APPLICABILITY OF MODELS FOR BOSTON OUTFALL PLUMES

Yongtai Chung, and Gyoung Wan Kim

Department of Earth Environmental System, Sunchon Chongam College, Chonnam, Korea

Abstract: In this study, laboratory study of the behavior of wastewater discharged from the Boston ocean outfall was compared with the predictions of mathematical models. The data sets cover broad ranges of discharge conditions and oceanic conditions, and are associated with a typical type of outfall discharges with multiport diffusers. The laboratory data sets were obtained in density stratified towing tanks. These data sets were used to evaluate four commonly used models: UM, UDKHDEN, RSB and CORMIX2 for minimum dilution, the height to the top of the wastefield, and wastefield thickness. For minimum dilution and height to the top of the wastefield, UM and RSB predictions agree well with laboratory data. UDKHDEN overestimated the minimum dilution and height to the top of the wastefield while CORMIX2 underestimated these values. All of the model predictions for the wastefield thickness were widely scattered about the measured values. The hydraulic model study reproduced the major features observed in the laboratory. It also afforded considerable insight into the mechanics of mixing of multiport risers which could not have been obtained either from the laboratory test or the mathematical models.

Key words: ocean outfall, dilution, rise height, wastefield thickness, model, multiport

1. INTRODUCTION

The objective of ocean outfalls is to discharge wastewater such that detrimental effects to the receiving water are minimal. It is common practice for coastal communities to dispose of their wastewater in the adjacent ocean by means of a deepwater outfall. Often, the natural density stratification present in the ocean prevents the wastewater from reaching the ocean surface (Fischer, et. al., 1979) and this is usually an objective of outfall design as the sight of sewage on the surface is obviated and the probability of sewage reaching the shoreline is greatly reduced. The outfall terminates in a diffuser which can simply be an extension of the outfall pipe with round ports along the sides (or contained in risers) from which the wastewater is discharged as a horizontal jet. Because the wastewater has a lower density than seawater the jets experience a buoyancy force pushing them upwards. The individual buoyant jets may merge together before collapsing at the terminal rise height and forming a horizontally spreading layer.

We are here concerned with predictions of the established wastefield characteristics and how they depend on diffuser design, receiving water stratification, and current seed and direction. The general situation under consideration is shown in Fig. 1. The characteristics of most

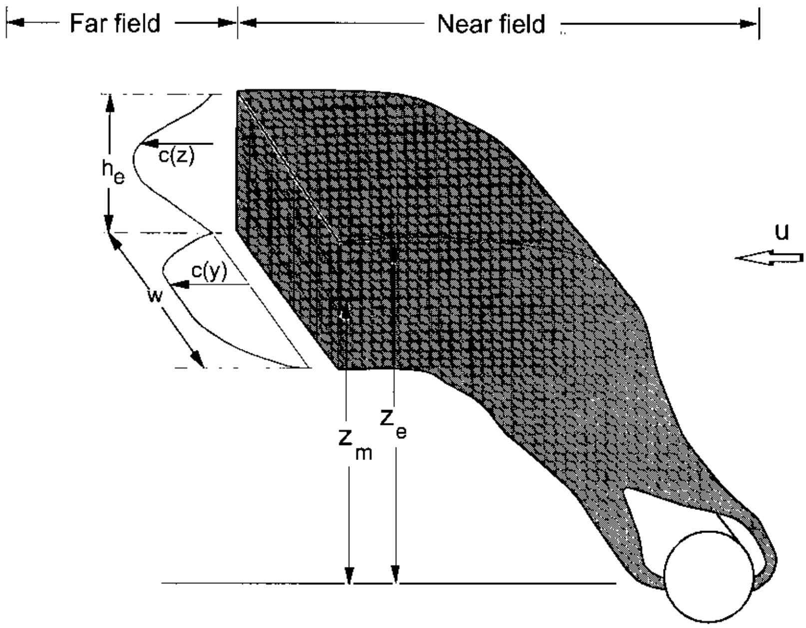

Fig. 1. Wastefield Details

interest are those at the end of the near field. These are the rise height to the top of the wastefield, z_e, the thickness of the wastefield, h_e, the height to the level of maximum concentration, or minimum dilution, z_m, and the length of the near field, x_i. The minimum, or centerline, dilution at the end of the near field is S_m which is defined as the smallest value of dilution (corresponding to maximum concentration) observed in a vertical plane through the wastefield at the initial mixing region.

A major problem in outfall design is prediction of the characteristics of this established layer, in particular dilution, rise height, and thickness. Prediction of these characteristics is difficult due to the large number of variables involved. These include the port spacing, diameter, jet exit velocity, ambient current speed and direction, and ambient density stratification. Because of this, many studies of outfall mixing processes have been conducted (e.g. Fischer et al., 1979; Wright, 1984; Roberts et al., 1989). Many numerical models have been developed to predict dilution and rise height and are commonly used in outfall design. Although some comparisons with experimental data of the predictions of these models have been made, there have been no systematic comparisons over the range of conditions typical of ocean outfalls. The purpose of this study is to evaluate the performance of four commonly used dilution models: UM, UDKHDEN, RSB and CORMIX by systematically comparing model predictions with measured data for a wide range of experimental conditions. The data to be used are those for multiport diffusers in stratified, unstratified, flowing and stationary currents. These include laboratory experiments for generic conditions consisting of physical model tests for specific outfall conditions, and laboratory tests of operating outfalls. The parameters of particular interest are the minimum dilution, height to the top of the wastefield, wastefield thickness at the end of the near field, and the length of the near field.

The hydrodynamics of the near field region are discussed in many publications, for example Roberts et al. (1989). In this region, intense mixing occurs due to turbulence driven primarily by the buoyancy of the discharge, resulting in dilutions of the order of hundreds or more. This mixing ends when the self-induced turbulence collapses under the influence of a stable density field. This collapse occurs in the horizontally spreading wastefield, and the nature of the stable density field that causes it depends on whether the wastefield is submerged by ambient density stratification or whether it surfaces. If the wastefield surfaces, the density field is self-induced; if the wastefield is submerged, it is due to natural density stratification present in the water column. These near field processes occur within a few minutes after discharge and within a distance whose dimensions are typically tens to sometimes hundreds of meters from the diffuser. Near field mixing processes are complex, and include jet- and plume-induced entrainment, internal hydraulic jumps, merging, and the collapse of the turbulence under the influence of stratification. Experimental studies (Roberts et al., 1989a, b, and c; Daviero, 1998) show that the dilution increases rapidly with distance near to the diffuser and eventually becomes essentially constant as the self-induced turbulence decays under the influence of the stable density field. The approximate distance where the dilution levels off defines the end of the near field, and the value of dilution at this point is the near field dilution.

2. DESCRIPTION OF MATHEMATICAL MODELS

In this study, four commonly used models: UM, UDKHDEN, RSB and CORMIX are selected to compare model predictions with laboratory data. The models fall into two main types: Entrainment, often referred to in the literature as jet-integral models, and Semi-empirical. UM and UDKHDEN are entrainment models. RSB and CORMIX are semi-empirical models that use experimental data (Chung and Roberts, 1997).

2.1 UM and UDKHDEN

UM and UDKHDEN are entrainment models that both solve the equations of fluid motion and mass transport using an integration scheme in which they march forward in discrete increments along the trajectory of the buoyant jet. UM is a Lagrangian model and uses time increments; UDKHDEN is an Eulerian model and uses a distance increment. The basic model building block in UM is the wafer-shaped plume element; in UDKHDEN it is the control volume. UM is a two-dimensional model, which is the latest in a series of models first developed for atmospheric and freshwater applications by Winiarski and Frick (1976). UM is a portion of a model interface and manager called PLUMES. UM is a revision of a previous U.S. EPA initial dilution model called UMERGE. In fact, UM may be interpreted to mean "Updated Merge." UM is based on the Lagrangian formulation of conservation of mass (continuity), momentum, and energy, and the Projected Area Entrainment (PAE) hypothesis (Frick, 1984) and the traditional Taylor entrainment hypothesis. The Lagrangian plume equations are solved at each time step to give dilutions along plume trajectories. UM can be used to simulate single port or multiport discharges. The minimum dilution and the height of the top of the waste field are calculated from centerline concentration and plume depth, respectively.

UDKHDEN is a three-dimensional model, which considers either single or multiport discharges at an arbitrary angle into a stratified, flowing current. Current direction can vary from 45° to 135° relative to the diffuser axis, and the current speed can vary with depth. Entrainment is calculated as a function of plume size, excess velocity, local Froude number, and ambient velocity. The program terminates when the surface is reached or the plume reaches its maximum rise height. UDKHDEN assumes that the ratio of the flux-averaged dilution S_{fa} to minimum (centerline) dilution, S_m, is given by $S_{fa} / S_m = 1.74$, and the predicted heights to the top of the waste field are estimated at trapping level.

2.2 RSB and CORMIX

RSB and CORMIX are empirical models that predict initial dilution by use of semi-empirical equations derived from length scales, dimensional analysis, and experimental results. Each length scale determines a distance along the trajectory where one parameter predominates (i. e., controls the flow). This modeling approach is called "asymptotic analysis". The length scales describe the relative importance of all parameters - discharge volume flux, momentum flux, buoyancy flux, ambient crossflow, and density stratification - throughout the trajectory. For example, the solution for a pure jet can be applied as an approximate solution to that portion of a buoyant jet in a crossflow where jet momentum dominates the flow. Likewise, the results for a pure plume can be applied to the buoyancy-dominated regions for the buoyant jet. The length scales are linked by appropriate transition conditions to create a path for the trajectory through completion of initial dilution.

RSB was developed based on the experiments on multiport diffusers in density-stratified currents described in Roberts et al. (1989a, b, and c). RSB predicts rise height, waste-field thickness, and minimum dilution at the end of the near field for fully submerged and surfacing waste fields. The diffuser in the experiments on which it is based was straight, and consisted of horizontal discharges from uniformly spaced risers, each with two horizontally opposed ports. The receiving water flowed at various angles relative to the diffuser axis, and was linearly density-stratified. RSB obtains a solution for nonlinear density profiles by linearizing the profile from the port level to the top of the established waste field. The range of the experimental parameters (port spacing, port diameter, jet exit velocity, current speed, current direction, and density stratification) was chosen to be representative of typical diffusers discharging sewage into coastal waters. When RSB is used outside the parameter range for with these experiments were conducted; it extrapolates the experimental results to obtain a solution. The ports discharge from both sides of the diffuser, a configuration that would include diffusers consisting of pipes with ports (holes along each side), or T-shaped risers each containing two ports.

CORMIX refers to "Cornell Mixing Zone Expert System" (Doneker and Jirka, 1990). CORMIX includes CORMIX1 for single port submerged discharges; CORMIX2 for multi - port submerged discharges; and CORMIX3 for surface discharges. Only CORMIX2 is applicable to the investigation reported herein. The principle methodology of CORMIX is to use asymptotic analysis to classify jet-flow patterns (Jirka and Doneker, 1991) and to use asymptotic solutions. Inherent in these solutions is a large number of constants that are estimated using a combination of experiments, theoretical analysis,

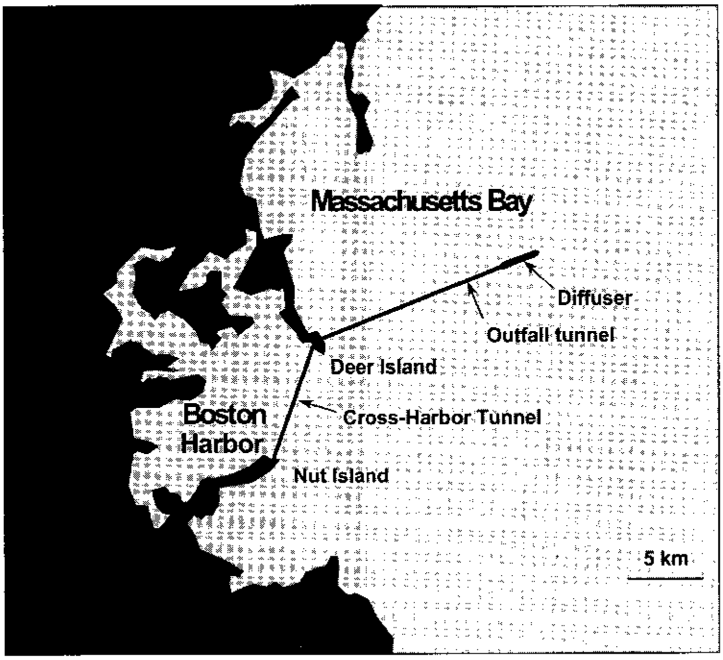

Fig. 2. Boston Harbor Wastewater Disposal Scheme

literature values, and engineering judgment. CORMIX includes both near-field and far-field models. For the purpose of this study, only the near-field model portion is used. The initial dilution predicted by CORMIX is the dilution at the plume centerline.

3. LABORATORY EXPERIMENTAL OBSERVATION

3.1 Boston Outfall

As part of the Boston Harbor clean-up process, a new offshore ocean outfall of unprecedented size is now under construction to discharge treated wastewater into Massachusetts Bay. This outfall is the final link in the proposed disposal scheme, shown in Fig. 2, whose other main elements include a cross-harbor tunnel and a treatment plant on Deer Island. The wastewater may contain stormwater runoff up to a peak design flow of 55.7 cms (1270 mgd). To accommodate such a huge flow, the outfall will be a deep rock tunnel with an internal diameter of approximately 7.3 m (24 ft) and a length of approximately 14 km (9 miles). The tunnel terminates in a diffuser 2012 m (6600 ft) long. This diffuser consists of many risers extending to the sea floor, which are capped with multiport outlets arrayed along a straight line. The preliminary diffuser design had 80 risers spaced 25 m (83.5 ft) apart. The risers are about 76 m (250 ft) long from the tunnel to the seabed, and are constructed by drilling downwards with an oil-drilling rig. This is an expensive process (in the order of US$1.5 million for each riser), and a considerable cost savings would be achieved if the number of risers could be reduced without impairing the dilution capability of the diffuser (Roberts and Snyder, 1993a).

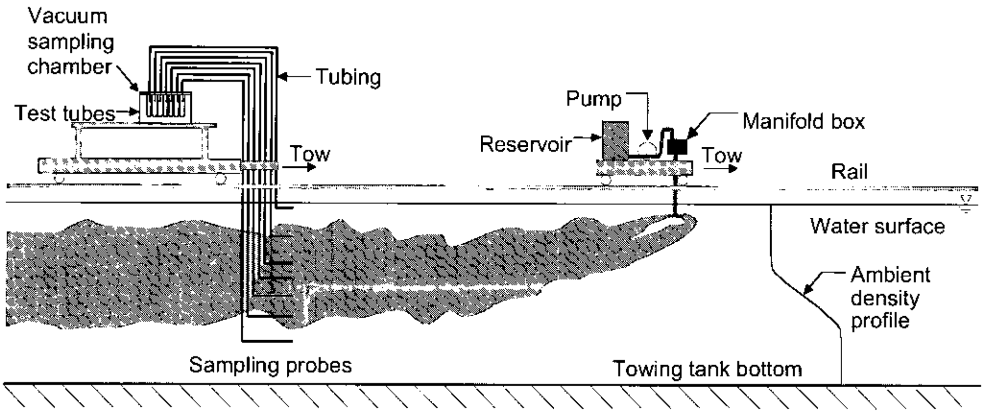

Fig. 3. Experimental Configuration used by Roberts et al. (1989).

3.2 Hydraulic Model Tests

As part of the hydraulic model studies for the design of the Boston wastewater outfall diffuser, tests were done to simulate these field results. The experiments were done in the large stratified towing tank of the U.S. EPA Fluid Modeling Facility in Research Triangle Park, North Carolina. The general configuration is shown in Fig. 3, and is described in Roberts (1989). The towing tank is 1.2 m (4 ft) deep, 2.4 m (8 ft) wide, and 25.3 m (83 ft) long, and can be filled with saltwater to an arbitrary stable stratification. An effluent more dense than the receiving water is discharged from the model diffuser near to the water surface and falls downward. This configuration is inverted compared to the prototype in which a buoyant plume of waste water is released near to the bottom and rises upwards. It is allowable because the relative density difference between the effluent and receiving water is small in both cases, and is significant only for buoyancy forces and not inertia forces. The same method was used for modeling the San Francisco outfall diffusers (Issacson et al., 1978, 1983), for modeling plume rise in the atmosphere or ocean (Snyder, 1981; Wright, 1984), and for more general studies of ocean diffuser discharges (Roberts et al. 1989a, b, and c), among others. Photographs and measured vertical profiles shown in these papers will be inverted and presented in the prototype orientation. The current was added to the effluent for dilution measurements and flow visualization (Roberts & Snyder, 1993a).

Physical model tests to design the diffuser were performed by Roberts and Snyder (1993a), using the towing tank and procedures of Roberts et al. (1989). Three density stratification profiles were modeled, as shown in Fig. 4. These profiles are a late summer profile, an early summer profile, and unstratified, which could occur during winter. These modeled oceanic conditions were chosen based on oceanographic observations. On the basis of these model tests, the final number of risers was chosen to be 55, spaced 37.2 m (122 ft) apart for a total diffuser length of 2,008 m (6,588 ft). The port diameter was 0.157 m (6.2 inches) with eight ports per riser. The flows tested were 55.7 cms (1270 mgd), 17.1 cms (390 mgd) and 27.2 cms (620 mgd). Current speeds were 0, 12, and 25 cm/s, and current directions were perpendicular and paral-

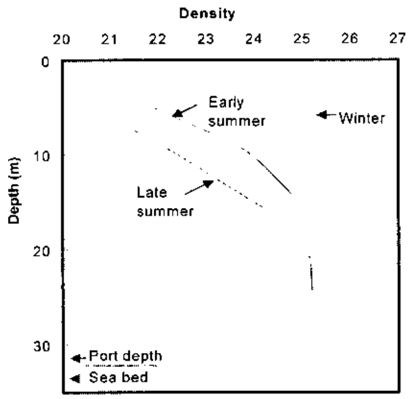

Fig. 4. Oceanic Density Profiles Modeled for the Boston Outfall

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Decreasing strength of density stratification increases dilution. For example, the dilution at 17.1 cms (390 mgd) increases from 81 with the late summer stratification, to 112 with the early summer stratification, and to 180 when unstratified. At 55.7 cms (1,270 mgd), the dilution increases from 56 with late summer stratification to 113 when unstratified with a surfacing waste field. Flowing current generally increases the dilution from its value with no current, For example, with perpendicular currents when unstratified at 17.1 cms (390 mgd), the dilution increases from 180 with no current to 272 with a 12 cm/s current to 561 with a 25 cm/s current. Parallel currents at 12 cm/s result in dilutions which are comparable to those with zero current speed, but faster parallel currents (25 cm/s) usually increase dilutions above these values.

Only the results for the final design are considered here. They are summarized in Roberts and Snyder (1993b), and in Table 1. In addition,

Table 1. Summary of Experimental Parameters

RUN Number	Total discharge	Effluent density	Number of total ports	Port spacing	Port depth	Current Speed	Ambient density profile	Port diameter	Diffuser length	Current direction
	(cms)	(g/cc)		(m)	(m)	(cm/s)		(m)	(m)	(degrees)
B2-1	17.1	0.998	440	4.58	31.3	0	UN	0.157	2008	90
B2-2	55.7	0.998	440	4.58	31.3	0	UN	0.157	2008	90
B4-1	17.1	0.998	440	4.58	31.3	12	UN	0.157	2008	90
B4-2	17.1	0.998	440	4.58	31.3	25	UN	0.157	2008	90
B4-3	17.1	0.998	440	4.58	31.3	12	UN	0.157	2008	0
B4-4	17.1	0.998	440	4.58	31.3	25	UN	0.157	2008	0
B4-5	55.7	0.998	440	4.58	31.3	25	UN	0.157	2008	0
B5-1	17.1	0.998	440	4.58	31.3	0	LS	0.157	2008	90
B5-2	27.2	0.998	440	4.58	31.3	0	LS	0.157	2008	90
B5-3	55.7	0.998	440	4.58	31.3	0	LS	0.157	2008	90
B5-4	17.1	0.998	440	4.58	31.3	0	ES	0.157	2008	90
B6-1	17.1	0.998	440	4.58	31.3	25	LS	0.157	2008	90
B6-2	17.1	0.998	440	4.58	31.3	12	LS	0.157	2008	0
B6-3	17.1	0.998	440	4.58	31.3	25	LS	0.157	2008	0
B6-4	55.7	0.998	440	4.58	31.3	25	LS	0.157	2008	0
B6-5	17.1	0.998	440	4.58	31.3	12	ES	0.157	2008	0
B6-6	17.1	0.998	440	4.58	31.3	25	ES	0.157	2008	0

Table 2. Comparison of Measurements and Mathematical Models

Run number	Minimum dilution, S_m					Height to top, Z_e(m)					Wastefield thickness, h_e(m)				
	Measured	RSB	DKH	UM	CMX	Measured	RSB	DKH	UM	CMX	Measured	RSB	DKH	UM	CMX
B2-1	180	153	95	82	165	31.3	31.3	31.3	34.9	27.8	16.5	23.5	9.0	1.2	3.7
B2-2	113	85	52	47	79	31.3	31.3	31.3	34.9	27.7	20.5	23.5	11.1	2.1	3.8
B4-1	272	250	512	119	526	31.3	31.3	31.3	35.4	31.3	22.0	27.9	49.1	0.8	27.3
B4-2	561	575	979	219	952	31.3	31.3	31.3	32.4	31.3	22.5	27.9	55.3	0.5	31.3
B4-3	210	192	509		426	31.3	31.3	31.3		31.3	18.0	25.7	47.6		31.3
B4-4	220	289	993		773	31.3	31.3	31.3		31.3	18.5	25.7	56.4		31.3
B4-5	111	122	344		251	31.3	31.3	31.3		31.3	20.0	25.7	57.5		31.3
B5-1	81	69	49	42	44	16.3	17.4	17.5	17.1	15.3	7.5	13.0	6.6	2.4	2.7
B5-2	70	60	41	35	39	17.8	17.4	18.0	17.6	17.3	10.5	13.0	7.2	2.8	4.1
B5-3	56	47	33	31	34	17.8	17.1	18.9	18.9	21.0	14.5	12.8	8.4	3.2	16.0
B5-4	112	84	55	46	46	20.3	20.2	20.0	18.9	15.7	9.5	15.1	7.1	2.2	2.8
B6-1	223	218	287	148	212	16.3	16.0	17.7	21.6	7.1	14.5	14.3	16.1	0.7	7.2
B6-2	83	87	189		62	17.3	17.4	20.8		9.8	12.0	14.2	18.9		2.6
B6-3	125	144	298		101	19.3	15.5	18.0		7.5	10.5	12.7	16.9		3.0
B6-4	63	74	147		58	21.3	16.7	24.3		11.3	13.0	13.7	25.4		4.3
B6-5	105	105	222		66	20.3	20.2	24.6		10.1	11.0	16.6	22.3		2.7
B6-6	133	166	337		106	20.3	18.0	20.5		7.7	12.0	14.8	19.5		3.1

comparisons are shown of predictions of the tow tank results by four commonly used models: UM, UDKHDEN, RSB and CORMIX, these being selected to compare model predictions with Boston outfall data

4. COMPARISONS OF LABORATORY AND MODEL RESULTS

4.1 All Experiments

Comparisons of the predicted values and results for the Boston outfall are shown in Table 2 and Figures 5 through 7. Predictions by RSB range from 47 to 575, from 33 to 993 by UDKHDEN, from 50 to 422 by UM, and from 34 to 952 by CORMIX2. Predictions by RSB and UM for the minimum dilution and height to the top of the wastefield agree well with measured values. UDKHDEN overestimates the minimum dilution and height to the top of the wastefield while CORMIX2 predictions for minimum dilution were usually scattered about

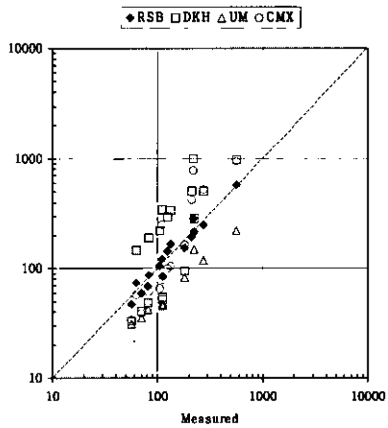

Fig. 5. Comparison of Measured and Predicted Minimum Dilution

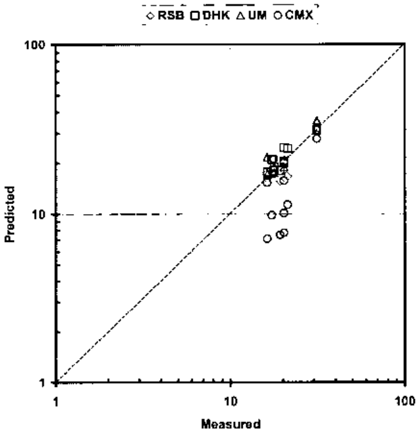

Fig. 6. Comparison of Measured and Predicted Height to Top

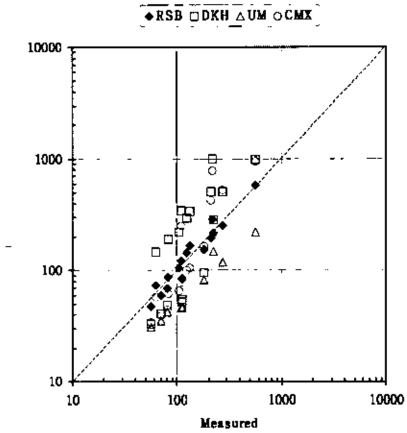

Fig. 7. Comparison of Measured and Predicted Wastefield Thickness

the measured values and CORMIX2 underestimates the height to the top of the wastefield. The model predictions for the wastefield thickness show a great deal of scatter about the measured values.

The percent difference between the mean of the observed and the predicted minimum dilutions by each model were computed. RSB and UM predictions are within 4% and were the best predictors of the measured values, and UDKHDEN and CORMIX2 predictions overestimated the dilutions by 89% and 45%, respectively. The percent difference between the mean observed and predicted height to the top of the wastefield was also computed. Here, RSB and UDKHDEN predictions are within 3% of the measured values, UM predictions overestimated the height by 17%, and CORMIX2 predictions underestimated the height by 18%. For the wastefield thickness, UM predictions agree well with the measured values, RSB and UDKHDEN predictions overestimated the wastefield thickness, and CORMIX2 predictions underestimated the measured values by 18%.

The deviation between measured values and predicted values was calculated, and this compared the performance of RSB, UDKHDEN, UM, and CORMIX2. In general, RSB, UM, and CORMIX2 are more likely to underestimate the minimum dilution and UDKHDEN is more likely to overestimate the minimum dilution. For predictions for the height to the top of the wastefield RSB and CORMIX2 are more likely to underestimate the height to the top and UM and UDKHDEN are more likely to overestimate the height to the top of the wastefield. When predicting the wastefield thickness RSB and UDKHDEN are more likely to overestimate the wastefield thickness, and UM and CORMIX2 are more likely to underestimate the wastefield thickness.

4.2 Unstratified Experiments

Comparisons of the predicted values to those measured for the unstratified experiments on the Boston outfall are were made. Predictions by RSB and UM for the minimum dilution agree well with the measured values while

UDKHDEN and CORMIX2 greatly overestimated these values. The model predictions for height to the top of the wastefield in the unstratified conditions agree well with the measured values. However, for the wastefield thickness, all of the model predictions showed a great deal of scatter about the measured values.

The percent difference between the mean of the observed and the predicted minimum dilutions, height to the top of the wastefield, and the wastefield thickness by each model were calculated. RSB and UM predictions are within 13% and were the best predictors of the measured values. UDKHDEN and CORMIX2 predictions overestimated the dilutions by 109% and 90%, respectively. The percent difference between the mean observed and predicted height to the top of the wastefield was also computed. All of the model predictions were within 9% of the measured values. For the wastefield thickness, RSB predictions overestimated the thickness by 30%, UM predictions underestimated the thickness by 12%, UDKHDEN predictions greatly overestimated the thickness by 107%, and CORMIX2 predictions overestimated the height by 18% of the measured values.

4.3 Stratified Experiments

Comparisons of the predicted values to those measured for the stratified experiments in Boston outfall are were also made. Predictions by RSB and UM for the minimum dilution and height to the top of the wastefield agree well with the measured values. UDKHDEN overestimated the minimum dilution and height to the top of the wastefield while CORMIX2 underestimated these values. All of the model predictions for the wastefield thickness were scattered a great deal about the measured values.

The percent difference between mean of the observed and the predicted minimum dilutions, height to the top of the wastefield, and the wastefield thickness as well as the maximum and minimum differences between these values for the stratified flow conditions were subsequently made. Here, RSB and UM predictions are within 7% and were the best predictors of the measured values. UDKHDEN predictions overestimated the dilution by 58% while CORMIX2 underestimated the dilution by 27% of these values. Predictions by RSB, UM, and UDKHDEN for height to the top of the wastefield were within 22% of the measured values, CORMIX2 predictions underestimated the height by 34% of the measured values. For the wastefield thickness, RSB predictions overestimated the thickness by 22%, UM predictions overestimated the thickness by 11%, UDKHDEN predictions overestimated the thickness by 29%, and CORMIX2 predictions underestimated the height by 18% of the measured values. When predicting the wastefield thickness all the models are likely to scatter about the measured values.

5. DISCUSSION AND CONCLUSIONS

Because of the wide variation and uncertainties in the laboratory test conditions, it is difficult to make direct comparisons between the model and prototype. For example, profiles obtained under seemingly similar conditions in the laboratory can exhibit large differences. Also, the time required to obtain a vertical profile in the ocean was of the order of 30 minutes. During this time the current and density stratification can vary significantly. Further complicating comparisons of the model and laboratory test results are uncertainties in the actual dye concentration in the effluent resulting from variations in the flowrate and also dispersion in the pipe. Finally, it is suspected that saline water is intruding into some of the ports and so the discharge conditions are not exactly known.

Despite these caveats it is apparent that the hydraulic model results simulate the observed laboratory results very well. In particular, predictions by RSB and UM for the minimum dilution and height to the top of the wastefield agreed well with measured values. UDKHDEN overestimated the minimum dilution and height to the top of the wastefield while CORMIX2 predictions for minimum dilution were usually scattered about the measured values and CORMIX2 underestimated the height to the top of the wastefield. The model predictions for the wastefield thickness showed a great deal of scatter about the measured values.

The best mathematical model predictions were those of RSB and UM. These predictions were within 4% and were the best predictors of the measured values. UDKHDEN and CORMIX2 predictions overestimated the dilutions by 89% and 45%, respectively. The percent difference between the mean observed and predicted height to the top of the wastefield was also computed. Here, RSB and UDKHDEN predictions were within 3% of the measured values, UM predictions overestimated the height by 17%, and CORMIX2 predictions underestimated the height by 18%. For the wastefield thickness, UM predictions agreed well with the measured values, RSB and UDKHDEN predictions overestimated wastefield thickness, and CORMIX2 predictions underestimated the measured values by 18%.

The physical model studies reproduced the major features observed in the laboratory. It also afforded considerable insight into the mechanics of mixing of multiport risers which could not have been obtained either from the laboratory test or the mathematical models.

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Yongtai Chung and Gyoung Wan Kim, Department of Earth Environmental System, Sunchon Chongam College, Chonnam, Korea

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