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EFFECTS OF SALINITY & TURBULENT DIFFUSION OF POLLUTANTS

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by

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CONTENTS

exploratory study was made experimentally in the laboratory for the molecular and the turbulent diffusion process in the fluid media with various salinity. Dye diffusions were performed in the salt water of known concentrations to simulate the dispersion of pollutant in tidal waters. Both the turbulent and the molecular diffusion coefficient increase as the salinity increases. The variation of the turbulent diffusion coefficient is approximately linear with respect to the salinity. However, the molecular diffusion coefficient tends to change non-linearly with the salinity The turbulent diffusion rate is rather uniform with comparison to the molecular diffusion rate.

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CHAPTER I INTRODUCTION

I-1 General Description and Scope of the Study

Industrial, municipal and agricultural waste discharges have produced increasing pollution problems in the rivers, estuaries, bays and coastal waters of Puerto Rico. Ocean disposals of wastes through the outfalls are commonly adopted in this island. For example, more than ten regional sewage outfalls have been planned by Puerto Rico Aqueduct and Sewage Authority. Some of them have been designed and the environmental impacts of these outfalls have been or are being assessed. Federal restrictions on waste disposal in waterways and oceans require that new outfalls should be well studied before the installations to assure no potential deleterious effects. For the design of ocean outfalls, mixing and diffusion of the waste in the sea water is one of the very important criteria.

According to the survey results on the water quality for the coastal waters by Department of Natural Resource of the Commonwealth of Puerto Rico, there is a strong indication that the salinity varies very much from place to place. The salinity ranges from 30 to 70 parts per thousand. Little is known about the diffusivity of wastes in the sea water with large variation in salinity. Since it is expected that the diffusivity in fresh water will be different from the diffusivity in an environment with presentation of high salinity.

This study presents the experimental results on the correlation between the turbulent diffusivity of pollutant and the salinity. Molecular diffusivity of pollutant as a function of the salinity was also investigated. The main purpose of this study is to test how sensitive the parameter of the salinity will influence the diffusivity. In an estuary, either well mixed or partially mixed, the salinity gradient still exists longitudinally from the river mouth to the upstream limit of the estuary. The diffusion coefficient of pollutant being concerned in the estuarine water quality study should not be considered to be constant if the turbulent diffusion coefficient is a strong function of the salinity in the ambient fluid. It is the attempt of this study to correlate the diffusion coefficient with the salinity.

1-2 Historical Studies

Harleman summaried the work having been done on the correlation of diffusion coefficients in an estuary with referring to the salinity intrusion (see Reference 3).

He and Ippen have shown that the ratio of local apparent and turbulent diffusion coefficient D_x'/D_t is an indicator of the degree of vertical mixing in an estuary. D_t is the diffusivity in an environment without any density effect. The ratio is correlated with the stratification parameter as the following:

$$\frac{D_x'}{D_t} = 1700 \left(\frac{G}{J_x}\right)^{-3/4} \quad (1)$$

In which J_x is known as the stratification parameter which is defined as the ratio of the turbulent energy dissipation to the rate of gain of potential energy of the fluid within the estuary. G is average rate of energy dissipation per unit mass fluid as given in Kolmogoroff's spectrum-of-turbulent theory. D_x' decreases as G increases. The larger values of G/J_x correspond to the well-mixed condition in an estuary. The small values correspond to an increasing tendency toward a two-layed stratification like the saline wedge. Specifically, they proposed the following equation to determine the diffusivity for the case of fresh and salt water in a partially mixed or well mixed estuary with the longitudinal concentration of dye or salt being considered.

$$\frac{D_x'}{D_t} = \phi\left(\frac{G}{g V f}\right) \quad (2)$$

$g' = g \frac{\Delta\rho}{\rho}$ is the reduced gravity. $\Delta\rho$ is the density difference between the salt and fresh water. V_f is the velocity of fresh water flow.

In their study, the vertical turbulent diffusion coefficient was investigated as a function of turbulent intensity, density effect, and the velocity of fresh water flow. No other study has been done with regarding to the effect of density on the turbulent diffusivity. In this study the nature of the work is quite different. The ambient fluid being considered is homogeneous in density. The salinity is uniform in the fluid media. Turbulent diffusivity is investigated with varying salinity while the turbulent intensity is held to be constant. No convective velocity is considered when the diffusion process is going on.

CHAPTER II EXPERIMENTAL CONSIDERATION

II-1 Diffusion Equation

The first order one-dimensional turbulent diffusion equation for the conservative substance in a fluid media of clean water without any convective velocity may be written as

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial y}\left(E \frac{\partial c}{\partial y}\right) \tag{3}$$

Where C is the mean concentration of the dispersant with turbulent fluctuations having been averaged out, t is time, y is the vertical distance from the source of dispersant released, and E is the vertical turbulent diffusion coefficient. It is expected that the turbulent diffusivity will be changed when salinity is presented in the water. If E is assumed to be independent of x, but is a function of salinity s, Equation (1) becomes

$$\frac{\partial c}{\partial t} = E(s) \frac{\partial^2 c}{\partial y^2} \tag{4}$$

where s is independent of y and t. This requires that the salinity is uniformly distributed throughout the fluid at the time being considered. Explicitly the diffusivity can be written as a function of the salinity in the ambient fluid media.

$$E = f_1 (s) \tag{5}$$

The molecular diffusivity, e, normally is small with comparison to the turbulent diffusivity E in the turbulent transport process. However e is also influenced by the salinity presented in the ambient fluid. Equations similar to Equations (4) and (5) can be written for molecular diffusion process,

$$\frac{\partial c}{\partial t} = e(s) \frac{\partial^2 c}{\partial y^2} \qquad (6)$$

$$e = f_2(s) \qquad (7)$$

II-2 Determination of Diffusion Coefficient

The diffusivity can be calculated if c is measured as a function of y and t. The solution to Equation (4) can be obtained with the following boundary conditions for a continuous sources of dispersant.

$$C(o, t) = C_o \quad , \quad t \geq o \qquad (8a)$$

$$C(x, o) = o \quad , \quad x > o \qquad (8b)$$

$$C(\infty, t) = o \quad , \quad t \geq o \qquad (8c)$$

The solution is given by

$$\frac{C}{C_o} = 1 - \text{erf}\left(\frac{y}{2\sqrt{E(s)\,t}}\right) \qquad (9)$$

C_o is the concentration of the source of the dispersant. If values of C/C_o are plotted as an ordinate on an arithmetic-probability scale vs $y/\sqrt{t}$ as an abscissa on a linear scale, Equation (9) will be a straight line if E is a constant (Ref. 1). The numerical value of E is evaluated by the following derivation. There is a point on the abscissa (as not known yet) at which $y/\sqrt{t} = \sqrt{\pi E}$ such that the following equations exist.

$$\frac{C}{C_o} = 1 - \text{erf}\left(\frac{\sqrt{\pi E}}{2\sqrt{E}}\right) = 1 - \text{erf}\left(\frac{\sqrt{\pi}}{2}\right) = 1 - \text{erf}\,(0.89) = 0.21 \qquad (10)$$

$$\frac{C}{C_o} = 0.21 \quad \text{for} \quad \frac{y}{\sqrt{t}} = \sqrt{\pi E} \qquad (11)$$

Time \ Transmittance (%)	NaCl (0%)	NaCl (1%)	NaCl (2%)	NaCl (3%)
0	89.2	89	89	89.9
23 hr. 55 min.	89.5	89	86.9	88.1
48 hr. 40 min.	88.0	86.1	82.8	78.2
72 hr. 20 min.	87.1	81.1	75.8	69.5
99 hr. 20 min.	86.1	74.0	69.9	60.0
122 hr. 10 min	84.1	71	63.7	50.8
initial concentration of dye source	0.1	0.9	1.6	1.2

Corresponding to $C/C_o = 0.21$, a value of $y/\sqrt{t}$ can be found. The numerical value of E is thus calculated.

II-3 Experimental Apparatus and Procedures

The turbulent diffusion processes were simulated in the laboratory. Figures 2, 3, 4, and 5 show the general layout of the experiment. The tank in which the diffusion of dye took place was plastic glass cylinder of 5.3/4 inches inside diameter and 25 inches high. The tank was filled up to 23 7/8 inches high with salt water of known concentration. The turbulence was created by means of the vertically oscillated screens submerged in the water near the free surface with a constant amplitute of 3 5/8 inches and frequency of 0.7 second per cycle. Six screens of size #18 were placed one inch apart. The oscillatory motion of the screen was driven by a motor with the arrangement shown in Figure 1. The set-up of the mixing tank was similar to the one used by Holley in his study on diffusion and turbulence in relation to reaeration (Reference 2). Dye of food coloring type was used. The dye was poured into a beaker which contained salt water with concentration a little bit less than the salt water concentration in the mixing tank. With this small adjustment in density the dye solution so prepared would have the same density as the salt water in the mixing tank. Then the dye solution was gradually introduced into the tank from below. The dye would neutrally stay at the bottom of the tank without any bouyant effect or gravity effect which tended to drag the dye being diffused. This step of introducing the dye solution into the tank had to be extremely careful. The thickness of the dye solution was about two inches. Samples were taken through a 1/8 inches tube at a position about 10 to 11 inches above the interface of the dye solution. Time was recorded for each sampling by means of a CMC Counter Timer (Model 901) starting when the oscillatory motion began.

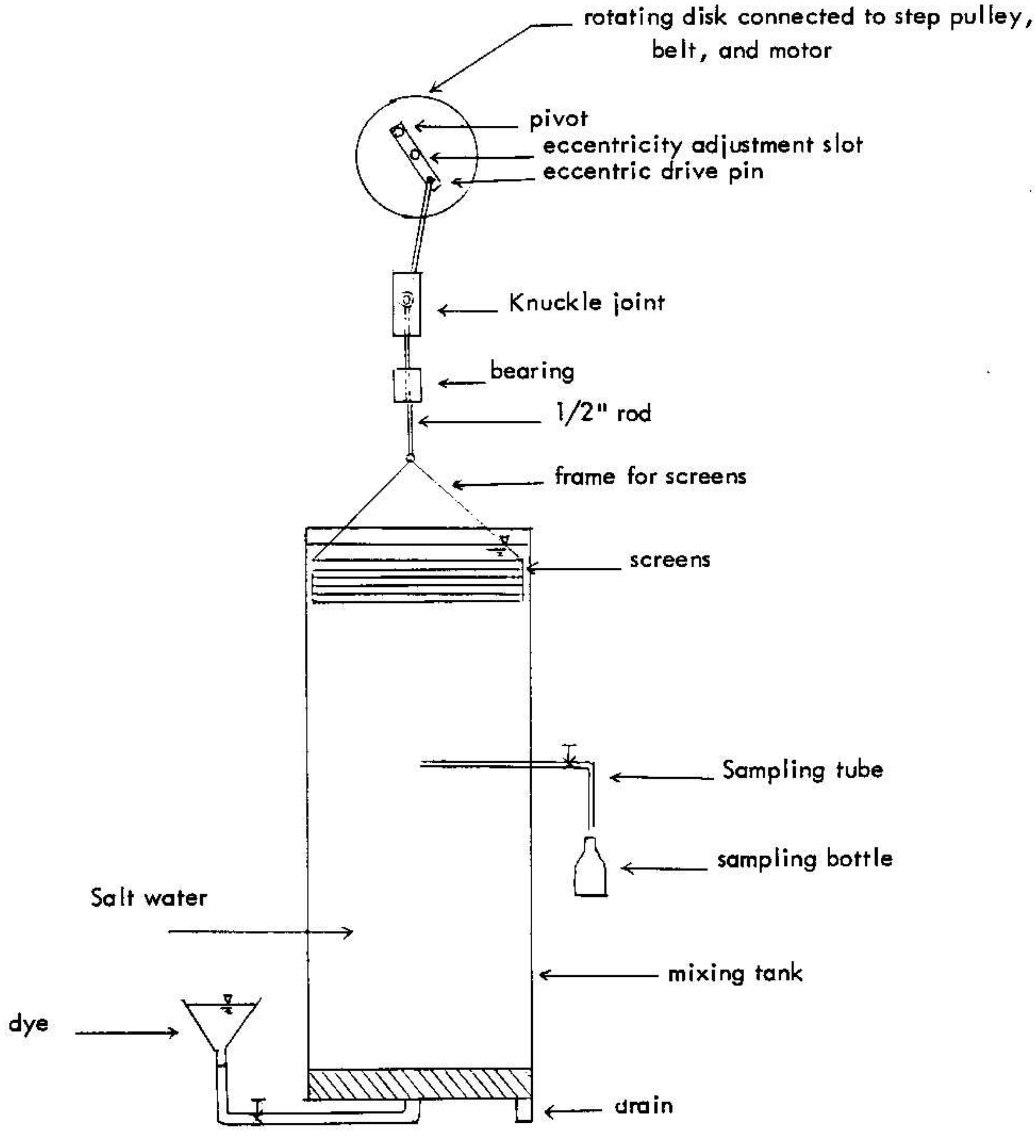

Figure 1 Schematic Diagram of the Mixing Tank

of salinity.

For turbulent diffusion study salt water concentration of 0.5%, 1.5%, 2% and 3% were simulated in the mixing tank. For molecular diffusion study salt water concentration of 1%, 2%, 3% and fresh water were used.

The experimental set-up for the molecular diffusion study was simple. Four 2000 ml glass cylinders were used and filled with salt water of different known solution. The methods to prepare the dye solution, samplings, and the determination of dye concentration were essentially the same as the study of turbulent diffusion.

CHAPTER III RESULTS AND DISCUSSIONS

Results from the laboratory experiment for the turbulent and the molecular diffusion of dye are shown in Tables 1, 2, 3, 4, and 5. Time of sampling in seconds or minutes and transmittance of each sample taken and initial dye solution were tabulated. Absorptances were calculated and hence the ratios of dye concentration C/C_o were found. Figures 6 and 7 show the plottings of C/C_o vs $y/\sqrt{t}$. From the curves the molecular and turbulent diffusion coefficients were calculated for different values of salinity according to the method described in section II-2. Figure 8 and Table 6 show the results of the turbulent diffusion coefficients. Figure 9 and Table 7 show the results of the molecular diffusion coefficient. It can be seen the diffusion coefficients are indeed a function of the salinity. Both turbulent and molecular diffusion coefficient increase as the salinity increases. The variation of the turbulent diffusion coefficient is approximately linear with respect to salinity. However, the molecular diffusion coefficients tend to vary non-linearly with the salinity. With the limited data obtained from the experiment, attempt was not made to derive the correlation equation to describe the functional relation between the diffusion coefficient and the salinity. This was an exploratory study. Intensive experiment should be done in the future in order to gather more data for the derivation of the correlation equation.

The difficulties in obtaining a great number of data was due to the preparation of the neutrally buoyant dye solution to be mixed in the tank. If the density of the dye solution is smaller than the salt water in the mixing tank, a buoyant fluid would be generated. Consequently, the buoyant effect is more prominent than the diffusion process. On the other hand, the gravitational effect would dominate if the dye solution is heavier than the salt water in the mixing tank. In the later case, the dye solution simply stays at the bottom of

Table 1 Turbulent Diffusion of Dye in 0.5% Salt Water

Salt concentration = NaCL 0.5%
Distance from dye source to sampling point = 11 1/4 inches
Wave length set for spectrophotometer = 610 mμ

Sample No.	Time (second)	Transmittance (%)
dye source		4.50
1	0	89.00
2	1160	88.80
3	1718	87.90
4	2246	86.70
5	3071	85.45
6	4193	83.40
7	5432	82.00
8	6987	80.00

Table 2 Turbulent Diffusion of Dye in 1.5% Salt Water

Salt concentration = NaCL 1.5% by weight
Distance from dye source to sampling point = 11 inches
Wave length set for spectrophotometer = 610 mμ

Sample No.	Time (second)	Transmittance (%)
dye source		1.20
1	0	89.60
2	726	87.50
3	1137	86.85
4	1563	84.70
5	2074	83.20
6	2660	79.30
7	3673	75.20

Table 3 Turbulent Diffusion of Dye in 2% Salt Water

Salt concentration = NaCL 2% by weight
Distance from dye source to sampling point = 10 inches
Wave length set for spectrophotometer = 610 mμ

Sample No.	Time (second)	Transmittance (%)
dye source		1.55
1	0	86.40
2	225	80.90
3	483	77.80
4	778	73.10
5	972	69.80
6	1231	65.80
7	1440	60.00

Table 4 Turbulent Diffusion of Dye in 3% Salt Water

Salt concentration = NaCl 3% by weight
Distance from dye source to sampling point = 11 1/4 inches
Wave length set for spectrophotometer = 610 $m\mu$

Sample No.	Time (second)	Transmittance (%)
dye source		2.50
1	0	85.10
2	209	78.00
3	355	69.70
4	485	64.00
5	748	57.90
6	1105	54.75

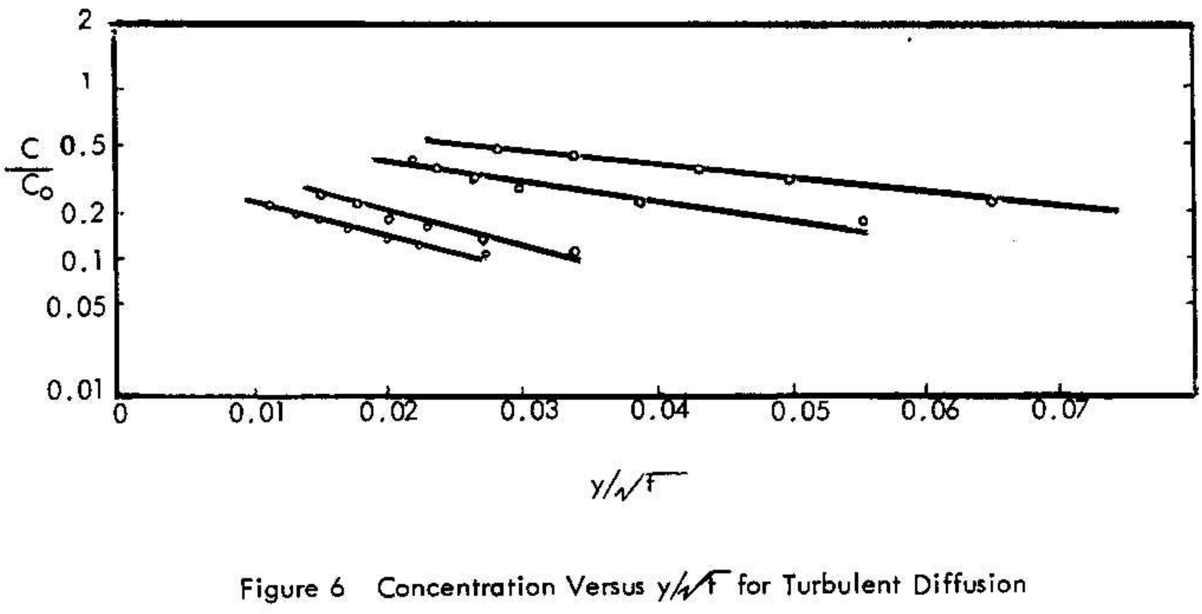

Figure 6 Concentration Versus $y/\sqrt{f}$ for Turbulent Diffusion

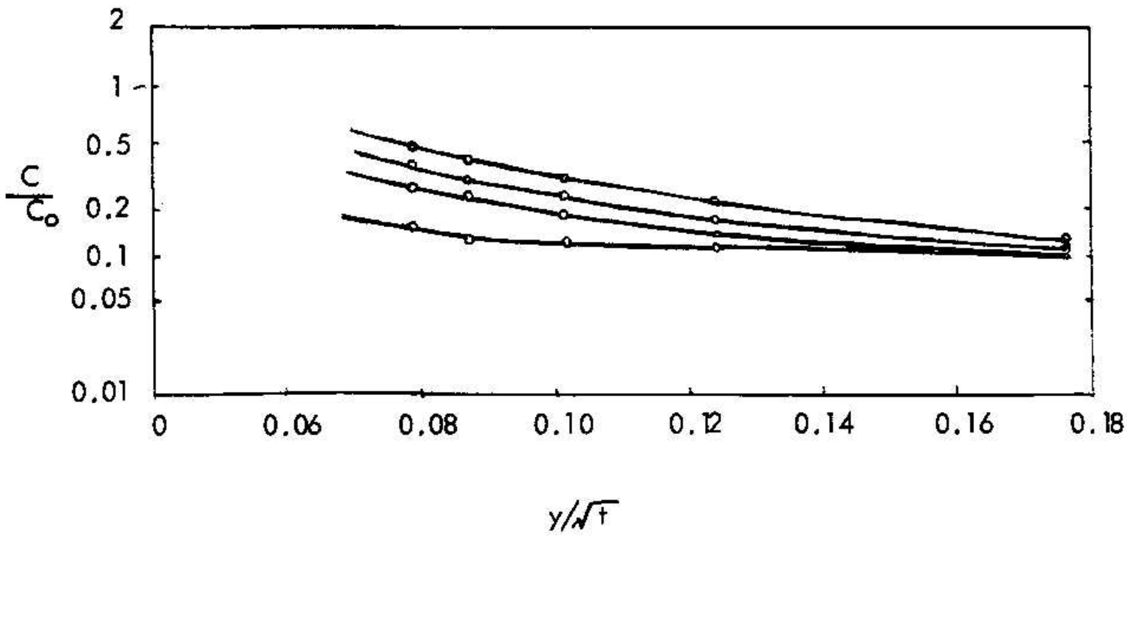

Figure 7 Concentration Versus $y/\sqrt{t}$ for Molecular Diffusion

Salt Concentration (%)	Molecular Diffusion Coefficient (ft^2/hr)
0	0.000796
1.0	0.0028
2.0	0.00414
3.0	0.00522

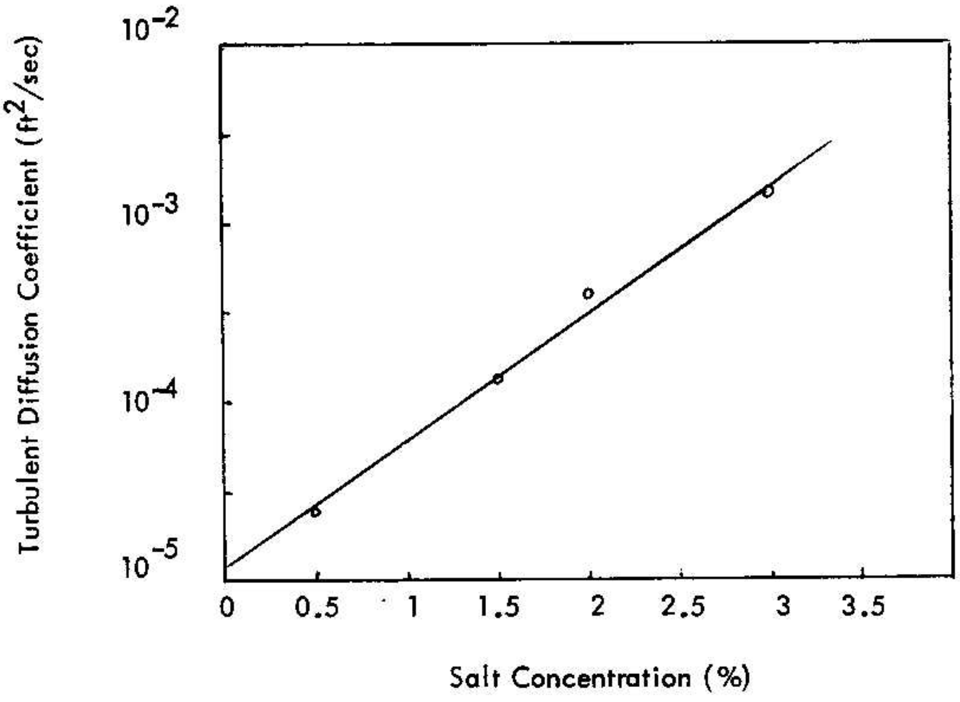

Figure 8 Turbulent Diffusion Coefficient Versus Salinity

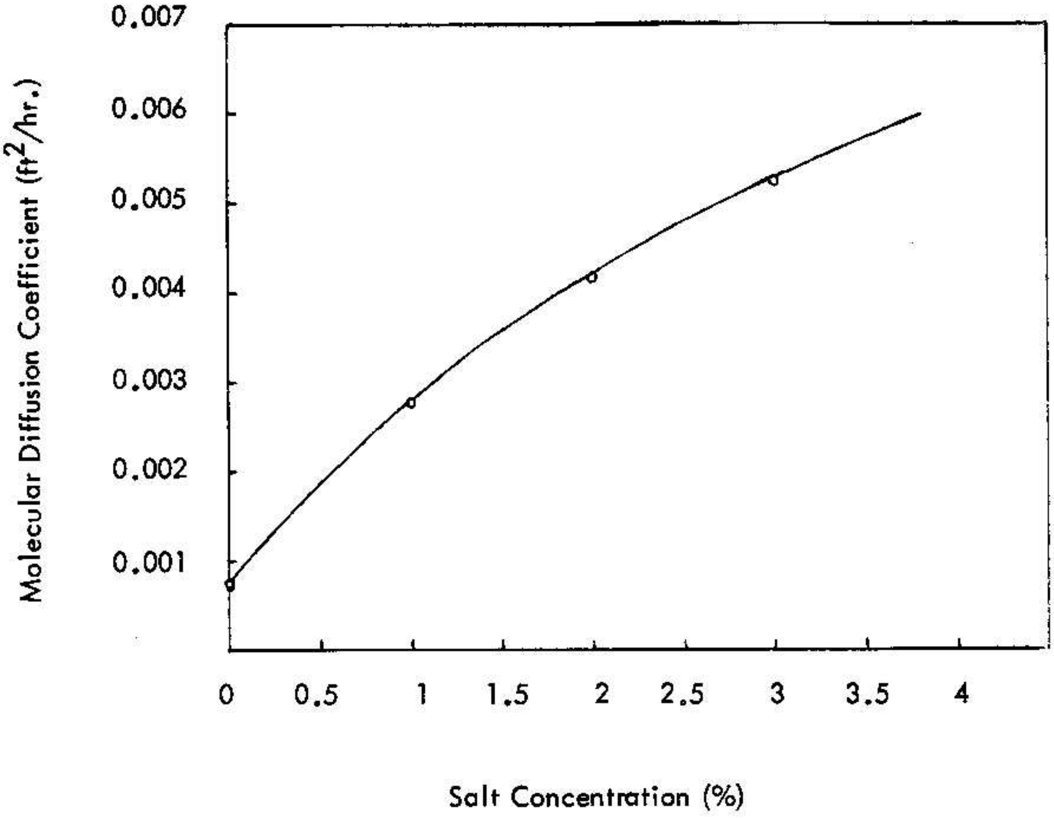

Figure 9 Molecular Diffusion Coefficient Versus Salinity

shows the experimental set-up used. Turbulence was generated in a long tank of salt water with known concentration by a screen moving vertically in simple harmonic motion. A barrier separated the tank into two chambers. The small chamber contained the dyed salt water. At time $t = o$, the barrier was removed and concentration measurements of the dye were made at various times and a fixed distance in the big chamber which was in the positive x region. The diffusion process was extremely unsatisfactory due to the generation of density currents or buoyant fluid at the surface. It was difficult to preciously prepare neutrally buoyant dye solution. The second scheme used was three dimensional round jet of dye solution issuing into a salt water body. Figure 11 shows the experimental set-up of this scheme. This method didn't produce satisfactory results either. The jet deflected if the dye solution issued was not neutral buoyant.

It can be seen from Figure 6 that the molecular diffusion rate is fast at the beginning of the entire process and reach a slower rate after a certain period of time. This phenomena is not pronounced for the turbulent diffusion process as shown in Figure 7.

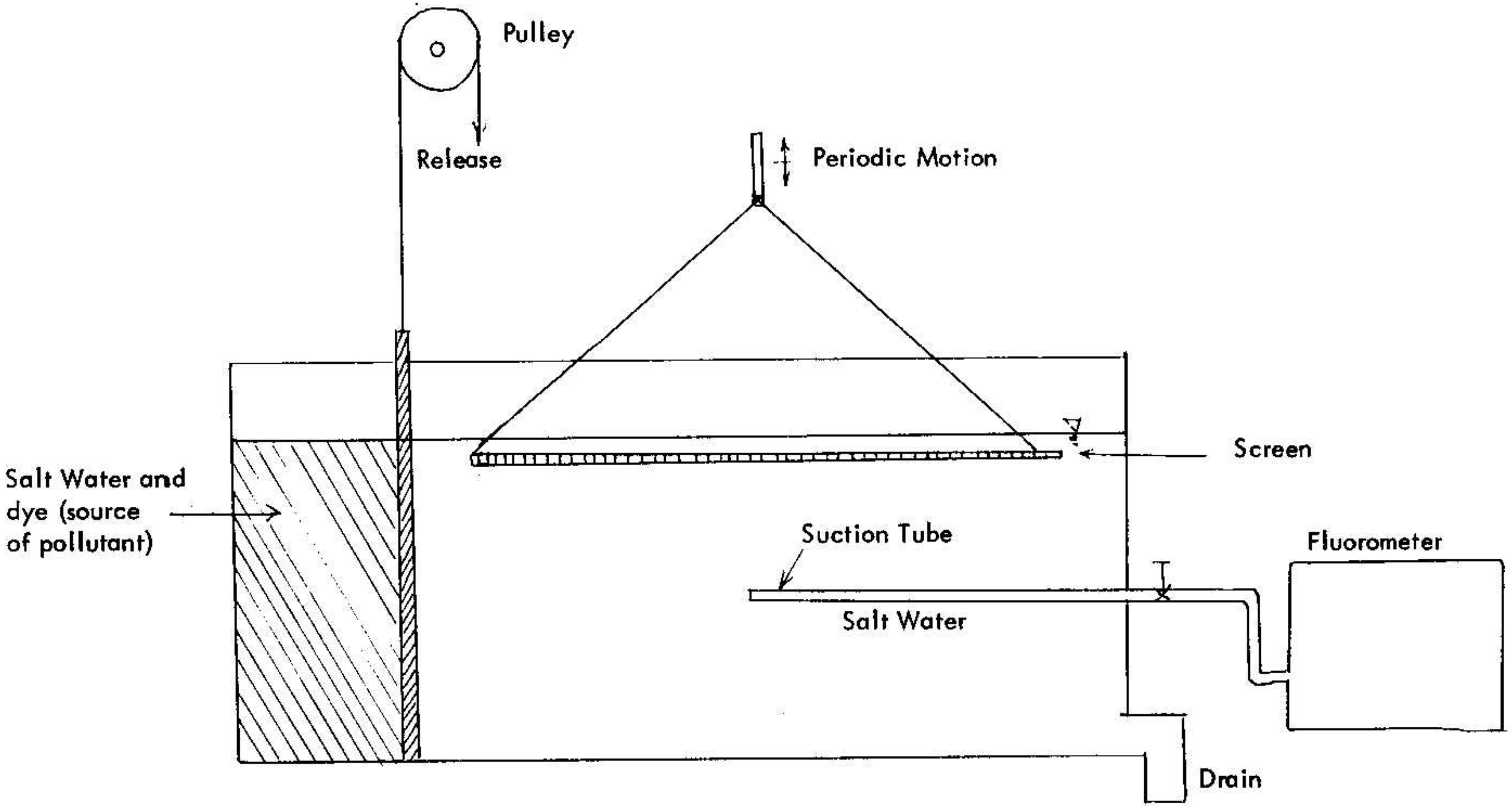

Figure 12 Schematic Diagram of the One-dimensional Approach

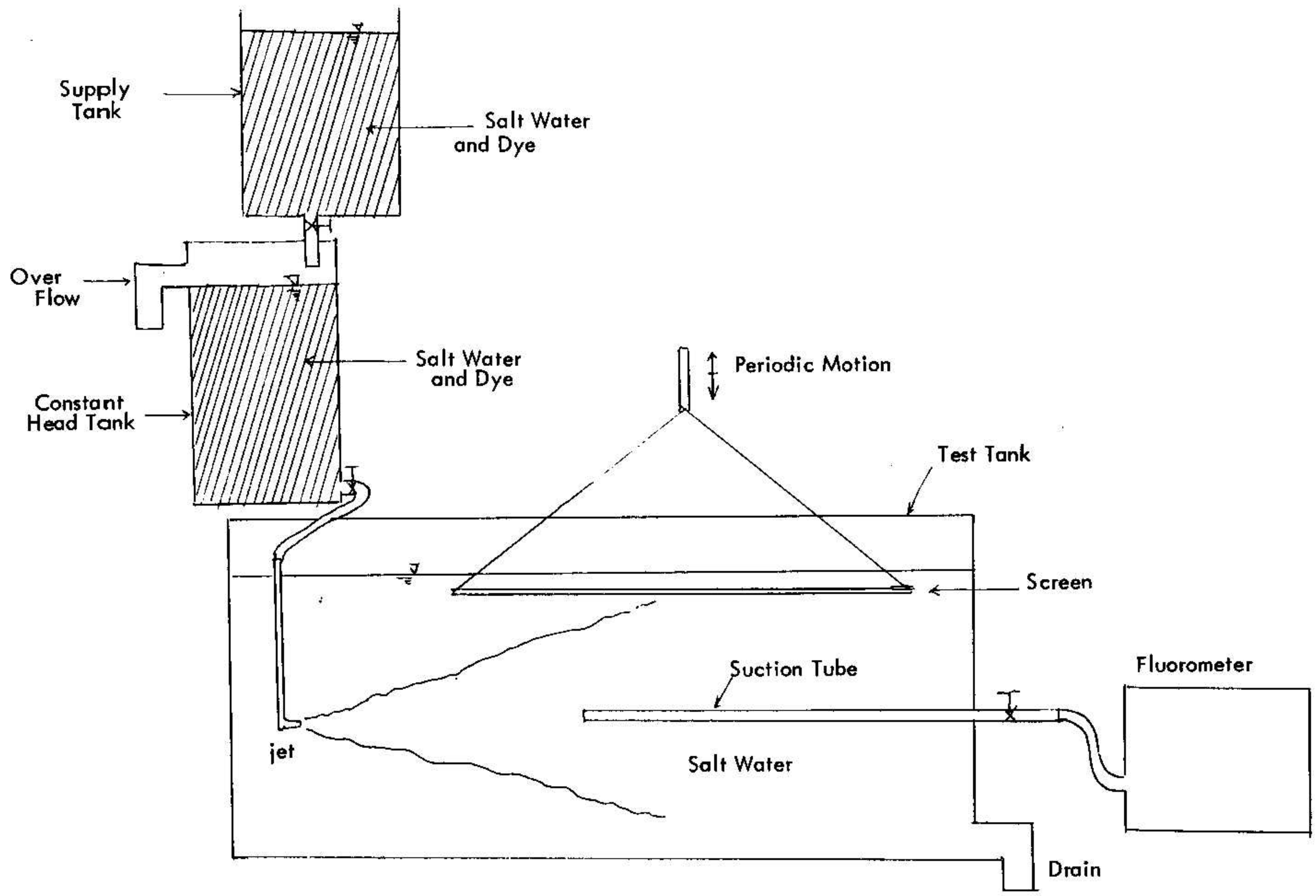

Figure 13 Schematic Diagram of the Round Jet Approach

The variation of the turbulent diffusion coefficient is approximately linear with respect to salinity. However, the molecular diffusion coefficient tends to vary non-linearly with the salinity.

2. The molecular diffusion rate is fast at the beginning of the entire diffusion process and reach a slower rate after a certain period of time. This phenomena is not pronounced for the turbulent diffusion process as the diffusion rate is rather uniform.

3. The density of the dye solution being used for diffusion study is a very sensitive parameter. The dye solution should be neutrally buoyant to avoid the buoyant or the gravitational effect on the diffusion.

CHAPTER V REFERENCES

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