EXPERIMENTAL STUDY OF THE BUOYANT SURFACE JET WITH THE PRESENCE OF BOTTOM BOUNDARY AND CROSS CURRENT.

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I. INTRODUCTION:

The problem of buoyant surface jet (BSJ) is relevant from the practical standpoint to the discharge of cooling water of power plants into the receiving water bodies. The buoyant surface jet has extensively been studied by numerous investigators both theoretically and experimentally. Most studies have been concerned with the problems of BSJ discharged horizontally into a surface of a deep ambient water with or without cross current.

From a practical standpoint, however, the design engineers are often confronted with the design of thermal outfalls in the coastal regions which are frequently shallow and have the boundary effects. Few investigators have studiedthe problem of BSJ discharged horizontally over slopping bottom into quiescent receiving water (1), (2), (4), (5), (6), and (7). However, no information on the foregoing problem with moving ambient water is available. The purpose of this paper is (a) to present the experimental results of BSJ which is discharged over slopping bottom into moving ambient water, and (b) to see the degree of error which is introduced by applying the deep water integral models to the case of a buoyant surface jet with a bottom boundary.

II. DIMENSIONAL ANALYSIS:

The BSJ is characterized by the following source parameters

1. Volume flux, $Q_o = U_o A_o$ $(L^3\ T^{-1})$;
2. Momentum flux, $M_o = U_o^2\ A_o$ $(L^4\ T^{-2})$;
3. Buoyancy or kinematic mass deficiency. flux

   $B_o = \frac{\Delta\rho o}{\rho_a}\ g\ U_o\ A_o$ $(L^4\ T^{-3})$;
4. Aspect ratio, $A_s = h_o/b_o$;

The subscript -o refers to source parameters and the subscript -a to ambient conditions (receiving water); U is velocity, A is area, h_o is discharge height, b is width, ρ is density, $\Delta\rho$ is $\rho_a - \rho$, and g is gravitational acceleration.

The bottom boundary is characterized by the bottom slope and the bottom friction. Howver, only the effect of bottom slope is considered in the present investigation.

In the present study, the direction of ambient current is assumed to be parallel to the shore line. Therefore the ambient current is characterized by current speed U_a.

By dimensional analysis one can show that the independent dimensionless numbers are

1. Source Densimetric Froude number,

$$F_o\ (A) = \frac{M_o^{5/4}}{B_o^{\frac{1}{2}}\ Q_o} = \frac{U_o}{\left(g_o'\ A_o^{\frac{1}{2}}\right)^{\frac{1}{2}}}$$

where $g_o' = (\Delta\rho o/\rho_a)\ g$

2. Discharge Aspect Ratio, $A_s = h_o/b_o$
3. Bottom slope, S
4. Current ratio, $U_r = U_a/U_o$

In this experimental study the range of values of the abovementioned dimensionless numbers have been chosen to be close to the typical range of values commonly encountered in the design of outfalls.

The range of the variation of the above dimensionless parameters in this experimental study are as follows:

1. $2 < F_o\ (A) < 13$
2. $A_s = 1.5$
3. $o \leq S \leq 0.04$
4. $0.2 < U_r < 0.7$

It should be noted that in developing the foregoing dimensionless parameters, it is assumed implicitly that the Reynolds number is high enough so that viscous effects are negligible, the heat loss to the atmosphere is insignificant, and since we are mainly concerned with the near field the effect of ambient turbulence is negligible.

III. EXPERIMENTAL ARRANGEMENT:

The experimental arrangement is designed in such a way that the preceding dimensionless parameters could be varied systematically and their effect on temperature field could be studied. The main feature of the experimental arrangement is shown in figures 1 and 2.

The experimental set up consisted of three major systems:

1. Receiving water system;

2. Warm water discharge system;

3. Data acquisition system.

These are described breifly in the following:

III.1 The Receiving Water System:

The main components of the receiving water system consisted of (a) a wind wave tank, 45.7m x 2.4m x 1.5m. In the middle section of this tank there was a 3.6m x 1.2m glass window on one of the side walls. Thus the flow pattern could be visualized from the side as well as from the top. (b) A circulating pipe and pump, which could generate a maximum current of 15cm/sec., was used to simulate the off-shore currents. (c) The bottom boundary consisted of a ply-wood "beach" 2.4m x 4.6 m with a supporting frame. The "beach" slope and the direction of the slope was adjustable. The direction of the "beach" slope was adjusted so that the ambient current was parallel to the shore. It should be noted that since the "beach" was installed in the tank in such a way that there was minimum obstruction to the ambient current, an excellent uniform and parallel ambient current could be obtained. In other words the "beach" was acting as a "flat plat" in the uniform flow field.

III.2 The Warm Water Discharge System:

The main components of this system consisted of (a) the main insulated tank with the dimensions 1.2m x 0.91m X 0.91m. This tank was insulated and was used to mix the warm and cold water to obtain the desired temperature of the Warm water discharge in the main tank. During the mixing process and during the experimental run a stirrer was used to assure temperature homogeneity of the water in the main tank. During the mixing of warm and cold water, water was continuously pumped through a bypass to the drain. By this procedure it was possible to warm the pipeline to the temperature of the warm water to be discharged. Also, using a continuous discharge, the water temperature could be monitored by the use of a digital thermometer which was placed in the line. Thus, proper adjustments could be made of the flow rate of the warm and cold water supply to expedite

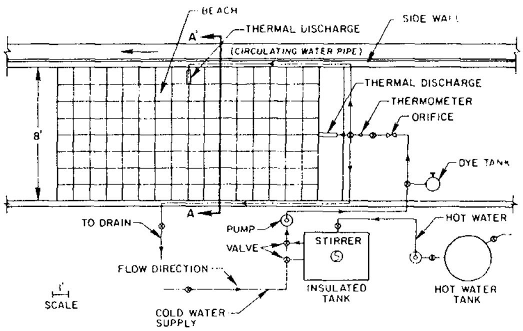

Fig.1 Schematic of the experimental set-up (Plan View)

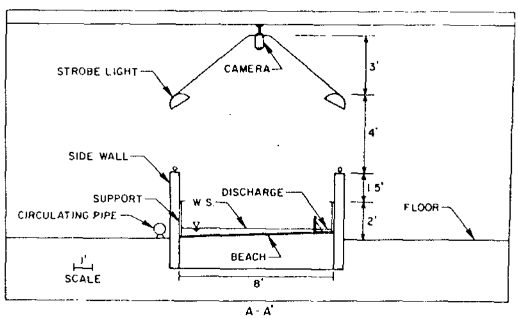

Fig.2 Schematic of the experimental set-up (Side View)
3a

achievement of the desired temperature.

b) The line from the main insulated tank to the discharge point: this "pipeline", most of which was a flexible hose, had an orifice meter installed in it which was used to measure the flow rate. It also had a dye injection assembly installed in it, which was used for the injection of dye into the discharge. Warm water was discharged from the side using a flexible hose (see figurres 1 and 2).

c) Dye injection assembly: this consisted of a stainless steel tank for the dye supply in which dye could be stored and be kept under constant pressure. A needle valve was used to give the desired dye flow rate.

III.3 Data Acquisition System:

The data acquisition system can be divided into two main subsystems as follows:

III.3.1 The phographic system: consisted of a remotely controlled camera and four stroke lights which were mounted on a four adjustable arms. The camera and floodlight assembly were mounted under a moveable base which in turn was mounted on a rail, located just under the roof. The rail was above the longitudinal centerline of the tank (see figure 2).

III.3.2 The temperature measuring system: consisted of a number of thermistor probes, a moving carriage on which thermistor probes were mounted, electronic boxes for the thermistor probes, shielded cables, five channels of digital to analog (DA) for control and operation of experiments and 256 channels of analog to digital (AD) convertors, a 16K Nova mini-computer, 2 flappy disk systems, an acoustic coupler for data transfer to the computer of UCB, and $\pm$ 15 volt power supply.

A more detailed descriptions of the experimental arrangements, the experimental procedure, and the methodology for data analysis are given in Ref. (4).

IV. AN OVERVIEW OF THE FLOW AND CIRCULATION PATTERN:

Figures 3 to 10 show the photographs of a typical flow pattern generated by the discharge of a BSJ over a slopping bottom into an ambient water with cross current. In these photographs the squares are 30.48cm x 30.48cm and are on the the beach. Figure 3 shows the start of the discharge. Note that the nucleous of a circulating cell is forming at the tips. Figure 4 shows the flow pattern

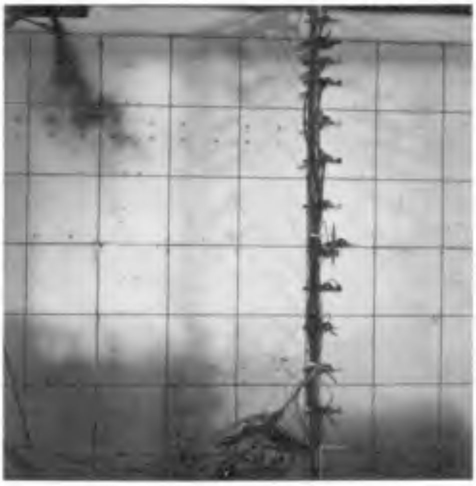

Fig.3 Photo of the Flow Pattern

Fig.4 Photo of the Flow Pattern

Fig.5 Photo of the Flow Pattern

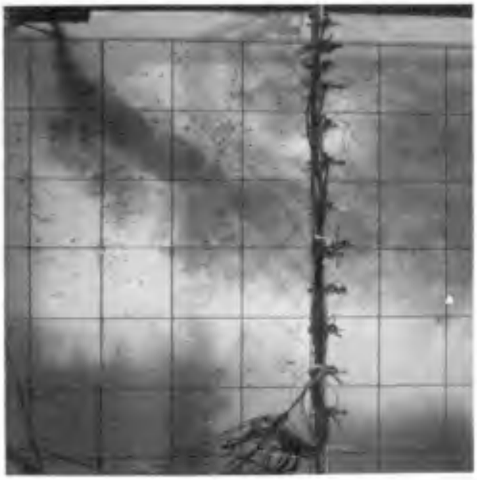

Fig.6 Photo of the Flow Pattern

Fig.7 Photo of the Flow Pattern

Fig.8 Photo of the Flow Pattern

Fig.9 Photo of the Flow Pattern

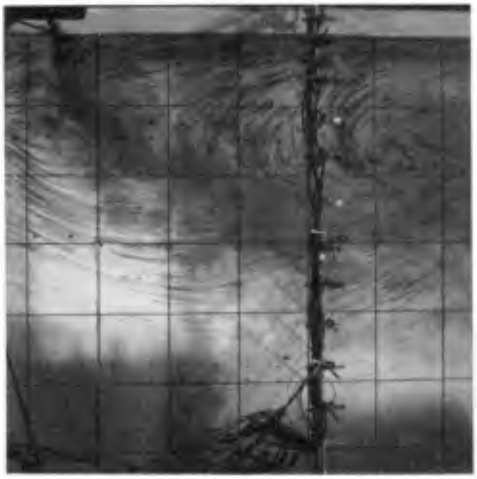

Fig.10 Photo Of the Flow Pattern

at a later time. As can be seen the BSJ is bent due to the cross current (parallel to the shore line). The circulating cell is still under development and have moved approximately 0.5m from the shore line. Figures 5 and 6 indicate that the circulating cell is reaching the equilibrium condition and has initiated the reentrainment of the warm water. Note the dye streaks from dye crystals is developing and showing the bottom flow pattern.

Figures 7 and 8 clearly show the recirculation pattern. As can be seen from these photographs the circulating cell has a two-dimensional character. Also to be noticed in these photographs is the interesting deflection pattern of the ambient current which was parallel to the shore line before discharging the BSJ. Figures 9 and 10 show the final equilibrium stage at which the reentrained warm water has completely filled the area between shore line and the BSJ. The bottom current pattern is also clearly shown by the developed dye streaks. Again note the interesting deflection pattern of the ambient current and the circulating cell in these photographs.

Based on these observations the flow field can be schematized as shown in figure 11. It was found that the location of the center of the circulating cell is mainly a function of the source Densimetric Froude number and the ambient current ratio.

V. PRESENTATION OF EXPERIMENTAL DATA:

The effect of the systematic variations of the independent dimensionless numbers on the centerline temperature and the jet trajectory is investigated experimentally. In this section the experimental results are presented.

Figure 12 shows the effect of the variation of the source Densimetric Froude number on the centerline temperature decay other parameters being constant. In this figure normalized centerline temperature, $\Delta T_m/\Delta T_o$ is plotted Vs. normalized distance, $S_c/\sqrt{A_o}$, for different values of the source Densimetric Froude number. Here $\Delta T_m = T_m - T_a$, $\Delta T_o = T_o - T_a$, T_m is maximum temperature at a given section, T_a is ambient temperature and T_o is source temperature along the curvilinear co-ordinate as shown in figure 11. As can be seen for all practical purposes, within the experimental range, the centerline temperature decay does not vary with the source Densimetric Froude number.

The effect of the ambient current ratio on the centerline temperature can be seen in figure 13. The other parameters being constant, an increase in the cross-current

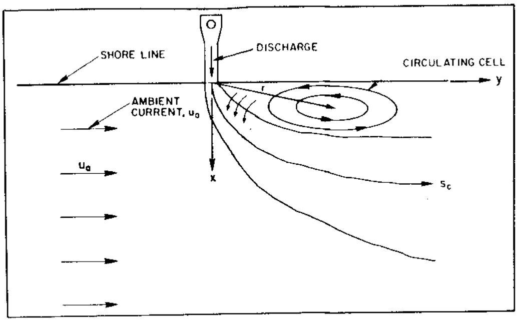

Fig.11 Schematic of the Flow Pattern

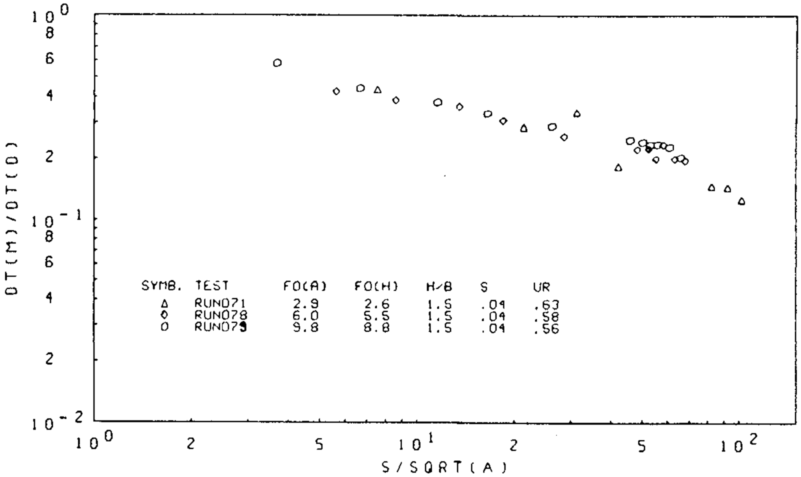

Fig.12 Normalized Centerline Temperature
vs Normalized Curvilinear Distance
(effect of F_o)

ratio will cause the centerline temperature to increase. The normalized centerline temperature is 26% higher for high ambient current ratio as compared to the one for low ambient current ratio, for $S_c/\sqrt{A_o} > 40$. The reason for this trend may be attributed to the increased recirculation, on the shore side, due to increase in the ambient current ratio, as well as the characteristics of the circulating cell which causes the warmer water to reentrain at a farther distance from the source. Shown in figure 14 is the effect of bottom slope on the centerline temperature decay. As can be seen increasing the bottom slope causes a decrease in the centerline temperature.

The effect of the important parameters on the centerline trajectory of a BSJ (i.e., the locus of the centerline temperature in the x-y plane) is depicted in figures 15 to 17. Figure 15 indicates that other parameters being constant an increase in the source Densimetric Froude number will cause a decrease in the radius of curvature of the jet trajectory. In other words the higher the Densimetric Froude number the closer is the jet trajectory to the shore line. This may be attributed to the high ambient pressure drag force at high Densimetric Froude numbers due to the jet attachment and the blockage of the ambeint current. Figure 16 indicates that the higher the ambient current ratio the closer is the jet trajectory to the shore line. Finally figure 17 shows that, surprisingly, the reduction in bottom slope will cause the jet trajectory to move offshore, i.e., the jet trajectory assumes larger radius of curvature.

Realizing the unavailability of satisfactory numerical model for buoyant surface jet over slopping bottom with ambient cross current, it is desirable for practical purposes to know the degree of error in predicting the centerline temperature and the trajectory of a buoyant surface jet discharged over slopping bottom into moving ambient flow, by applying the simple integral models which have been developed for BSJs discharged into deep water. For this purpose, the Prych's model (3) was selected. An example of the results is shown in Figures 18 and 19. As can be seen from Figure 18, Prych's model over estimated the centerline temperature. Such overestimation was generally observed for other conditions as well. It was observed that in general Prych's model overestimates the centerline temperature by 10 to 36 percent. However, the predicted jet trajectory shows considerably less deflection than the observed jet trajectory. This can be seen in Figure 19. The comparison for additional conditions is reported in Ref. (4). In general, based on these results, one may conclude that the application of the simple integral modles for the prediction of the characteristics of the

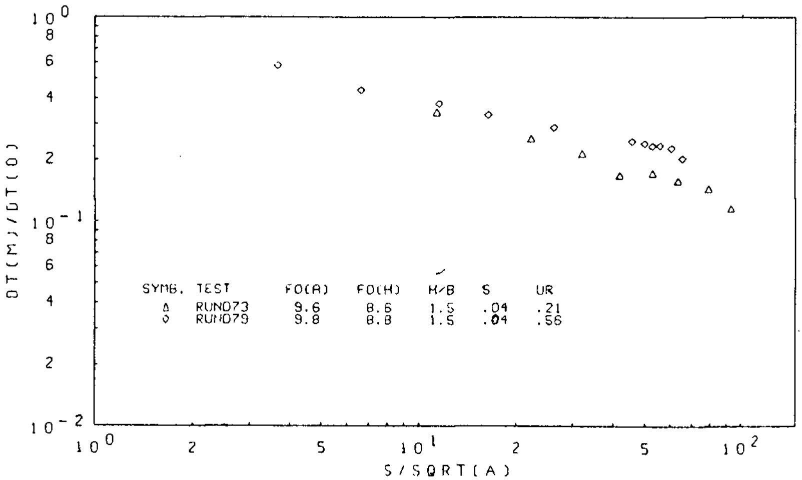

Fig.13 Normalized Centerline Temperature
vs Normalized Curvilinear Distance
(effect of U_r)

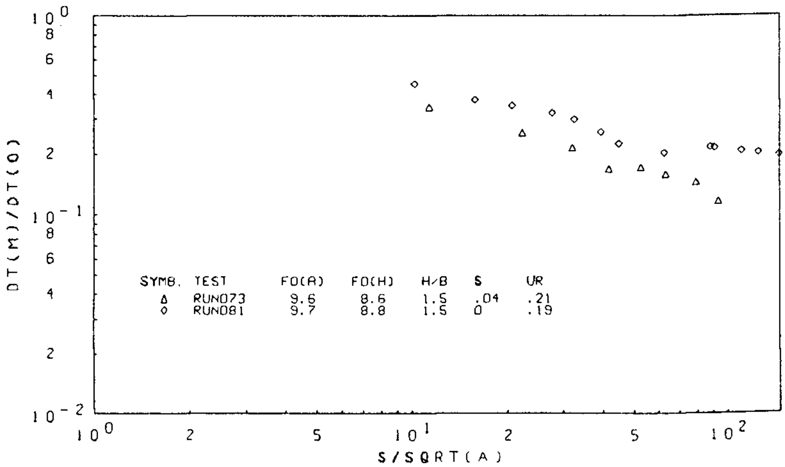

Fig.14 Normalized Centerline Temperature
vs Normalized Curvilinear Distance
(effect of bottom slope)

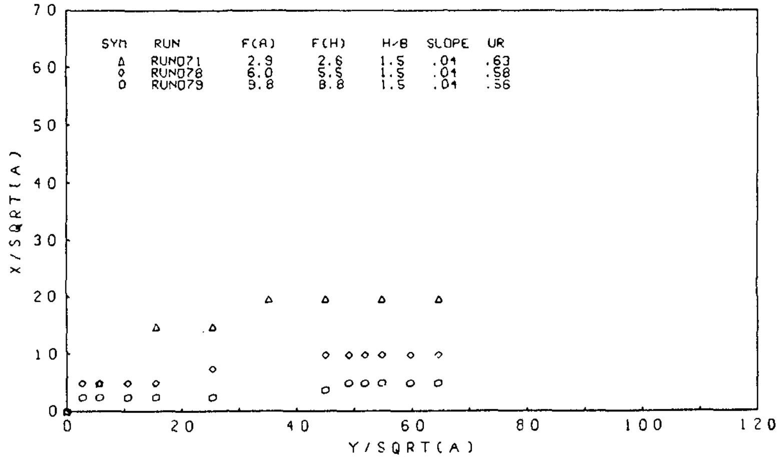

Fig.15 Normalized Jet Trajectory
(effect of F_O)

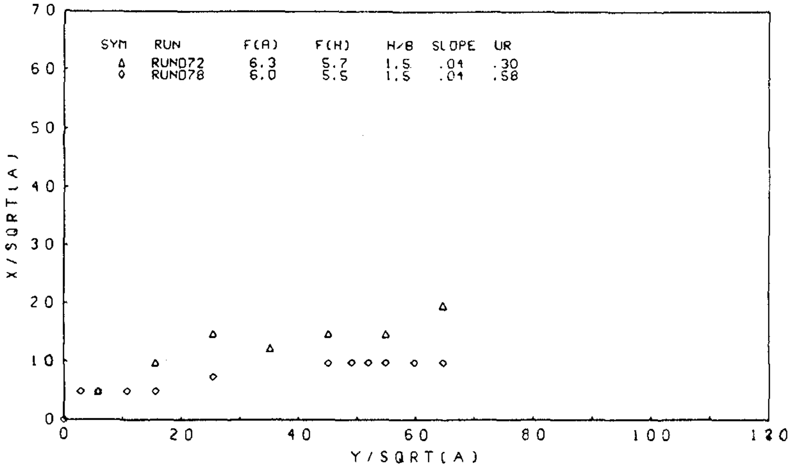

Fig.16 Normalized Jet Trajectory
(effect of U_r)

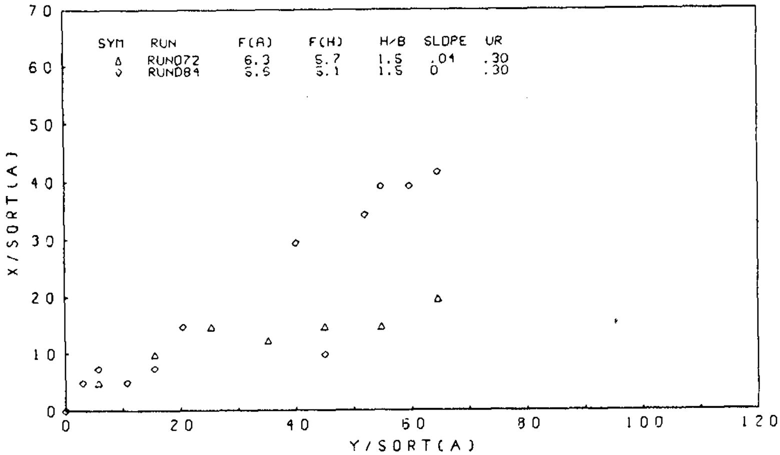

Fig.17 Normalized Jet Trajectory
(effect of Bottom Slope)

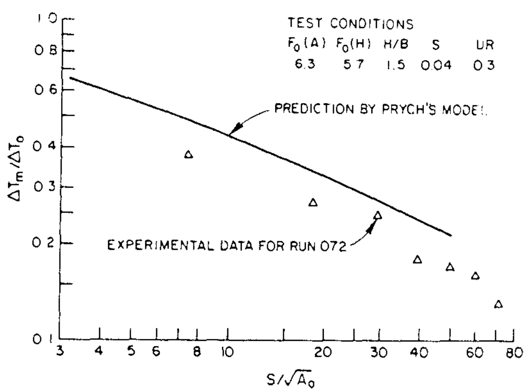

Fig.18 Comparison of the Experimental and
Theoretical results for Centerline Temp.

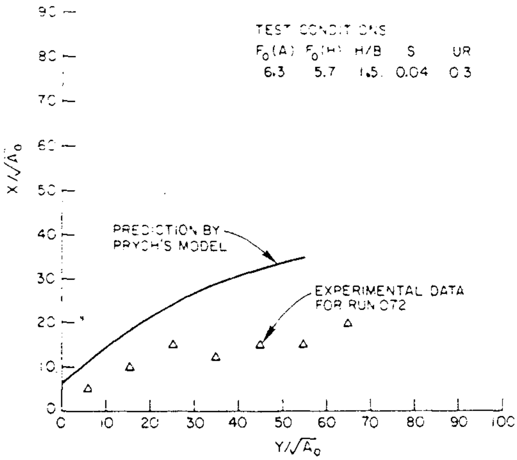

Fig.19 Comparison of the Experimental and Theoretical Results for Jet Trajectory

BSJ discharged over slopping bottom into moving ambient water, will result in conservative estimates.

VI. SUMMARY AND CONCLUSIONS:

The effect of important dimensionless parameters on the characteristics of a BSJ discharged over a slopping bottom into moving ambient water is investigated experimentally. The main results are presented in Figures 12 to 17 and are summarized in Table 1.

TABLE 1. Summary of the Experimental Results.

Increase in →	F_o	S	U_R
Centerline Temperature	No effect	Decrease	Increase
Jet Trajectory	Deflect further	Deflect further	Deflect further

The obtained results are expected to be helpful as general guidelines in the design of thermal outfall in the coastal regions.

The comparison between the experimental results and the predictions by Prych's model reveals that the integral models for BSJs discharged into deep water, generally overestimate the centerline temperature and jet trajectory of a BSJ discharged over slopping bottom into moving ambient water.

VII. LIST OF SYMBOLS:

A_o Discharge Area

A_s Discharge Aspect ratio, $A_s = h_o/b_o$

B_o Discharge Buoyancy flux, $B_o = g'_o Q_o$

$F_o(A)$ Source Densimetric Froude number based on area

$F_o(A) = M_o^{5/4} / B_o^{\frac{1}{2}} Q_o$

M_o Kinematic momentum flux, $M_o = U_o^2 A_o$

Q_o Volume flux, $Q_o = U_o A_o$

S Bottom slope

S_c Curvilinear co-ordinate (along trajectory)

S_n Normalized curvilinear co-ordinate, $S_n = S_c/\sqrt{A_o}$

T Fluid temperature in ^oC.

U_o Magnitude of discharge velocity

U_a Magnitude of ambient cross current

U_r Dimensionless velocity ratio for ambient current,

$U_\gamma = U_a/U_o$

b_o Discharge width

g gravitational acceleration

g_o Modified gravitational acceleration, $g'_o = (\Delta\rho o/\rho_a)g$

h_o Discharge depth

x Longitudinal cartesian co-ordinate axis

y Transverse cartesian co-ordinate axis

ΔT Excess temperature, $\Delta T = T - T_a$

$\Delta\rho$ Water density deffficiency, $\Delta\rho = \rho_a - \rho$

ρ Fluid density

VIII. REFERENCES:

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SUBSCRIPTS:

o The value of a parameter at the discharge.

a The value of a parameter for the receiving water.

m The value of parameter at the centerline of the surface buoyant jet.