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MASTER

RESULTS OF A NEAR FIELD PHYSICAL MODEL STUDY

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Abstract

A physical model study is ongoing to investigate the sensitivity of recirculation and near field plume dynamics to variation in OTEC plant design and ambient ocean conditions. A thermally-stratified 18 x 12 x 0.6 m basin at a nominal scale of 1/300 allows the upper 180 m of the ocean to be studied for plant sizes up to 600 MWe. Tests have been conducted for stagnant conditions and for conditions with a current, using both the mixed discharge (combined evaporator and condenser) and non-mixed discharge concepts. Separate tests were made to investigate interactions between evaporator and condenser discharges in a non-mixed concept. Measurements include temperature, dye concentration, mean velocity and visual observations obtained from still and motion pictures. Results for the stagnant water tests showed no significant recirculation except for those tests where the discharge ports were oriented (slightly) upward or where the largest plant size (600 MWe) was tested. No significant difference in recirculation could be discerned between the mixed and the non-mixed discharge designs although differences in the equilibrium positions of the discharge plumes were noted. Tests in a current are still in progress but some preliminary results are presented.

Introduction

OTEC plants interact with the ocean environment by withdrawing water through their intake ports and exhausting it through their discharge ports. The resulting flow field external to the plant is of significance in regards to plant performance (as affected by any potential recirculation) and environmental impacts (such as the transport of nutrients, ocean temperature modification, etc.). The goal of the experimental research program at MIT is to understand the external fluid mechanics associated with generic OTEC designs, under a range of ocean environments, so that these considerations can become a part of OTEC plant optimization.

With the present program it will be possible to extend the range of conclusions which could be drawn from previous physical model studies reported in Jirka, et al.(1977), and Fry et al.(1978). By way of background, these previous tests were performed for a somewhat narrower range of plant and ambient conditions. In particular

a) the ocean was assumed to be discretely stratified, consisting of a warm, well-mixed upper layer, and a cold, well-mixed lower layer.
b) the evaporator and condenser flows were assumed to be mixed within the plant and discharged horizontally at the interface between upper and lower layers.
c) plant sizes were limited to a range of 100-200 MWe, and
d) ambient currents were limited to a range of 0 - .1 m/s.

The original motivation for these tests was to provide detailed documentation of typical OTEC flow fields for the purposes of calibrating mathematical models and studying the underlying physical processes. In addition, it was possible to draw some direct conclusions regarding plant performance, and recirculation in particular, within the range of conditions which were tested. For instance, a formula was developed to estimate the onset of recirculation, and an exercise of this formula suggested that for typical ocean profiles (and the relatively low range of current speeds tested) recirculation could be avoided for plants employing mixed discharges with capacities up to about 200 MWe.

The objective of the present set of tests is to extend the range of plant and ambient conditions which can be modeled by relaxing each of the limitations a-d) described above. The resulting tests will thus provide a direct measure of OTEC performance under a more realistic range of operating conditions. Of course the tests can also be used for the calibration/verification of mathematical models.

Model Description

Experimental Characterization

The OTEC plant type. Several different designs have been proposed for a prototype OTEC power plant. The designs considered in this study are limited to those which can be modeled as symmetrical vertical columns.

Figure 1 shows the parameters which characterize the OTEC plant model and the range within which these parameters vary in the model. The evaporator intake, drawing a flow Q_i, is located at a depth of h_i below the surface. The condenser intake is not modeled. The previous study (Jirka, et al.1977) utilized a model which assumed that the evaporator and condenser flows would be mixed within the plant and that the combined discharge flow ($Q_o = 2Q_i$) would be discharged horizontally as shown in Figure 1. This study examines both mixed discharges and non-mixed discharges (flow rate $Q_o = Q_i$). In either case the discharge depth is h_d and the vertical angle is α. (α is positive downward.) For the non-mixed discharges, only the evaporator discharge is modeled, thus assuming that no interaction between evaporator and condenser discharge takes place.

Two types of generic discharge configurations

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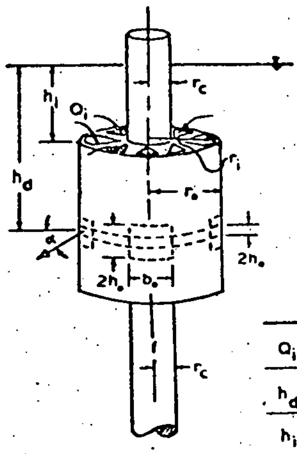
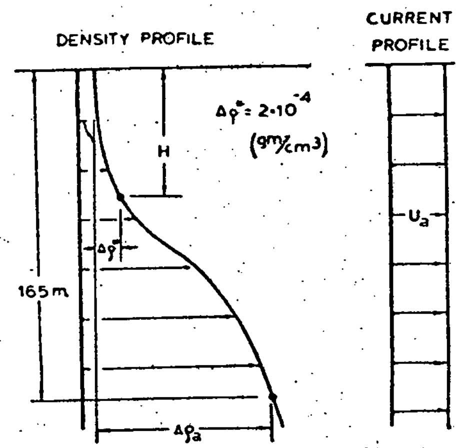


RADIAL OR SEPARATE JET DISCHARGE

	EXPERIMENTAL MODEL (1:300)
Q_i	500-2500 m^3/sec
h_d	23-170 m
h_i	0-60 m.
α	0° ¢ 45°
r_i	20 m.
r_o	23 m.
r_c	11 m.
h_o	Depends
b_o	on Q_i



	EXPERIMENT PROFILES (1:300)
U_a (m/sec)	0 - 1.
$\Delta\rho_a (10^{-4} gm/cm^3)$	4. - 34.
H (m.)	25. - 150.

Figure 1 New Experimental OTEC Schematizations (with experimental parameter ranges)

were evaluated in this study (see left side of Figure 1).

a) Radial discharge: The discharge geometry is assumed as a radial slot of height $2h_o$ which completely encircles the plant circumference. Although none of the presently proposed OTEC designs exhibit this geometry, it is a useful basis for evaluation. It has an obvious advantage for analytical (cylindrically two-dimensional) and experimental modeling and it preserves many of the characteristics of more complicated three dimensional separate discharge designs as long as equality of mass, momentum and heat fluxes is maintained.

b) Separate discharge: Four separate jets with rectangular cross-sections (height $2h_o$ and width b_o) are arranged around the plant circumference at angles of 90° to one another. This closely approaches probable (round port) design conditions with the mixed or non-mixed discharge concept.

For either discharge geometry, A_o is defined as a characteristic cross-sectional area equal to 1/8 of the total port area. Thus for the radial discharge, $A = \pi/2\ r_o h_o$, while for four separate jets, $A_o = h_o b_o$. Using the square root of A_o as a length scale, a discharge densimetric Froude number is defined, for either radial or separate jet discharge, as

$$F_o^* = \frac{u_o}{\sqrt{g\left|\frac{\Delta\rho_o}{\rho}\right| A_o^{1/2}}}$$

where u_o is the discharge velocity ($Q_o/8A_o$) and $\Delta\rho_o/\rho = [\rho_{amb}(z = h_d) - \rho_o] / \rho_{amb}(z = h_d)$ where $\rho_{amb}(z)$ describes the ambient density profile and ρ_o is the discharge density. A positive value of $\Delta\rho_o$ implies positive buoyancy and corresponding values of F_o^* are denoted with an upward arrow. Negative values of $\Delta\rho_o$ imply negative buoyancy, and values of F_o^* have a downward arrow. A final parameter used to characterize the discharge is the jet Reynolds number, defined for either radial or separate discharge configurations as

$$R_e = \frac{4u_o r_h}{\nu}$$

where r_h is the hydraulic radius of the discharge structure. ($r_h = h_o$ for the radial jet and $h_o b_o/(2h_o + b_o)$ for the separate jet experiments.)

The ambient ocean. Figure 2 (Miller, 1977) shows ocean density profiles for several tropical locations. Near the surface water is typically well-mixed, while below densities increase with the steepest density gradient (pycnocline) usually located near the bottom of the mixed layer. The previous study (Jirka, et al.,1977) approximated the ocean profile with two well-mixed layers of

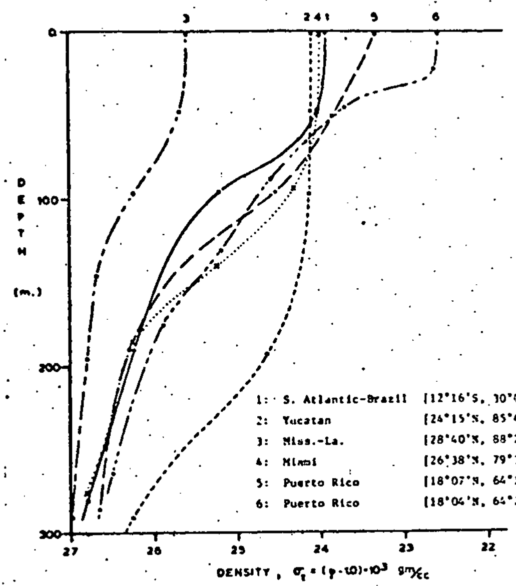


Figure 2 Ocean Density Profiles [Miller, 1977]

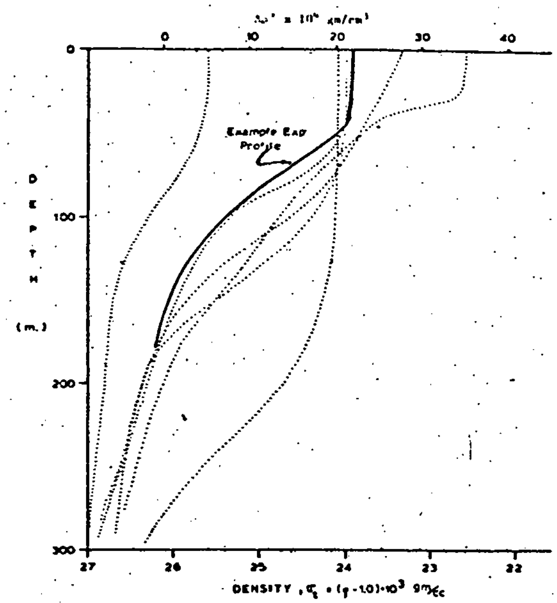


Figure 3 Superimposed Experimental Profile (Scale 1:300) for Comparison of Density Variation

water of distinctly different densities. Thus the profile was characterized by a density difference and a surface layer depth. As shown in Figure 1, the present study considers more realistic, continuous, density profiles. Since the profiles are experimentally produced, each is somewhat different. However, for purposes of summary they are characterized by the parameters H and $\Delta\rho_a$. H is the mixed layer depth, defined as the depth at which the ambient density differs by an arbitrarily small amount - taken here as $2 * 10^{-4}$ gm/cm^3 - from the surface density. $\Delta\rho_a$ is the density difference between the surface and 165 meters. Figure 3 shows a typical profile generated in the lab and indicates that it is representative of actual ocean conditions.

Experiment Layout

The OTEC model. The experiments were conducted in a 12.2 m x 18.3 m x 0.60 m (40' x 60' x 24") basin located on the first floor of the Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics at M.I.T. The basin has a 4.57 m (15 ft) long plexiglass window in one wall of the basin which allows for visual observation and photography of the velocity field close to the wall. Figure 4 presents a general layout of the basin and the water flow circuits for both the set up for the stagnant water tests and the tests in a current.

An undistorted Froude scale model with length ratio of 1:300 was chosen to provide a compromise between the competing objectives of obtaining large jet Reynolds number and measurement resolution (dictating large scale ratios) and ability to model large ocean depths (dictating a small ratio). The 1:300 scale and 0.60 m basin depth allows the upper 180 m of the ocean to be tested. This was sufficient depth to prevent interaction of the discharge with the bottom for any of the horizontal discharge configurations. The basin was not deep enough to model either the condenser discharge in a non-mixed design involving large separation between evaporator and condenser discharge, or the condenser intake at the bottom of the cold water intake. These limitations were not considered to be significant. With the 1:300 scale ratio, the minimum jet Reynolds number was 3100 obtained for the case of a 200 MWe plant with a non-mixed (evaporator), radial discharge.

For stagnant water tests only half of the OTEC model is used; the half model is attached to the plexiglass window so that the wall is taken as a plane of symmetry. For tests in a current, the model is towed along the center of the basin with the discharge and intake flows conveyed to and from the model by flexible 2" hoses. In either case, the intake flow (hot water) enters the model through a radial configuration of circular port holes. It then travels through a large plexiglass tube where it is pumped out of the model. The discharge flow enters the top of the model through brass tubes, which pass inside the intake flow tube to the discharge ports. To simulate a radial discharge, twelve discharge ports (6 for the half model) are used while for separate jet tests four ports (2 for the half model) are used. To insure uniformity, flow to each of the ports is individually metered.

Stratification system. In order to simulate an actual ocean density profile, the basin is filled with water of different temperatures starting with cold city water on the bottom followed by warm water near the surface. During filling, diffusion takes place resulting in a smooth thermocline. Also, once filling has ceased, surface cooling

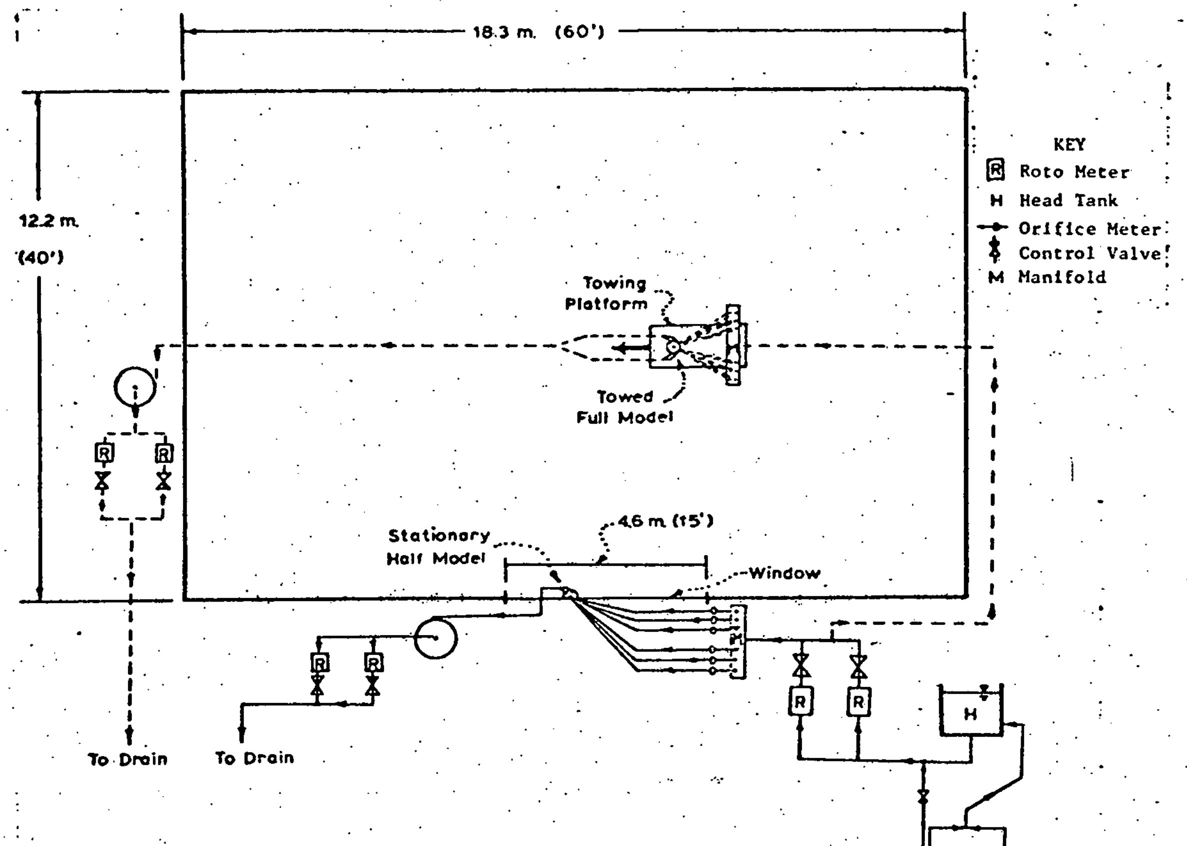


Figure 4 Schematic Diagram of Experimental Setup

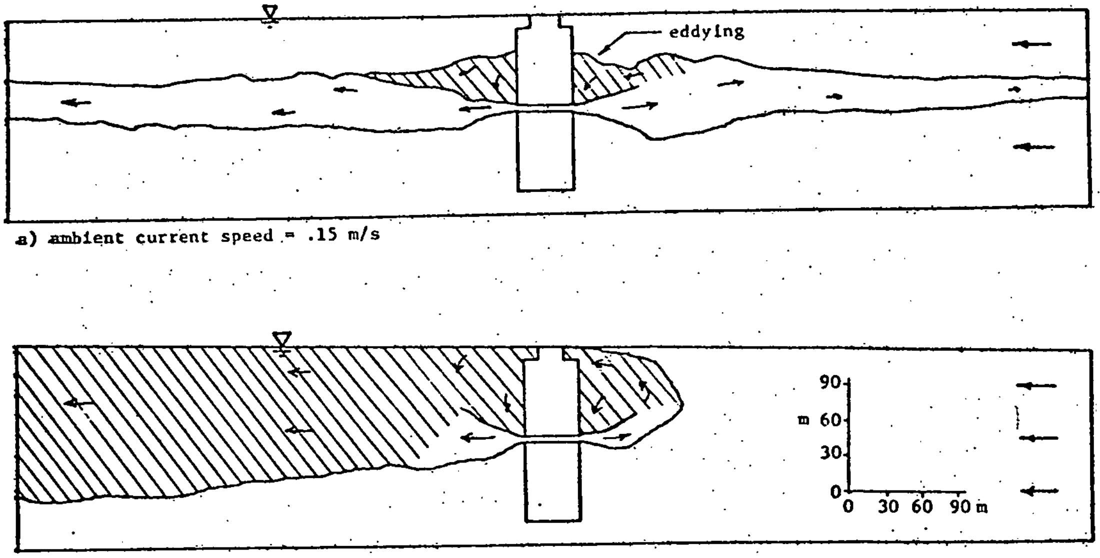
mixes the upper layers thereby decreasing the surface temperature. Because the difference in density between the entering hot and cold water is designed to be greater than the desired density difference $\Delta\rho_a$, a run is begun once the surface has cooled and the desired density difference between the upper and lower layers has been achieved. This takes from 1-4 hours from the time the hot water inflow is turned off.

The spatial and temporal variability of typical temperature profiles obtained with this procedure was examined. The maximum standard deviation in horizontal temperature variation was about .25°C while the maximum rate of change of the mean temperature was about 1°C per hour occuring on the surface. Since a typical experiment lasts for 30 minutes this was considered small, but was nonetheless accounted for in the data reduction.

Measurement systems. Temperatures are measured by approximately 100 Yellow Springs Incorporated thermistors (time constant = 1 sec.) located throughout the basin, and in the discharge and intake lines. A digital electronic volt meter with the capability to scan the 100 thermistor probes records temperature on a paper printout and on punched paper tape. During a typical experiment between 5000 and 6000 temperature readings are recorded.

Fluorescent dye measurements are used to complement temperature measurements in determining recirculation and discharge dilution. Concentrations are measured with a Turner Model IV fluorometer with a threshold detection of 1 part per billion (ppb). Experiments can be run with discharge concentrations of as much as 50,000 ppb and basin background concentrations of less than 30 ppb. A dye concentration of 10 ppb above the background concentration is distinguishable and thus it is estimated that measurement of direct recirculation down to 10 ppb/50,000 ppb = 0.0002 or 0.02% is possible.

Injection of the fluorescent dye into the flow stream serves to tag the discharge jet for photographic purposes. A pair of slide projectors supported above the water are used to emit a narrow slit of light which illuminates a cross section of the flow stream. In order to quantitatively measure the position and thickness of the spreading layer, six marker poles containing fiber optic strands are mounted beneath the light slit. When illuminated, these strands produce dots of light down the marker pole providing a reference grid. Figure 5 shows tracings, made from photographs, of the dyed discharge plume for two typical runs involving an ambient current.



a) ambient current speed = .15 m/s

b) ambient current speed = .51 m/s

Figure 5 Photographic Tracings of Longitudinal Plume Crossections for a 400 MWe Plant with Horizontal Radial Evaporator Discharge

Results

Experiments are being performed in three parts. The first two, involving observations of OTEC external fluid mechanics in stagnant water, have been completed. The first set was designed to study OTEC performance under a range of realistic plant designs and profiles of ambient stratification. The second set looked in detail at the interaction which might take place between adjacent discharge jets in a non-mixed discharge concept or between a single discharge and the free surface in either a mixed discharge concept or a non-mixed discharge concept involving substantial separation between evaporator and condenser discharges. The third set of experiments is presently ongoing and involves observations of OTEC external fluid mechanics in ambient currents up to 1 m/s for similar ranges of plant designs and profiles of ambient stratification tested under stagnant conditions. A summary of the results of parts one and two, and preliminary results from part three are described below.

Stagnant Water Tests

An experimental program involving 21 tests was established to examine the influence of discharge type (mixed or non-mixed and radial or individual jet), nominal net power (200 MWe - 600 MWe), relative discharge and mixed layer depths h_d and H, discharge angle α and discharge area A_o. The results of each run are presented in Adams et al. (1978) and include, for each run, photographic tracings of the plume outline, undisturbed and disturbed temperature profiles, intake temperature depression (if any), percentage of direct intake recirculation, and the equilibrium jet dilution, thickness and position (vertical elevation). While it is not practical to present the results here, several observations can be summarized.

Perhaps the most important is that direct recirculation was observed in only two tests. In the first, the discharge trajectory had a vertical component ($\alpha = -21°$) due to improper distribution of flow emanating from the discharge ports. The fact that changing the discharge angle by 21° (to a horizontal discharge) completely eliminated recirculation suggests that recirculation is very sensitive to discharge angle. The second observance of recirculation involved a larger plant (nominally 600 MWe) which was selected so as to produce recirculation. The percentage recirculation (40%) was high suggesting that a nominal plant size of 400 MW (with horizontal discharge in stagnant water) may be near the limit of no recirculation. This is confirmed by the photographic tracings which show the plumes from many "400 MW experiments" approaching, but not quite reaching the water surface and thus not recirculating. These two runs were, not surprisingly, the only runs in which significant intake temperature drops were observed. Because the discharge mixes with a (stratified) ambient, any direct recirculation involves a lowering of intake temperature due both to the direct recirculation itself and the fact that the discharge has been mixed with ambient water of lower temperature (than that which the intake would normally draw). In each of the two cases where recirculation occurred, the latter (indirect) type accounted for more than 50% of the intake temperature drop.

Although dilution was measured for each test it was hard to discern any trends in the variation of dilution with discharge or ambient conditions. The mean value of dilution was about 7 indicating that peak concentrations in the intermediate field of any chemicals contained in the discharge will be about 14% of the discharge concentrations. It should be noted that the discharge velocities in these tests are relatively high (u_o = 3.5 to 7.8 m/sec).

In contrast to dilution, the shape and the equilibrium depth of the plume are strongly correlated with the discharge and ambient conditions. For instance, for cases of horizontal discharge, all positively buoyant plumes rose while all negatively buoyant plumes fell. For this reason it was often difficult to notice the effect of the discharge on the ambient profiles; the plumes tended to hide in ambient water of their own density (temperature). However a general tendency for the density gradient to decrease at the equilibrium depth was observed. Also, profiles at the smaller radii often show positive temperature anomalies above the plume (indicating that warm entrainment water is being drawn down from above) and negative anomalies below the plume (indicating that cooler water is being drawn up from below).

Interaction Tests

These tests studied in detail the balance of forces involved in two possible near field flow phenomena. Both can significantly affect the vertical trajectory of the discharge jets.

The first involves interaction between the discharge and the free surface which was the cause of the only significant recirculation observed in the previously described tests. This attachment is associated with an attraction or Coanda effect between the discharge jet and the water surface which occurs despite any negative buoyancy of the jet. The evaporator intake flow helps magnify this interaction. The second interaction phenomena studied was the possible mixing of evaporator and condenser jets exterior to the OTEC plant. The jets originate at different vertical levels with different buoyancies. Analogous to the previous phenomena, a low pressure zone exists between the jets tending to attract them together. The vertical trajectory of the discharge jets in both cases, then, is a function of buoyancy and low pressure zones (created by jet-surface or jet-jet interactions). The low pressure is caused by water flowing toward the OTEC plant outside the jet boundaries and originates due to both the evaporator intake and the discharge entrainment demand.

Two sets of tests were carried out to investigate this phenomena. In both cases the OTEC discharge was radial to insure that all flows directed toward the OTEC plant were either above or below the jets. Furthermore the receiving water was stagnant and unstratified. Because any interaction is expected to take place near the plant, this is not a significant limitation. In the first set of tests a single submerged, negatively buoyant jet was discharged horizontally with the water surface much closer than the basin floor. In some tests an intake of equal flow rate existed near the surface. In other tests the intake was absent. Temperature measurements and photographs were used to observe under what conditions jet-surface interaction forced the jet to the surface overcoming the jet's negative buoyancy. For the tests with an intake recirculation was also measured. Either the jet reached the surface resulting in 30-40% recirculation or the jet did not reach the surface and there was 0% recirculation. There were no observations of a steady flow regime with recirculation between these values. A movie of the experiments, shown at the conference, clearly indicates the two regimes.

Dimensional analysis shows that if the discharge radius is kept constant and the intake geometry is ignored, two dimensionless members should characterize the flow. Two such numbers are the discharge Froude number and the relative port width,

$$\mathbb{F}_r = \frac{u_o}{\sqrt{g \frac{|\Delta\rho_o|}{\rho_a} h_o}} \qquad W = \frac{h_o}{H}$$

(Note that this definition of $\mathbb{F}_r$ differs slightly from the definition of $\mathbb{F}_\rho^*$ used previously.) As $\mathbb{F}_r$ decreases, buoyancy effects can be expected to increasingly dominate. As W goes down the surface interaction should decrease as low pressure affects the jet path less. Experiments established critical sets of $\mathbb{F}_r$ and W values where the flow pattern switched between jet-surface attachment (30-40% recirculation) and no jet attachment (0% recirculation). A hysteresis effect was also observed analogous to those found in other Coanda effect experiments. For a given value of W, it took a higher value of $\mathbb{F}_r$ to obtain attachment than the value needed to get an attached jet to fall away (detach) from the surface. The presence of an intake flow increased surface interaction and hence lowered the critical $\mathbb{F}_r$ values (for a given W). Figure 5 presents the experimentally determined critical value of $\mathbb{F}_r$ and W. Figure 6 shows jet centerlines (obtained from photographs) for a series of tests with an intake flow and the same value of W.

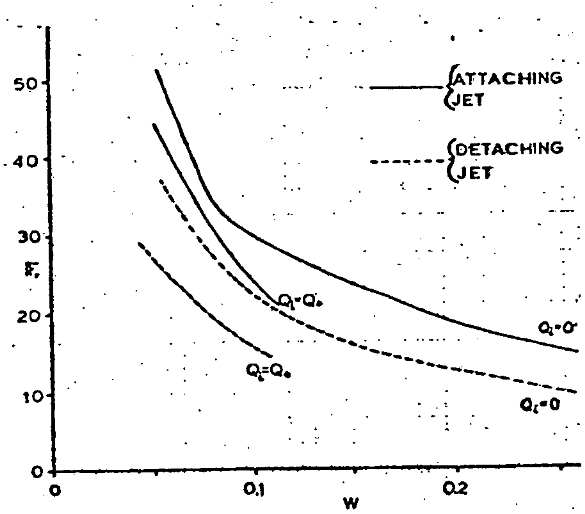


Figure 6 Critical Values of $\mathbb{F}$ and W as Determined by Experiments

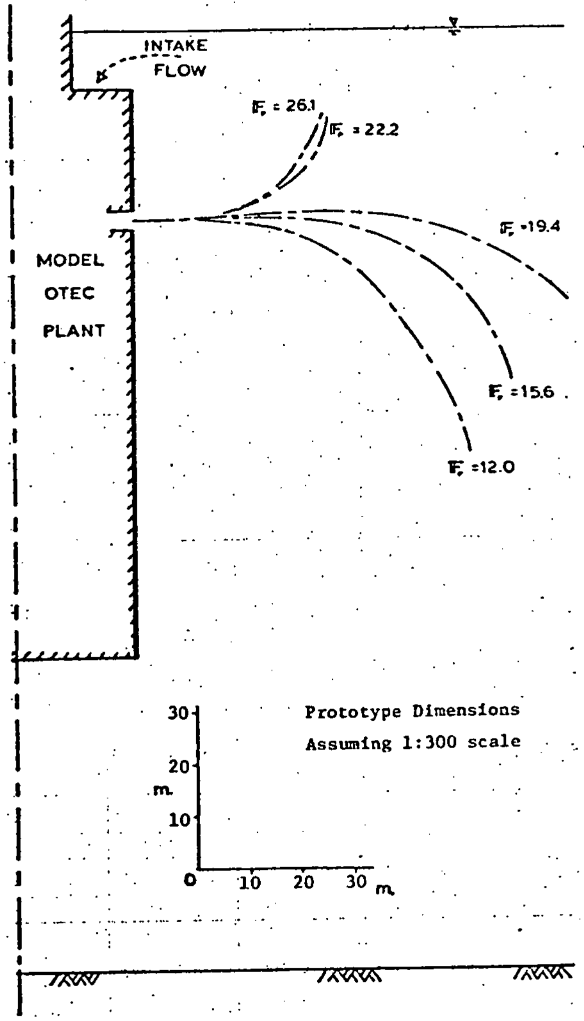


Figure 7 Experimental Discharge Jet Centerline Trajectories W = .105

In the second series of tests, two jets were discharged horizontally at different vertical levels. They were closer to each other than either was to the water surface or basin floor. The upper jet was positively buoyant and the lower jet was negatively buoyant. Both had the same port characteristics and value of

$$\mathbb{F}_r = \frac{u_o}{\sqrt{g \frac{|\Delta\rho_o|}{\rho_a} h_o}}$$

Also, there was no intake. For the case of no jet-jet attachment the flow field was symmetrical about a horizontal plane placed midway between the jets. The observed behavior was exactly similar to the jet-surface interaction experiments (with no intake flow) with the plane of symmetry replacing the surface boundary. Therefore the analogous dimensionless port width is

$$W' = \frac{2h_o}{h_{sep}}$$

where h_{sep} is the separation distance between evaporator and condenser water discharge. For a given value of W', the jets merged when $\mathbb{F}_r$ for both jets reached a critical number. Just as with recirculation in the surface interaction experiments, either the merger was complete or did not occur at all. The experimental data for these experiments is still being reduced.

Tests in a Current

To date approximately twenty tests have been performed. Recirculation results are presented herein for one set of tests involving a 400 MWe plant with a horizontal, non-mixed (evaporator), radial discharge at a depth of h_d = 77 m into a stratified ambient with a mixed layer depth of H = 54 m. Current speeds of .15, .28, .40, .51 .87 and 1.00 m/s were tested to complement a corresponding test in stagnant water. Photographic tracings in Figure 5 show vertical plume crossections for runs with current speeds of .15 m/s (indicating little or no recirculation) and .51 m/s (indicating partial recirculation). Percentage dye recirculation (direct recirculation) for all the current speeds is plotted in Figure 8, which indicates that maximum recirculation occurs at intermediate current speeds. This confirms observations made by Sundaram et al. (1977, 1978) under more idealistic conditions. The maximum percentage recirculation for these tests is approximately 6-7% suggesting that, even under recirculating conditions, much of the intake flow is still being drawn from fresh ambient water. This situation is contrasted to that of the stagnant water tests in which the direct recirculation percentage was either zero (all intake flow being drawn from fresh ambient water) or in the neighborhood of 30-40% (about one third of the intake flow being drawn directly from the discharge flow with

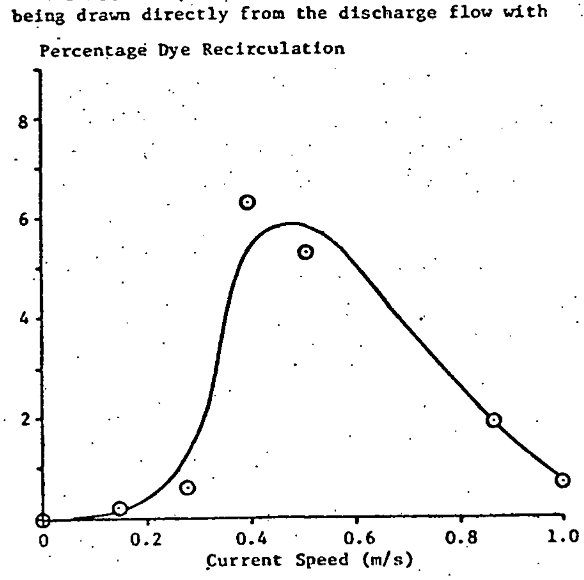


Figure 8 Recirculation Percentage as a Function of Ambient Current Speed for a 400 MWe Plant with Horizontal Radial Evaporator Discharge

most of the remainder being drawn from the near field plume).

Summary

This paper has described an ongoing experimental program to investigate the detailed external fluid mechanics associated with OTEC Plants. Results have been discussed for tests performed in stratified, stagnant, ambient receiving water and for special tests which investigate jet-boundary interaction. Further detail concerning these tests is available in Adams, et al. (1978). Together with tests presently being performed in stratified, flowing, ambient receiving water, these tests should provide valuable data concerning potential recirculation and near field plume transport for a range of both OTEC plant designs and ambient conditions.

Acknowledgement

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