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EVALUATION OF MIXING AND RECIRCULATION IN GENERIC OTEC DISCHARGE DESIGNS

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ABSTRACT

This paper has two parts. The first summarizes the results of an experimental and analytical study of the external fluid mechanics of generic OTEC designs, which was conducted at M.I.T.'s R.M. Parsons Laboratory for Water Resources and Hydrodynamics from March 1976 to July 1977. In this study it was concluded that plants of 100-200 MW, utilizing mixed evaporator and condenser discharges, could be designed to operate with no recirculation under typical ocean conditions. The primary design variables affecting recirculation were identified and recommendations for future research were made. The second half of the paper outlines a continuing research effort. This effort consists of further study of near-field mixing processes currently underway at M.I.T. and study of the intermediate field disturbances of the ambient ocean now underway at Cornell University.

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 our research 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.

The study described in the first part of this paper is a step in this direction. Here the flow associated with a simple design concept -- involving a mixed evaporator and condenser discharge located at the interface of a two-layer ocean -- was studied in detail, both experimentally and analytically. Aside from supplying useful design information for this concept, a major purpose of the experiments was to provide data for use in the calibration of numerical models, which could be applied to different design concepts.

The research program outlined in the second part of the paper is aimed at extending the range of design options and ambient ocean conditions which are considered. Both the experimental and analytical procedures involve

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refinements of the initial effort. In addition, an analytical study of intermediate field disturbances (order of 1-100 km from the plant) is undertaken to arrive at OTEC siting guidelines.

1. Results To-Date

1.1 Background Information

Experimental and analytical studies were carried out to determine the characteristics of the temperature and velocity fields induced in the surrounding ocean by the operation of an OTEC plant. In particular, the condition of recirculation, i.e., the re-entering of OTEC discharge water back into the plant intake, was of interest due to its adverse effect on plant efficiency. However, the results of the study could also be used to address other design or environmental issues associated with the external fluid mechanics of OTEC plants. A brief description of the study is included below. For further information the reader is referred to Jirka et al. [1977a,b].

Figure 1 depicts the situations which were studied. Emphasis was placed on the mixed discharge concept in which the evaporator and condenser water flows are exhausted jointly at the approximate level of the ambient ocean thermocline. Both a radial slot discharge and four separate ports oriented at 90° were considered. The ocean was assumed to be discretely stratified and to have a uniform current velocity.

In order to simplify the experimental program, only flow in the upper layer of the ocean was considered. This layer was modeled in an inverted manner and the actual OTEC discharge at the ocean thermocline was simulated by a model discharge at the free surface. The conservativeness of this procedure, regarding the prediction of any recirculation, was demonstrated by analytical techniques.

The experiments were conducted in an 18 m x 12 m x .4 m basin. Temperatures were measured by an array of thermistors surrounding the model. Recirculation was detected by measuring both temperature and dye concentrations in the plant intake, while an assessment of the induced flow was made through dye observation.

The parameters which were studied centered around a 100 MW OTEC plant operating at a thermocline depth of about 70 m. However, considerable variation in size, design and operating conditions of this plant was considered. Typical model dimensions, based on an approximate model scale of 1/200, are shown in Table 1.

The analytical studies consisted of the formulation and application of integral jet models for both the radial and the separate jet cases. These models compute the primary jet properties (temperature, thickness, etc.), under conditions of no ambient current or intake recirculation, by incorporating the effects of discharge geometry and flow rate, stabilizing

effects due to density differences, and the effects of the return flow induced by the combination of the evaporator intake and the jet entrainment flow. A list of the variables considered in the model is given in Table 1.

Comparison of model predictions with experimental measurements indicates generally good agreement. Although the model cannot predict the extent of recirculation, it was found to provide a good measure of the onset of recirculation when experimental measurements were used for calibration.

1.2 Summary of Results

Based on the combined experimental and analytical results, the following conclusions are made.

i) The major characteristic zones of the temperature and flow field of the OTEC plant are a jet mixing zone and an intake flow zone in the near field (of the order of a few hundred meters in extent) and density and ambient current zones in the far-field. Of these, the jet discharge mixing zone is probably the most important one. Effective jet entrainment causes the accumulation of large quantities of mixed water at the edge of this near-field zone.

ii) This accumulation of fluid mass, which ultimately may result in intake recirculation, is counteracted by two mechanisms: buoyant convection in the form of density currents and convection by ambient ocean current. For the relatively low current speeds which were studied experimentally, the role of the first mechanism seems to be the more important. In fact, little difference in the tendency for recirculation could be identified for ambient currents in the (prototype) range of $0 < U_a < 0.1$ m/s.

iii) The jet mixing is controlled predominantly by the discharge velocity (i.e. by the discharge area for a given flow rate). This is reflected in the definition of the governing discharge parameter, a densimetric Froude number

$$F_o^* = \frac{u_o}{\sqrt{\frac{\Delta\rho_o}{\rho} g A_o}} \quad (1)$$

where u_o = discharge velocity (equal to $Q_i/4A_o$)

$\Delta\rho_o/\rho$ = relative density difference between discharge and upper ocean layer (i.e. one half of the total relative

density difference between the upper and lower layer for the mixed discharge concept).

g = gravitational acceleration

A_o = characteristic discharge area equal to one half of the area of one of the four discharge ports or one half of the area of a quarter section of radial discharge slot. (The one-half comes from the symmetry of the mixed discharge.)

The shape of the discharge ports appears to have a secondary effect on the discharge dynamics. While the flow patterns observed with radial and separate jets (which represent extremes in the shape factor) were quite different, the overall induced temperature field was similar.

iv) The principal parameter governing the dynamics of the intake flow is another densimetric Froude number,

$$IF_i = \frac{Q_i}{\sqrt{\frac{\Delta\rho_o}{\rho} gH}} \quad (2)$$

Although the sensitivity of the external flow field to the evaporator intake design and location was not considered, the optimal intake level would appear to be as close to the surface (above the discharge ports) as possible without causing excessive flow velocities and surface drawdown. Furthermore, due to its potential flow characteristics, the flow field is expected to be nearly independent of the intake opening dimensions and horizontal location except in the immediate vicinity of the intake. Since the intake flow accounts for only a small portion of the double sink return flow (jet entrainment accounting for the remainder), specific intake design parameters will only affect that portion and the effect will be felt only near the intake opening.

v) A condition of recirculation is generally associated with a high degree of jet discharge mixing and high intake flow rate, i.e., a combination of large values for IF_o^* and IF_i . The analytical model for discharge mixing was used in conjunction with the experimental results to determine a criteria for the onset of recirculation for a radial discharge in stagnant water. The criteria states that recirculation of mixed discharge water back into the evaporator intake will occur if the jet zone occupies more than 50% of the available mixed layer depth, H . This can be interpreted as a "blocking" of the ambient water flow toward the intake. In terms of the governing parameters

of the problem IF_o^* , IF_i , and the geometric ratio of plant radius to radius to discharge length scale, $r_o/\sqrt{A_o}$ Jirka et al. (1977b) show that recirculation will be prevented when

$$\left[1 + 4.0 \left(\frac{r_o}{\sqrt{A_o}}\right)^{-2}\right] \left[1.4 IF_i + 4.4 \times 10^{-4} IF_o^* \left(\frac{r_o}{\sqrt{A_o}}\right)^{5/2}\right] < 1 \quad (3)$$

By using the actual design parameters, Equation (3) can be rewritten as:

$$1.39 \left[\frac{u_o^3 r_o}{\Delta \rho_o} \right]^{1/2} \left[\frac{r_o^2 u_o}{Q_i} + 1 \right] \left[\left(\frac{Q_i}{u_o r_o H} \right)^{5/2} + 2.6 \times 10^{-3} \right] < 1 \quad (4)$$

The set of operating parameters in Equation (4) is complete in the sense of determining the recirculation potential of an OTEC plant in stagnant water with a radial, mixed, discharge jet. Because there should be less blockage of the intake flow, it should also provide a conservative measure of the recirculation potential for a (symmetrical) separate port mixed discharge provided that the appropriate value for A_o is used. In either case, recirculation sensitivities can then be studied by varying one of the parameters while leaving the others fixed:

Recirculation potential increases for	Increased discharge velocity,	u_o
	Increased flow rate (i.e., plant size)	Q_i
Recirculation potential decreases for	Increased mixed layer depth,	H
	Increased thermal gradient,	$\frac{\Delta \rho_o}{\rho}$
Recirculation potential changes with variable sensitivity depending on other parameters for	Increased plant radius,	r_o

Equation (4) can be used: 1) to assess the recirculation likelihood for specific design concepts or parameters and 2) to estimate the effect of variable conditions (such as the seasonal changes in $\Delta \rho_o/\rho$ and H). The following examples illustrate the use of the design formula:

A) 100 MW Plant

$$Q_i = 500 \text{ m}^3/\text{s}, u_o = 2 \text{ m/s}, \Delta\rho_o/\rho = 0.003 (11^\circ\text{C}), r_o = 23 \text{ m}.$$

$$H = 50 \text{ to } 100 \text{ m}.$$

Denoting the left-hand side of Equation (4) by C

$$C = 0.4 \text{ to } 0.1 \text{ (as } H = 50 \text{ to } 100 \text{ m)}$$

$C \ll 1$ No recirculation likely.

B) 200 MW Plant

$$Q_i = 1000 \text{ m}^3/\text{s}, u_o = 8 \text{ m/s (comparable to discharge velocities for submerged diffusers)}, \Delta\rho_o/\rho = 0.003, r_o = 23 \text{ m}.$$

$$C = 0.9 \text{ to } 0.5 \text{ (as } H = 50 \text{ to } 100 \text{ m)}$$

$C < 1$ No recirculation likely, although critical value would be approached for small H and decreases in ΔT_o .

C) 400 MW Plant

$$Q_i = 2000 \text{ m}^3/\text{s}, u_o = 8 \text{ m/s}, \Delta\rho_o/\rho = 0.003, r_o = 23 \text{ m}.$$

$$C = 1.5 \text{ to } 0.5 \text{ (as } H = 50 \text{ to } 100 \text{ m)}$$

$C \sim 1$ Incipient recirculation likely.

On the basis of such preliminary calculations, it might be concluded that a maximum possible OTEC plant size which carried a degree of conservativeness (i.e. is designed for no recirculation under a range of ambient conditions) would be on the order of 200 MW. However, remember that Equation (4) applies only to the mixed discharge concept and that it does not predict the extent of recirculation, but only whether or not recirculation takes place.

2. On-Going Investigation

2.1 Near Field Mixing and Recirculation

While the work described above contributes to the knowledge of the near field flows, both the experimental and analytical model schematizations allowed only limited design options to be explored under simplified ocean conditions. The most specific conclusion of the study - that 200 MW plants operating with a mixed discharge concept can avoid recirculation - is not sufficient to allow design optimization.

Upgraded laboratory facilities and more development time now makes more realistic schematizations and larger plant sizes amenable to experiments and analytical models. The plant designs and ambient conditions which can now be studied are indicated in Figure 2. The experimental improvements and proposed experimental and analytical programs are discussed below.

2.1.1 Experimental Improvements

a) Ocean Schematization

The previous study considered a discretely stratified ocean with a fixed thermocline position relative to the (mixed) discharge. The analytical analysis was limited to the condition of no ambient current while experiments considered only low (0-.1 m/sec) current speeds.

In order to examine the effect on evaporator intake temperature of withdrawal from a continuously stratified ocean, the present experimental effort involves tests in a thermally stratified basin. Different profiles can be obtained by varying the basin fill-up procedure. Parameters varied are: 1) inflow rates, 2) inflow temperature, and 3) stratification decay time between "fill-up" and the start of an experiment. Examination of sample profiles reveals good horizontal uniformity and agreement with reported ocean profiles.

In order to simulate stronger and spatially uniform currents, an apparatus for towing the model is being built. Current speeds up to 1 m/sec can be considered.

b) Mixed Versus Non-Mixed Discharge

The most basic design choice involves the relative orientation of the condenser and the evaporator discharge flows. In the "mixed mode" concept, the flows are either combined before being discharged or are discharged close enough together so that the jets merge near the outlet. In the "non-mixed mode", the discharge flows are separated such that there is little or no interaction between them.

The major part of the previous experimental program was devoted to the mixed mode of discharge. In this mode, the difference in temperature between the discharge waters and the evaporator intake water was approximately 11°C. It is the buoyancy caused by this temperature differential that counteracts recirculation tendencies. A basic result of the experimental program was that for the plant sizes which were tested, near-field recirculation could be wholly prevented for this mode discharging into a stagnant or slow current environment.

The "unmixed mode" discharge, on the other hand, has a greater tendency for evaporator intake recirculation than the "mixed mode" due to lower temperature and density differentials (2 or 3°C rather than 11°C) between

evaporator intake and discharge water. Several exploratory experiments conducted with smaller temperature differences (but the same discharge rates as the mixed tests) showed definite recirculation based on dye measurements and visual observations. The observed change of intake temperature, however, was small (less than 0.02°C) and would not suggest a complete disqualification of the "unmixed" discharge mode.

The new ocean schematization allows simulation of a mixed discharge placed anywhere above a depth of approximately 150 m. More importantly, the OTEC evaporator discharge can now be modeled for the non-mixed mode. This simulation is limited to cases of little interaction with the condenser discharge jet and a point of discharge above a depth of about 150 m.

c) Other Design Variables

In addition to the basic choice of mixed versus non-mixed discharges, it is important to consider both larger plant sizes and different design concepts (e.g. angle of discharge ports, position of intakes and discharge ports with respect to the ambient thermocline, etc.).

With regard to plant size, it is important that tests be conducted at sufficient sizes to effect significant recirculation. In this way the tradeoff between economies of scale associated with large plants and the loss of generating efficiency due to recirculation can be made.

The new experimental plant model (built at a nominal scale of 1:300) allows variation of the above and other design variables (see Figure 2). Plant sizes up to the 400-500 MW range can be simulated.

2.1.2 Experimental Measurements

A system of 100 thermistor temperature probes and an electronic scanner provides a detailed record of the plant induced temperature field. Most probes are mounted on a vertically traversing frame that allows one probe to measure temperature at any depth for a single horizontal location. Temperature measurement accuracies are approximately 0.1°C . For experiments simulating currents, thermistor probes mounted on the towed platform will document recirculation and temperature perturbations in the immediate vicinity of the plant. Fixed thermistor probes throughout the basin will document the development of the thermal wake.

The assessment of recirculation will involve fluorometer measurements of dye concentrations as well as temperature measurements. A measurement of the relative concentrations of dye in the discharge and intake flows gives recirculation directly.

The fluorescent red dye also provides a visual means to trace the fate of the discharge waters. Photographs taken through a vertical window will

record the discharge flow depth and thickness for half-model experiments.* Overhead pictures will especially be important in recording the thermal wake left by the towed full model.

2.1.3 Analytical Model Developments

The recirculation design formula (Equation (4)) was developed from a radial two-dimensional integral jet model in a two-layered ocean. Like the actual experiments, the model assumed a mixed discharge at the position of the thermocline.

The inclusion of a continuous density profile and the ability to treat discharge flows at any elevation are logical first steps in generalizing the model. Using models of plane, "ducted jets" as a guide, an attempt will then be made to model conditions after the onset of recirculation. The inclusion of different boundary conditions and the addition of buoyancy will be necessary to apply these models to OTEC. Some tuning of these models with our experiments will also be necessary.

Finally, the relationship between radial jets and separate jets located symmetrically around a plant central axis will be investigated. While previous experimental and analytical results have shown little difference in the induced temperature field of a radial discharge and a four port (directed at 90° to each other) discharge results may be different under considerations of recirculation. The experimental program in progress is expected to yield more information on this question and to tune the analytical model.

2.2 Intermediate Field Environmental Perturbations Induced by OTEC

Whether a mixed or non-mixed discharge mode is utilized, the discharge plumes will find an equilibrium level where jet entrainment ceases and the plume density is equal to the ambient density. This constitutes the beginning of the "intermediate field". In the intermediate field, the OTEC effluent is distributed horizontally by the interaction of three mechanisms: buoyancy currents arising from the induced density discontinuities, advection by the ambient currents and diffusion by the ambient turbulence in the ocean.

The analysis of the intermediate field has two important implications: First, and from an environmental viewpoint, it determines the downstream influence of a plant effluent, that is the area over which the physical, chemical and biological disturbances of the plant can be felt and measured. This is important for siting strategies of multiple plants.

* In half-model experiments a basin wall takes the place of a vertical plane of symmetry.

Secondly, and from a resource viewpoint, it provides information on the resource depletion effect from one plant to other plants (and possibly a feedback to the first plant, in the case of weak ambient currents). It provides an answer to a dichotomy in present OTEC studies: (i) Near-field studies (such as reported in the earlier part of this paper) indicate that it is possible to operate an OTEC plant without decreasing the ocean surface temperature. (ii) Global studies on the scale of an ocean basin indicate that a number of OTEC plants (or even a single plant) must decrease the ocean surface temperature for reasons of the energy budget. The resolution of this dichotomy lies in the spatial scale of the processes and can be obtained from the intermediate field analysis. For example, a likely sequence of events is: A single plant causes a perturbation of the ambient thermocline structure over a downstream distance of say 10 km; the thermocline stability is modified; wind mixing results in a different thermocline formation at a larger downstream distance of say 100 km and the surface temperature will be decreased at this point. Thus, the OTEC operation at one location can have an effect at a very different location. Even though this single plant effect is small (likely on the order of 0.01°C), the cumulative effect becomes important when considering multiple plant siting.

2.2.1 Analytical Model Development

Research is in progress to develop predictive models for the internal spreading of the discharge layer in the stratified ocean. Specifically, the steady-state spreading in a uniform ambient current and the transient motion under stagnant conditions will be investigated. The model results will be compared with experimental data from the ongoing laboratory studies. The ultimate purpose of this study is the development of siting guidelines for the interaction of multiple OTEC plant modules in the tropical ocean.

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TABLE 1
SUMMARY OF GEOMETRY AND FLOW VARIABLES
USED IN EXPERIMENTAL AND ANALYTICAL MODELS

Variable *	Range in	
	Experimental Model **	Mathematical Model
Q_i	500 - 1000 m ³ /sec	unlimited
H	70 m	unlimited
H_d	70 m	equals H
H_i	6 m	***
r_i	8 m	***
r_o	23 m	unlimited
h_o	radial : 1.2 & 0.6 m 4 port : 3.8 m	unlimited unlimited
b_o	4 port : 6.0 & 12.0 m	unlimited
$\frac{\Delta\rho_o}{\rho} = \frac{\rho_2 - \rho_1}{2\rho_2}$	.05 - 3.4 ($\times 10^{-3}$ gm/cm ³)	unlimited
U_a	0 & 0.1 m/sec	0

* Refer to Figure 1

** Assume undistorted 1/200 Froude scaling

*** The plant intake is distributed along the plant axis over the upper layer depth of $H_d - h_o$.

Figure 1 Geometry and Flow Parameters for Mixed Discharge Design

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.
$\Delta \rho$ (10^{-4} gm/cm ³)	4. - 34.
H (m.)	25. - 150.
$\frac{d\rho/dz}{(\Delta\rho - \Delta\rho^*)/(180 - H)} \Big _{\max.}$	1.1 - 3.3

Figure 2 New Experimental and Analytical OTEC Schematizations (with experimental parameter ranges)