the D.O.

concentration was measured with each of the three sensors. Simultaneous measurement of the D.O. concentrations of two or three different samples of this water were made using the Winkler method. Table 2 shows comparison results. With these in series measurements, no discernible effect of oxygen consumption by sensors was detected. The values measured by polarographic instruments were within ±0.48 mg/L of the values obtained by the Winkler method.

Originally, the plan was to use separate sensors to measure the D.O. concentration of water from each sample line. This arrangement would have provided simultaneous measurements of the D.O. concentrations and, thus, on-line calculation of the amount of oxygen released in the predeaerator and evaporator. However, upon field operation of the sensors it was found that the discrepancy between readings of the sensors measuring the same seawater sample was about ±0.4 mg/L, causing an extra 6% random error in calculating the fraction of oxygen released. Therefore, all three D.O. sensors were used to measure the same water sample, either from In, Spout, or Out. Readings from sensors for a particular water sample were averaged to provide a value with increased confidence. This approach was more dependable and proved necessary when halfway through the testing period, one sensor malfunctioned and was removed for repair, and only the other two sensors were used. The effect of averaging the readings of two sensors rather than three was to increase the random error element. All the data were analyzed based on the results of two D.O. sensors.

Experimental Procedure

The experimental procedure used is briefly described here.

1. At the beginning of each testing day, the dissolved oxygen detectors were calibrated in moisture-saturated air according to the manufacturer's recommendations [13].
2. The cold seawater flow rate was adjusted to the desired value.

Table 2. Comparison of Dissolved Oxygen Concentrations Measured with the Polarographic Instruments and by the Winkler Titration Method

	Polarographic Instruments (mg/L)						Winkler Method (mg/L)					
A	B	C	D	E	F		G	H	I	J	K	L
Date	Sensor 1	Sensor 2	Sensor 3	Mean	STD_{mean}		Sample 1	Sample 2	Sample 3	Mean	STD_{mean}	R_{cal}^{+}
6/15/89	6.18	6.27	6.41	6.29	0.07		6.76	6.74	6.76	6.75	0.01	0.46
6/17/89	6.20	!	!	6.20	--		6.59	6.75	6.71	6.68	0.05	0.48
	!	6.75	!	6.75	--		6.77	7.02	6.75	6.85	0.09	0.10
	!	!	0.35	0.35	--		0.75	0.81	0.83	0.80	0.02	0.45
6/23/89	6.77	!	6.75	6.76	0.01		6.71	6.73	*	6.72	0.01	0.04
	4.49	4.63	4.87	4.66	0.11		4.41	4.37	*	4.39	0.02	0.27
	0.60	0.63	0.77	0.67	0.05		0.37	0.40	*	0.39	0.02	0.28
6/28/89	6.77	6.86	6.82	6.82	0.03		7.02	6.98	*	7.00	0.02	0.18
	5.48	5.64	5.66	5.59	0.06		5.98	6.10	*	6.04	0.06	0.45
	2.47	2.52	2.57	2.52	0.03		3.07	2.85	*	2.96	0.01	0.44
8/02/89	!	6.88	6.90	6.89	0.01		6.98	6.93	*	6.96	0.02	0.07
	!	5.14	5.19	5.17	0.03		5.42	5.51	*	5.47	0.03	0.30
				Mean	0.04					Mean	0.04	
				Maximum	0.11					Maximum	0.11	
									Mean of Root-Sum-Square B_{cal}@		= 0.33	

! This sensor was not used at the time.
*Only two water samples were taken for Winkler titration.
+ R_{cal} = Absolute value of (Instruments mean - Winkler mean) or absolute value of (Column E - Column J).

$$@B_{cal} = \sum_{i=1}^{12} R_{cal,i}$$

3. The vacuum pump was turned on, and vacuum was drawn into the system to about 2.4 kPa absolute. As evaporator pressure decreased, warm seawater rose in the supply and discharge pipes.
4. Flow controls were adjusted to maintain proper levels in the supply and discharge tanks to obtain the desired warm seawater flow rate.
5. The pressure in the evaporator was adjusted to the desired value.
6. System performance was recorded when steady-state operation was achieved and an overall heat balance was assessed satisfactory.
7. A water sample from one of three sampling ports was passed through the three D.O. sensor holders, and, after steady state was reached, data were recorded. Then a water supply from another sampling port was connected to the D.O. sensor holders, and data were recorded after the lines were purged with new sample water. The same procedure was repeated for the third sampling port.
8. Operating parameters were adjusted for another set of conditions, and the above steps were repeated.

Experimental Experience

After some preliminary tests, a few problems were encountered. During the tests, it were observed that there was a significant number of bubbles in the "Spout" and "Out" water sampling lines. Most of these bubbles were entrained at sampling locations into the seawater. Some bubbles in the sampling line were also generated at flow obstructions and impeller pumps. Some of the bubbles were reabsorbed at high pressures in the sampling lines and increased the D.O. readings. In addition, passage of bubbles by D.O. sensors caused unstable readings. Sometimes the pumps cavitated and generated unwanted bubbles. The D.O. sensors drifted from day to day. Even with filters in the sample water lines, small sand particles and other debris in the warm seawater were carried to the D.O. sensors and gradually eroded the surface of the D.O. membranes, giving wrong D.O. readings. To resolve these problems the following precautions were taken.

An examination of the impeller pumps revealed that a few air leaks around the impeller seal were the major cause of the cavitation. This problem was fixed by using a better sealant and tightening the seal components, but still there was some cavitation at the pumps. The impeller pumps were replaced with a peristaltic pump (Masterflex Model 07459-30) that did not have an impeller and thus did not cavitate. Although the peristaltic pump had a maximum rated capacity of about 1 L/min, it did not deliver a sufficient amount of flow rate to the D.O. sensors because of low back-pressure. Thus, the impeller pumps were reinstalled for the tests. The number of flow obstructions (such as bends and valves) was reduced. The sensors had to be air calibrated every day to overcome the problem of drifting. There were a few instances where a D.O. sensor could not be calibrated and its membrane had to be replaced. The membranes were replaced every week to overcome the problem of erosion resulting from debris in the seawater.

To resolve the problem with bubbles, two solutions existed: reabsorbing all the bubbles, e.g., by compression, or removing the bubbles, e.g., by separation before they enter the D.O. sensor holders. Because it was both effective and easy to install, a "bubble separator" device was used to remove the entrained bubbles from the sample lines before D.O. measurement. The bubble separator acted like a settling chamber: the bubbles were exposed to a free surface and released before the water entered the D.O. sensors. One drawback to this method was that only the dissolved amount of oxygen in the "debubbled" solution was measured, and the total amount of oxygen in the original water sample was not measured. (The total oxygen content consisted of both dissolved oxygen in the solution and gaseous oxygen in bubbles surrounded by water.)

Although these efforts resolved some of the problems, the D.O. measurements still had shortcomings: the repeatability of measurements from day to day was not always satisfactory; the D.O. instruments drifted; and at times the water flow rate through the D.O. sensors was not sufficient, causing a lower D.O. content reading. As a result, a large scatter exists in the data.

RESULTS AND DISCUSSION

In this section, a post-test error analysis and the typical results obtained are presented, and the effect of pressure, water flow rate, and bubble injection are discussed. Potential ways to improve the measurements are discussed later. The results are presented in fraction of oxygen desorbed or

$$F_{pd} = (C_{in} - C_{spout})/C_{in} \qquad (1)$$

$$F_{ev} = (C_{spout} - C_{out})/C_{spout} \qquad (2)$$

$$F_t = (C_{in} - C_{out})/C_{in} \qquad (3)$$

$$F_{eq} = (C_{in} - C_{eq})/C_{in} . \qquad (4)$$

Post-test Error Analysis

Water samples were collected periodically from the sample lines to measure D.O. using the Winkler method to verify and calibrate the D.O. sensors. These results are presented in Table 2 and show that the sensor-measured values are within 0.48 mg/L of the Winkler-measured values, which is worse than predicted from pre-test error analysis.

A post-test uncertainty analysis was performed to estimate the overall uncertainty in the fraction of oxygen desorbed. Errors due to analysis and water sampling for the Winkler method, sensor calibration, sensor-to-sensor variations, and sensor fluctuations were estimated and propagated into an estimation of fraction of oxygen desorbed. To estimate the uncertainty in the calculated fraction of oxygen desorbed, the root-sum-square model [14] was applied to the bias and random errors. The root-sum-square model accounts for 95% of the variations. The following errors were identified in the D.O. measurements.

Uncertainty in standard Winkler values
$$U_{Wink} = \pm 0.24 \text{ mg/L}$$
Error in sensors relative to sensor measurements
$$R_s = \pm 0.11 \text{ mg/L}$$
Error in sensors relative to Winkler results
$$B_{cal} = \pm 0.33 \text{ mg/L}$$
Random error in sensor reading $\quad R_{read} = \pm 0.05 \text{ mg/L}.$

Combining the last three random errors by root-sum-squaring resulted in an overall random error of $C_{random} = \pm 0.35$ mg/L. Propagating this error and U_{Wink} into 100 randomly selected data points for estimating fraction of oxygen desorbed F_{pd} resulted in

Overall average bias error $\qquad F_{bias} = \pm 0.045$
Overall average random error $\quad F_{random} = \pm 0.066.$

Combining these two errors using the root-sum-square model and using a value of 2 for Student's t [14], the overall average uncertainty in fraction of oxygen desorbed was found to be

$$U_{F_{pd}} = \pm 0.14 .$$

This represents a large uncertainty in the absolute value of F_{pd}, which ranges from 0 to 1. This uncertainty accounts

for <u>absolute</u> values of the fraction of oxygen desorbed obtained over 2 months of testing. Two error bands are shown on some of the graphs. One shows this absolute, and the other shows only the error due to random reading of sensors. If data are obtained in a short period (e.g., 2 hours), they can be compared on a relative basis. Then the calibration and bias errors do not need to be considered.

Results

In all the tests, the temperature of incoming warm seawater was about 26.5±0.5°C. Data presented here are based on the date or the flow-path configuration. The data grouped on a given date can be compared more confidently because the calibration and other bias errors for 2 hours of testing did not change and can be ignored for relative comparison.

Also shown on some of the figures presented in this section is the fraction of oxygen desorbed at equilibrium F_{eq} (as estimated by Eq. 4). The equilibrium value is the upper limit of how much oxygen can be desorbed at a given pressure. The equilibrium level was obtained, assuming water at 26.5°C, inlet D.O. content of 6.6 mg/L, and oxygen mole fraction of 0.2095 in the air in equilibrium with water (the actual oxygen mole fraction in the equilibrium may differ slightly from this value).

Figures 3 shows all the data sets obtained with no baffle plate in the chamber. The graph shows the fraction of oxygen desorbed (Eq. 1) in the predeaerator chamber as a function of pressure at various water flow rates. Even with the scatter of the data, a general trend can be seen from the figure: the fraction of oxygen desorbed in the predeaerator chamber increases with decreasing chamber pressure. This was expected because as pressure decreases, water becomes increasingly supersaturated with oxygen and releases the dissolved oxygen. Previous investigators observed the same trend [5-7]. Other data sets also show the same trend: an increase of the fraction of oxygen desorbed with decreasing pressure. Note also that F_{eq} increases with decrease of pressure. As can be seen, there is a large scatter on the absolute values of the results. Overall, about 10% to 60% of oxygen in the warm seawater
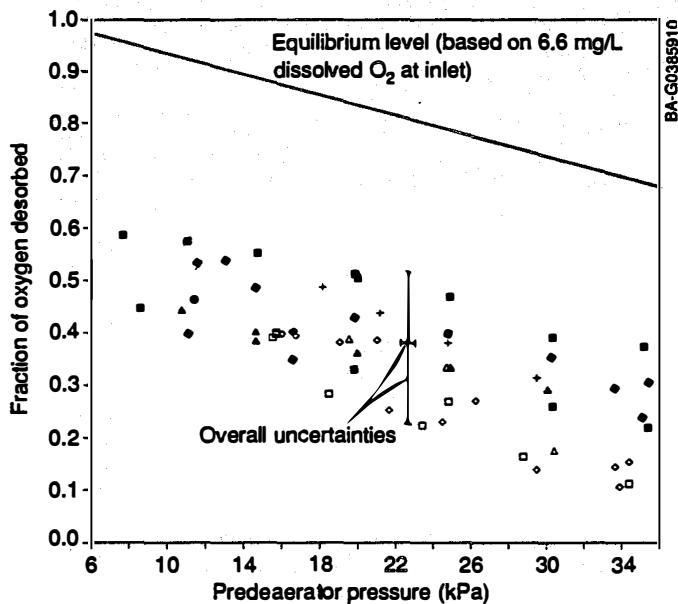
Fig. 3. Warm seawater predeaerator oxygen desorption data as a function of pressure at various water flow rates

can come out of solution in the predeaerator at pressures between 9 and 35 kPa. The lower values on 06/21/88 as compared to those for 08/09/88 are due to experimental error such as sensor drift.

It is also possible that the quality (size and number density of bubbles and nucleation sites) of incoming seawater has changed during these days because of ocean surf conditions and climatic changes, such as rain and storm, that, in turn, affect the rate at which oxygen desorbs. Because the seawater quality was not measured during the tests, the contribution of change in water quality on fraction of gas desorbed cannot be estimated.

From most of the experiments performed and a close look at data in Figure 3 and other obtained data, it can be observed that a functional dependence of the fraction of oxygen released in the predeaerator with water flow rate cannot be determined for the following reasons. When water flow rate decreases, the residence time in the deaeration chamber increases and the dissolved gases have more time to desorb from the solution and, thus, the fraction of gas released increases. A deaeration model [8] supports this expectation. However, in the HMTSTA the decrease in flow rate was obtained by closing a valve in the supply pipe upstream of the supply tank (Figure 2). Closing of the valve caused higher pressure drop and cavitation; therefore, larger bubbles were generated. These bubbles were easily separated in the open-top, well-agitated supply tank, causing fewer bubbles to enter the upcomer and the deaeration chamber. The gas desorption from seawater is governed by the nucleation and bubble growth phenomena; as the amount of incoming water decreases, less gas is desorbed and, thus, the fraction of gas released decreases. Change in water flow rate in the HMTSTA configuration had two effects: change in residence time and change in number density of bubbles entering the upcomer. These effects had opposing impacts on the fraction of oxygen released; one would increase the fraction of oxygen released, the other would decrease it. Therefore, the fraction of gas released, rather than depending on the flow rate, depended on the effects that the flow rate caused. Since no effort, other than visual observation, was made to measure the bubble density, the separate effects of residence time and bubble density could not be determined. In addition, scatter in the data added more uncertainty to the dependence of fraction of oxygen released on the water flow rate. To obtain the dependence of gas desorption on water flow rate, future experiments should be designed such that a change in water flow rate would not change the bubble density of the entering water.

The effect of bubble injection can be seen from Figures 4a and 4b. Figure 4a shows the fraction of oxygen desorbed as a function of pressure at various bubble injection rates. High injection rate occurred when 150 cm³/min of nitrogen was fed into each of four bubble injectors. Low injection occured when 40 cm³/min of nitrogen gas was injected into each of four bubble injectors. The bubbles were injected into a section of upcomer where the pressure was about 65 kPa. The quantity of gas injected into the flow stream was only a small fraction (less than 1%) of the gas content in the water. That is, the net addition of noncondensable gases is small.

During the tests, it was observed that more bubbles were generated at the high injection rate than at the low injection rate. The size of the bubbles released from the injectors was observed to range from 0.1 to 3 mm. The bubble size and number density were not measured with any instrument.

If the absolute values of the data presented in Figure 4 are compared, taking into account their overall uncertainty, no discernible differences between the results with and without injection could be observed. However, comparison should be done on a relative basis where only random errors need to be considered. This is reasonable because the calibration and systematic errors were the same for the short period of time (less than 2 hours) in which the data were obtained with and
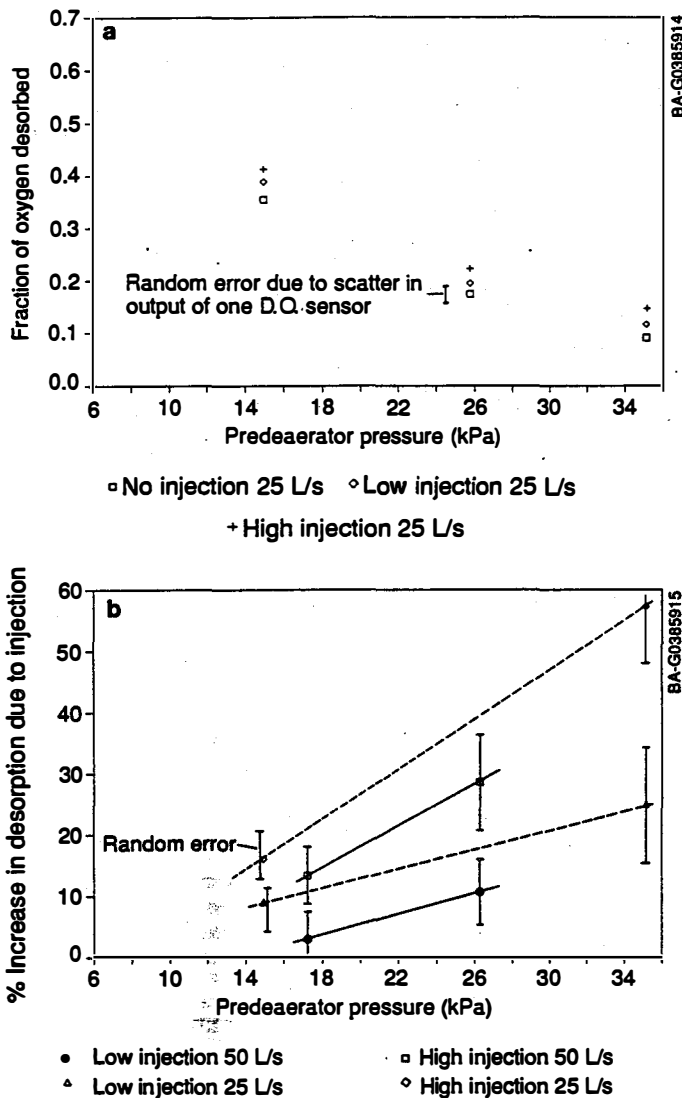
Fig. 4. (a) Impact of gas injection on warm seawater oxygen desorption; (b) Increase of oxygen desorption due to gas injection

without bubble injection. Furthermore, only the results of one D.O. sensor are presented in Figure 4 to eliminate sensor-to-sensor random error. On a relative basis, it can be seen that more oxygen was desorbed when bubbles were injected.

To show the validity of the above conclusion, results of Figure 4a are replotted in Figure 4b as a percentage increase in the fraction of oxygen desorbed due to injection, which is defined as

$$\frac{(F_{pd} \text{ with injection}) - (F_{pd} \text{ with no injection})}{(F_{pd} \text{ with no injection})} . \quad (4)$$

Figure 4b shows the percentage of increase in the fraction of oxygen desorbed due to injection as a function of flow rate and pressure, and injection rates. The error bands shown in this figure were obtained by propagating the random error of 0.05 mg/L due to sensor reading into the calculation of the percentage of increase. From Figure 4b, bubble injection increases the oxygen desorption rate. Another observation is that the increase in gas desorption increases with an increase in predeaerator pressure. At the high injection rate, the

oxygen desorption level has increased by 20% to 60%. The increase in oxygen desorption level from seawater upon bubble injection has been observed by others [7].

Bubble seeding (gas reinjection) can enhance oxygen and possibly nitrogen release from seawater in the predeaerator. It may have a potential in OC-OTEC power plants to increase the amount of noncondensable gases removed in the predeaerator before noncondensable gases enter the evaporator. The range of optimum bubble size and density gas flow rate, the pressure at which gas should be injected, and the effect of bubble injection on production of net power for an OTEC plant should be investigated in future studies.

Figure 5 shows the total fraction of gas desorbed from the warm seawater in the system as a function of evaporator pressure at various water loadings (i.e., flow rate divided by the cross-sectional area of the predeaeration chamber). The fraction of oxygen desorbed increased with a decrease in pressure. Depending on the pressure, 45% to 95% of the dissolved oxygen was desorbed from the warm seawater. The typical operating pressure of an OC-OTEC evaporator is about 2.4 - 2.7 kPa. At this pressure range, flash evaporation occurred, and 75% to 95% of the dissolved oxygen was released in the evaporator. At these typical OC-OTEC pressures, the pressure in the predeaeration chamber ranged from 10 to 12 kPa, and the fraction of oxygen desorbed from seawater in the predeaeration chamber was about 0.4 - 0.6.
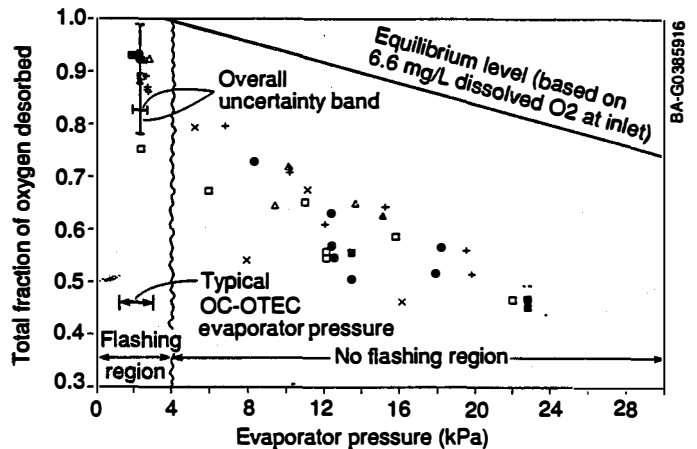
(6/21-23/88) □ 28.7 kg/s m² ＋ 57 kg/s m² ▵ 85.7 kg/s m²

(6/27-29/88) ■ 28.7 kg/s m² ● 57 kg/s m² ▲ 85.7 kg/s m²

× 42 kg/s m²

Fig. 5. Combined warm seawater oxygen desorption in both evaporator and deaeration chambers

Potential Improvements in D.O. Measurement Accuracy

To improve the dissolved oxygen measurement results and obtain reliable on-line data, the following actions are recommended:

- Design a better sampling system
- Replace the Clark-type sensors with recently commercialized "balanced electrode reaction" sensors, which are insensitive to water flow rate
- Use peristaltic pumps for delivering water to the sensors to avoid cavitation in the lines
- Calibrate sensors against the Winkler method frequently to establish accuracy and stability with time.

Impact of Predeaeration on OC-OTEC Power Consumption

As discussed before, noncondensable gases must be removed from OC-OTEC heat exchangers (evaporator and condenser) to maintain the required vacuum levels for their operation. The power required to remove these gases reduces the net power production of an OC-OTEC plant. If noncondensable gases are removed before they enter heat exchangers, e.g., at predeaerators, then less noncondensable pumping power is consumed because gases are removed at pressures higher than exchanger pressures.

Using the obtained data and simulating a single stage predeaeration scheme in a system model [3], it was found that relative to the no predeaeration baseline, the power to remove noncondensable gases in an OC-OTEC plant decreased by 25% when predeaerating at about 10 kPa. Accounting for the uncertainty in the oxygen desorption data, this decrease can be 25±8%.

CONCLUSIONS AND RECOMMENDATIONS

Scoping tests on warm seawater deaeration were obtained during June-August 1988. The tests provide the first set of data with a large-scale OC-OTEC experiment. From the tests and analysis the following observations can be made:

- The observed fraction of oxygen desorbed in the predeaeration chamber was from 0.1 to 0.6 for a predeaerator pressure range of 9 to 35 kPa.
- The scatter in data was large because of difficulties and uncertainties in field measurements of the D.O. concentration of seawater.
- The dependence of the fraction of oxygen desorbed on water flow rate could not be determined because a change in flow rate caused two effects: change in residence time and entering bubble density. These effects had opposing impacts on the fraction of oxygen desorbed.
- The oxygen desorption rate in the predeaerator was increased by 20% to 60% upon injection of bubbles in the upcomer.
- Observation showed that oxygen desorbed from seawater in the predeaeration chamber was in bubble form. Tests showed that oxygen was desorbed from the seawater but was not completely released in the predeaerator, and bubbles containing desorbed oxygen were carried into the evaporator.
- At a typical OC-OTEC evaporator pressure of 2.4 kPa, 75% to 95% of D.O. content was desorbed from the warm seawater in the predeaerator and evaporator combined.

To obtain the dependence of the warm seawater gas desorption on water flow rate for design purposes, system model simulations, and deaeration model verifications, experiments should be designed that separate the effect of residence time and entering bubble density when flow rate changes. Also, more dependable and more accurate D.O. sensors or other measurement techniques should be used. Use of a "balanced electrode reaction" sensor, which is flow rate insensitive, is recommended in place of Clark-type sensors. The sensor should be calibrated frequently using the Winkler method to establish accuracy and stability with time.

Future tests should be conducted on deaeration of cold deep seawater, as well as surface warm seawater, and should quantify the desorption of not only oxygen but also nitrogen and carbon dioxide. Use of gas analyzers such as gas chromatographs and mass spectrometers is necessary for nitrogen and carbon dioxide. Techniques to measure total gas release, such as volumetric measurements, and water bubble density and bubble size are also recommended. The accuracy of the results obtained in future experiments should be established with a rigorous error analysis.

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