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VERIFICATION OF EPA PLUME MODEL UDKHDEN

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A number of different numerical models have been developed to compute the initial mixing from outfall discharges. Initial mixing involves the first few hundred meters from the point of discharge in which the mixing is mainly controlled by the differences in velocity and density between the discharged and receiving fluids. The USEPA has supported the development of several numerical models that may be used for this purpose (Muellenhoff, et al, 1985). Of these models, one of the most often used is UDKHDEN because of its general flexibility. That is, it models the effects of both ambient currents and density stratification and also models the flow from individual diffuser ports as they spread and begin to interact with each other. This latter feature is becoming increasingly relevant as a trend in many recently constructed wastewater diffusers is to construct the diffuser with relatively large port spacing (e.g. Isaacson, et al, 1983) and it may not be conceptually valid to consider the diffuser flow field to be two-dimensional, a feature of some of the other models.

An examination of the computer code for UDKHDEN reveals a major discrepancy in the model formulation. Although there are also other questionable components of the model formulation, a major issue is with respect to the entrainment coefficients utilized in the model. For example, it is known from a large amount of experimental data that the entrainment coefficient for a round plume should be approximately 50 percent greater than for a nonbuoyant jet. Also the entrainment coefficient for two-dimensional buoyant jets is not necessarily the same as for round buoyant jets. In spite of these generally accepted results which are supported by an extensive body of experimental data, UDKHDEN contains only two entrainment coefficients with fixed values, one coefficient that models jet mixing in stagnant surroundings and another that describes the entrainment due to aspiration in a crossflowing stream. The former entrainment coefficient was apparently selected to optimize the computed dilution for two-dimensional flows with large buoyancy. However, it is often currently the practice to construct diffusers as tunnels with a few risers at fairly large spacings and the flows may behave more like single round jets over a large portion of the trajectory. This investigation examines the deficiencies with regards to the entrainment coefficients utilized in the model, suggest alternate values, and compare the results obtained with the adjusted model, both with the original model and also with a wide variety of experimental data.

A second difficulty with the existing model that has been previously documented (e.g., Wright, et al, 1988) is the manner in which the model predicts the dilution in a stratified fluid. In particular, the model output gives the initial dilution (initial dilution implies that achieved after active mixing due to jet momentum and buoyancy has ceased) as that predicted by the model as the rising jet passes the the point of neutral buoyancy. This is clearly a problem in the limiting case of a nonbuoyant jet in which the neutrally buoyant level will be encountered at the point of discharge. The model would yield a dilution of 1.0 which is obviously inconsistent with physical intuition and with available experimental data. It has been shown by Wright, et al (1982 and 1988) that a more satisfactory procedure is to compute the initial dilution as that predicted at the maximum height of rise. A comparison of model predictions with experimental data in this report also confirms this approach.

Finally, the UDKHDEN formulation considers only a single row of ports along the diffuser whereas most multiport diffusers are constructed with ports on both sides of the diffuser. There is no convenient way to model the differences between the two situations. This investigation explores possible resolutions of this difficulty in a preliminary fashion.

This analysis proceeds in a fashion that recognizes that various types of experimental data are subject to more certainty (at least with regard to interpretation of a comparison with the model predictions) than others and this is utilized to recalibrate the numerical model. After the calibration effort is completed, additional data are analyzed to examine the agreement of the adjusted model predictions. The initial effort begins with the examination of single round buoyant jets in stagnant and nonflowing ambient fluids. The entrainment coefficients are estimated from recommended values of dilution constants and then compared against specific data. The model is then extended to consider discharges into stratified receiving fluids but still without crossflow to examine the nature of the agreement. Then the entrainment coefficient for crossflow induced aspiration is adjusted to provide agreement with available data on round buoyant jets in unstratified crossflows. This adjusted model is then applied to round buoyant jets in stratified crossflows to examine the nature of the resulting predictions. Finally, the entire process is repeated for diffuser discharges so that the the model performance in predicting the merging of adjacent buoyant jets may be assessed.

The EPA plume model UDKHDEN solves a set of integral equations (mass, momentum, buoyancy, and tracer concentration) that describe the jet motion and mixing as it is influenced by the discharge velocity, the density difference between jet and ambient fluids, ambient stratification, and ambient flows. In general, the only requirement for solution of the equations is that the shape of velocity,tracer, and density profiles must be specified and entrainment relations must also be specified. The profile shapes assumed in UDKHDEN are somewhat different than the Gaussian profiles assumed in most analyses, but the differences are minor. One major consideration is that UDKHDEN assumes that flow profile widths for velocity and scalar quantities such as tracer and density difference are the same. However, this is known not to be the case from experimental measurements (e.g. see Chen and Rodi,1976 or Fischer, et al, 1979) and the tracer concentration is known to have a greater profile width than the velocity. No attempt has been made to account for this deficiency in the present adjustments to UDKHDEN since the current effort has been directed only to properly compute average jet dilution rather than all jet properties. The values of the entrainment coefficients are adjusted to make up for the specific profile assumptions.

When the jet is discharged into more complex physical environments, additional interpretation difficulties exist. For example, the jet behavior when discharged into a linearly stratified ambient fluid is altered by a gradual deceleration of the jet until its vertical motion is eventually arrested and it begins to collapse laterally with very little additional mixing in an internal layer within the fluid column, (Figure 1). This behavior arises from the entrainment of more dense fluid at lower elevations which eventually increases the jet density until it becomes equal in average density to the fluid at a given higher level. The jet continues to rise due to its residual momentum but eventually must fall back to a neutrally buoyant level. The integral equations encounter a singularity at the maximum height of rise and thus numerical computations are halted at that level. The collapse of the jet into a horizontal spreading layer is neither described by the model nor is the presence of that layer accounted for as the rising jet passes through it. Thus, there is considerable reason to question the general validity of integral jet models in stratified ambient fluids. Nevertheless, the experimental results of a number of researchers, including those of Wong and Wright (1988) indicate that reasonably accurate predictions of jet properties may be attained with integral models.

In crossflowing ambient fluids, the jet tends to bifurcate into a pair of counter-rotating vortices (as shown by Fan (1967) and others) which do not exhibit the profiles assumed in UDKHDEN or in other similar models. When the model prediction is in terms of average dilution and measurements are in terms of some other quantity, a difficulty exists in that the assumed profiles cannot be used to convert from one definition of dilution to another. This issue is addressed in the model analysis below. Finally, most model formulations employ the use of a pressure drag term which deflects the jet in the downstream direction in addition to the entrainment of horizontal momentum from the crossflow. In order to properly compute jet trajectories without the pressure drag term, larger entrainment coefficients would be required. UDKHDEN does not include pressure drag in its formulation. The addition of the pressure drag term to the model was not part of the present investigation, and it was found that the computed jet trajectories are not deflected as much in the downstream direction as the corresponding experimental measurements. In order to avoid the dilemma in interpretation of results posed by this feature, only those experimental data in which the jet is significantly deflected by the crossflow were considered in the analysis and a comparison is made at the corresponding horizontal position without regard to the vertical position of the jet.

In order to present results in a self-consistent fashion, some basic definitions are introduced for the purpose of presentation of results in this report. z refers to vertical distance above the discharge port while x refers to distance in the downstream ambient flow direction. Other geometrical scales include the total water depth H and the spacing s (on one side of the diffuser) between individual ports on a multiport diffuser. The port may be considered to be a source of volume, momentum and buoyancy flux. These are designated by Q, M, and B, respectively. Q is the volumetric flow rate per port unless otherwise specified while M is defined as the product of the port discharge velocity, U_j and Q, $M = U_jQ$. B is equal to the product of Q and the reduced gravitational acceleration $g'_0 = g\,\Delta\rho_0/\rho_0$ (where g is the acceleration due to gravity, $\Delta\rho_0$ is the initial density difference between the discharged fluid and the ambient fluid and the level of the discharge, and ρ_0 is the ambient density at the level of the discharge). Although this may lead to confusion, the same symbols are used to refer to the two-dimensional fluxes of the same, so the specific application must be kept in mind. The two dimensional fluxes are computed by dividing by the port spacing if a single row of ports exists along a diffuser and by one-half this spacing if a double row of ports exist (one on each side of the diffuser). The horizontal ambient velocity is designated as U_a and the linear ambient stratification is given by $N^2 = -(g/\rho_0)(d\rho_a/dz)$ with $d\rho_a/dz$ the vertical density gradient, assumed to be a constant in the various applications.

The basic variables are combined into dimensionless groups that distinguish between individual data in a meaningful way. For example, the ratio $l_M / l_{b'}$ distinguishes the relative importance of buoyancy for jets in a stratified stagnant ambient fluid, see Wright (1977) For round buoyant jets this ratio is given by $l_M / l_{b'}$ = $[MN/B]^{3/4}$ and the ratio is replaced by the exponent 2/3 (but with the same variables) if defined for two-dimensional flows. For large values of this ratio, the jet basically behaves as a nonbuoyant jet all the way to the maximum height of rise while low value of the ratio imply plumelike flows. In a similar fashion the ratio U_a^3/B defines the relative importance of the crossflow for two-dimensional flows. At low values of the ratio (say less than 1), a buoyancy driven jet behaves similar to a plume in a stagnant ambient fluid and the crossflow has a major influence for large values of the ratio.

S_{avg} is the average dilution within the jet and is generally defined as equal to the local volume flux within the jet divided by the source volume flux. In many experimental applications, it is not convenient to measure the average dilution and the minimum dilution S_{min} is determined instead. The minimum dilution is defined as the ratio of the source concentration of a passive tracer material to the maximum concentration found in any flow cross-section. If both the velocity and concentration profiles are known, the relationship between S_{avg} and S_{min} can be established. However this is not the case in many of flows so assumptions are needed to relate the average dilution predicted by UDKHDEN and the minimum dilutions measured in most experimental investigations. This issue is discussed on a case by case basis. Using the profiles specified in UDKHDEN, the ratio S_{avg}/S_{min} is equal to 1.926 and 1.426 for round and two-dimensional jets and plumes, respectively with an intermediate value for jets that are in the merging region. In contrast, the model formulation by Wright, et al (1984) specifies values for these ratios of 1.69 and 1.24 and these values follow from the recommendations by Chen and Rodi (1976), Fischer, et al (1979) and other experimental results.. The difference between the dilution ratios is sufficient enough to complicate interpretation of the results, but in most cases, the scatter in experimental data is at least of the order of the differences between the two, and this is not considered to be a relevant factor in most comparisons. For experiments in stratified fluids, the only measurement available is the minimum dilution within the horizontal spreading layer beyond the location of the jet collapse. The ratio S_{avg}/S_{min} is not known, but it should be somewhat less than the value in the active jet mixing zone. Private communication with Philip Roberts at Georgia Tech and personal experience indicates that a value for this ratio should be on the order of 1.1 - 1.2 for two-dimensional discharges and probably not too much greater for round buoyant jets. Note that in Roberts, et al (1989) the definition of measured average dilution is different than that used in this and other analyses and therefore the presented average dilutions may not be directly compared to model predictions. The same holds for the average dilution data presented by Isaacson, et al (1978), but apparently their method of computing average dilution is more consistent with the volume flux ratios.

Round and Two-Dimensional Buoyant Jets in Unstratified and Nonflowing Ambient Fluids

The present version of UDKHDEN has three entrainment coefficients with variables names of A11, A2, and A7. The first is associated with nonbuoyant jet entrainment, the second is a multiplier on the local densimetric Froude number (following Fox (1970) and others) while A7 is the entrainment coefficient associated with crossflow induced aspiration. The value of A7 is irrelevant for the present analysis since the effect of crossflow is not studied in this section. The general form of the entrainment relation is

$$E = (\alpha_1 + \frac{\alpha_2 \sin\theta}{F^2}) U_m b^i$$

where i is an exponent equal to 0 for two dimensional jets and 1 for round buoyant jets, b and U_m are characteristic local jet width and velocity, respectively, $F^2 = U_m{}^2/(g' \, b)$ is the square of the local densimetric Froude number with g' the characteristic local density difference. α_1 and α_2 are entrainment coefficients related to A11 and A2, respectively, depending upon the specified velocity and density profiles. The essential result is that for a nonbuoyant jet, the term in α_2 vanishes ($1/F^2 = 0$) and thus α_1 is the nonbuoyant jet entrainment coefficient. For a pure plume, F^2 is a constant and thus the quantity inside of the parentheses is a constant and equal to the plume entrainment coefficient. Thus the values of A11 can be determined by consideration of nonbuoyant jet discharges, while A2 can be determined after A11 has been selected by the consideration of a pure plume. This approach was taken in the present investigation. Actually, the values of A11 for round buoyant jets and two-dimensional jets can be derived analytically from the closed form solutions for pure jets. This step was taken and yielded values for A11 of 0.0284 and 0.055 for round buoyant jets and two-dimensional buoyant jets, respectively. These values are required to give the limiting solutions for average dilution of:

Round Nonbuoyant Jet: $$S_{avg} = 0.276 \frac{M^{1/2} z}{Q}$$

Two-dimensional Nonbuoyant Jet: $S_{avg} = 0.558\frac{M^{1/2}z^{1/2}}{Q}$

The coefficient values in the above expressions were selected to reflect the recommendations of Chen and Rodi (1976) and List (in Fischer, et al (1979). These compare to the value for A11 in the existing implementation of UDKHDEN of 0.05. Thus, the existing model should predict nearly twice the correct average dilution for round nonbuoyant jets (0.05 vs. 0.028 entrainment coefficient), but reasonably close to the correct dilution for two-dimensional nonbuoyant jets (0.05 vs. 0.055). The estimates of 0.028 and 0.055 for A11 were verified in the model by simulating a jet with no initial density difference (actually nearly zero since zero density difference is not allowed as a model input). The results for two dimensional jets were obtained by selecting a very small port spacing and running the simulation for a very long distance to make sure that the effect of the initial configuration was not important and a two-dimensional calculation was being performed. In both cases, the correct asymptotic solutions were obtained and thus, the above values for A11 verified. In order to apply the appropriate value (i.e. depending upon the port spacing), it is necessary to implement a change in the model code to recognize whether or not adjacent jets are considered to be fully merged (in which case the two-dimensional value for the entrainment coefficient is to be applied) This change in the model is also required for the other entrainment coefficients and was implemented in a manner that is consistent with the definition of merging in the original program development.

Once the values of A11 were fixed, then A2 was determined in a trial-and-error fashion by estimating coefficient values and running a set of data for which buoyancy effects are very important in order to retrieve the following theoretical limiting asymptotic solutions for pure plumes:

round plume: $S_{avg} = 0.155\frac{B^{1/3}\, z^{5/3}}{Q}$

Two-dimensional plume: $S_{avg} = 0.5\frac{B^{1/3}\, z}{Q}$

There is considerable disagreement in the literature regarding the value of the coefficient for the two-dimensional solution and the value selected is based upon a judgement of the quality of available data. In order to make sure that the numerical model approaches the appropriate limiting solution, the simulations are run for long distances. The value of the dilution coefficient (in the above relations) computed from the numerical simulation is checked at various distances from the source in order to ensure that it in fact approached a constant value. With this technique, the appropriate values for the coefficients A2 were found to be 0.118 and 0.40 for round and two dimensional buoyant jets respectively.

In order to provide a final verification of the model for round buoyant jets in unstratified and nonflowing fluids, model simulations were performed for several of the data sets presented by Wong (1984) involving measurements of minimum dilution along the jet trajectory, some of which were essentially nonbuoyant jets while other discharges had very large initial buoyancy. Both the original model (i.e., the single fixed value of A11) and the model with variable entrainment coefficient were run for the same data sets and the results presented in Figs. 2 and 3. The conversion between average dilution and minimum dilution is on the basis of the profiles specified in the numerical model; although these may not necessarily be the best choice, their influence will be minor relative to the choice of entrainment coefficient. As can be seen by the results, the original model predicted a dilution nearly twice the observations for low buoyancy jets. Of course, this can be anticipated directly from the ratio of the original entrainment coefficient to the nonbuoyant round jet entrainment coefficient of (0.5/0.0284 = 1.76) For flows in which the buoyancy is more important, the discrepancy in predictions is not so great, but the original model clearly over-predicts the observed dilution. The adjusted model is in much better agreement with the experimental data and the agreement would be even better if more consistent profile assumptions were used to relate average and minimum dilution. Thus it is concluded that the adjusted model does a better job of predicting dilutions for single round buoyant jets and furthermore is consistently computing the correct average jet dilution in unstratified, stagnant receiving fluids.

Diffuser Discharges in Unstratified and Nonflowing Ambient Fluids

Interpretation of these simulations poses a more difficult problem because of the merging process, both between individual port discharges on one side of the diffuser and between rows of ports on opposite sides of the diffuser if that configuration exists. Also, the data available are somewhat less satisfactory for purposes of comparison. The two data sets relied on in this comparison were those by Liseth (1971) and Bühler (1973) which involved generally similar configurations. Unfortunately, the results presented by Liseth, while voluminous, do not include specific test conditions, and only ranges of parameters are given from which approximate experimental conditions may be estimated. A further difficulty is that there is apparently considerable scatter in his data, making results difficult to interpret if individual experimental conditions are unknown. The data of Bühler, while fewer in number, contain some valuable information in that a discharge from a single row of ports was studied in addition to the study of discharges from double rows of ports. Measurements were taken along the surface, both just above the source and just beyond the location where the discharge impacted upon the surface. This poses a problem in that the jet profiles would no longer be valid in this region and the possibility exists for additional mixing processes as the jet impinges upon the surface. Nevertheless, Wright (1985) and Wright and Bühler (1986) demonstrated that a reasonable estimate of the minimum surface dilution directly above the source for two-dimensional plumes could be obtained by considering the dilution to be that at 83.5% of the total depth. The change in dilution due to surface mixing was also estimated and agrees well with the data. It should be mentioned that all of the experiments performed by Bühler were of the type that can be approximated as plumes. The relation between minimum and average dilution directly above the source may be estimated from the profiles assumed in the model, but in the surface spreading layer, the profiles measured by Bühler indicate that $S_{avg}/Smin \approx 1.15$.

UDKHDEN does not explicitly consider the effect of a double row of ports and the model can thus be applied directly only for the case of a single row of ports. However, if the input data are altered to indicate port discharges twice the actual value, the correct fluxes of mass, momentum, and buoyancy per unit length of diffuser may be retained and consistent results obtained if the diffuser behaves as a line source. An additional possibility used in the simulation of Bühler's data is to use one-half of the port spacing that exists on one side of the diffuser. This was a reasonable approach because Bühler examined diffusers with alternating ports such that the spacing between adjacent ports along the diffuser is actually s/2. A relevant parameter in this regard is the ratio of the total water depth (above the discharge port) to the spacing between ports H/s. At small values of this ratio, the individual port discharges will not have merged and the individual jets may be expected to not interact to a significant extent. At very large ratios, the flow field should be nearly two-dimensional with discharges from both rows of ports used to compute the fluxes. In between, there is a transition in which neither assumption is completely reasonable.

A comparison of the predicted results to the experimental observations bears out the above discussion as indicated in Fig. 4. Included are the simulation results for a port spacing of the correct value (for a single side of the diffuser) and one-half that value. There is not a major difference in the quality of the comparison for data collected directly above the source versus that at a short distance away, indicating that the recommendations by Wright (1985) are generally valid. At values of H/s on the order of 10-15, the effect of spacing is minor, because the individual plumes have not been significantly merged. At larger values of H/s, merging is complete and the dilution predicted by a single row of jets is too high because the two-dimensional buoyancy flux is only one-half of the true value for two-sided diffusers. A reasonable conclusion from Fig. 4 is that if the water depth relative to the port spacing (on one side of the diffuser) is greater than about 15-20, the two rows of jets are essentially merged into a single slot plume while at shorter distances, the simulations considering only a single row of ports is more satisfactory although either can be used since there is not significant merging. Note also that the results for a single row or ports on the diffuser are also well simulated. The agreement between predictions and observations is quite satisfactory given the uncertainties in the data and the difficulties in interpretation of results. Thus, it is concluded that the model provides a realistic prediction of diffuser dilutions provided that a proper description of the port spacing is utilized in accordance with the above discussion.

The original UDKHDEN model predicts somewhat too low of dilution, both for the single row of ports and for the double rows of ports if the simulation considers both sides to determine the port spacing. This comparison is presented in Fig. 5. These results are consistent with the fact the the entrainment coefficient is somewhat too low for two dimensional discharges in the original model (as discussed above). From the comparison of this data, it is concluded that the adjusted model is a more accurate method for determination of plume dilution in stratified and stagnant ambient fluids.

Buoyant Jets in Linearly Stratified Ambient Fluids

The data selected for comparison in this section include the experimental results of Wong (1984) for round jets that are discharged either horizontally or vertically into a linearly stratified, nonflowing receiving fluid and the data of Wright, et al (1982) for diffuser discharges with a similar ambient condition. No adjustments to the model need to be made to perform the simulations; however, the question of interpretation of model results in important here. As discussed previously, the existing implementation of UDKHDEN assumes the initial dilution is that predicted at the elevation for which the average density within the jet is equal to the ambient density. Also, as discussed previously, this should be a more severe difficulty for low buoyancy jets because that level may be much less than the total jet rise for that type of flow and thus the dilution may be severely under-predicted. That this is the case is seen clearly in Fig. 6 which presents a comparison of the predictions at the neutrally buoyant level (also called the trap level) for several vertical buoyant jets studied by Wong. These numerical results were generated from the original model. The ratio $l_M / l_{b'}$ = $(MN/B)^{3/4}$ is a measure of the relative importance of the jet buoyancy and large values of the ratio (say greater than about 1) imply that the effect of the buoyancy is negligible. Thus dilutions at large values of the ratio should be under-predicted according to the preceding discussion and this is in fact observed. Using the altered model with the adjusted entrainment coefficients changes the magnitude of the predicted dilutions but does not have a significant qualitative impact on the comparison, see Fig. 7.

A different interpretation of the model would be to consider the dilution over the entire jet travel distance, or in other words to utilize the predictions at the maximum height of rise and not at the trapping level as discussed previously. This results in much better agreement between the model and the observations as indicated in Figs. 8 and 9. The results presented are in as ratios of the predicted average dilution and the measured minimum dilution in the horizontal spreading layer after the jet has collapsed into a nonmixing intrusion. The ratio between average and minimum dilution should be closer to unity than within the jet itself and this is indicated by the results; no direct measures of this ratio have been made in the experiments to indicate the proper relationship. A major reason for scatter in the data is associated with the current model output in which dilution is printed out versus distance at every few computational intervals. Without alteration of the output routine, only the last printed value of dilution before the maximum height of rise can be obtained and this may be somewhat less than the computed value at the maximum height of rise. This contributes to the increase in apparent data scatter between Figs. 6 and 8, for example.

Note that the differences between the two versions of the model are less than indicated for unstratified fluids in Figs. 2 and 3. This can be anticipated from the consideration that too large of an entrainment coefficient in the existing model reduces the maximum height of rise so that the larger dilution rate is largely counterbalanced by a shorter mixing distance. This effect has been observed for other simulation models and implies that the prediction of dilution for nearly vertically rising jets in linearly stratified fluids is relatively insensitive to the selection of entrainment coefficient. This would not necessarily be the case however for jets with a significant component of horizontal motion as discussed next. In spite of this result, the original model still predicts dilutions somewhat higher than the adjusted model. While there may be some trend in the ratio of predicted average dilution to measured minimum dilution with $l_M / l_{b'}$, the range of values is not too great with an average value on the order of 1.15 or about what might be anticipated from other experimental results. Thus it is concluded that the adjusted model does a remarkable job of predicting average dilution considering all the uncertainties in the numerical formulation. The original model is not all that different and it is difficult to argue that it does not also predict average dilution reasonably well.

When the buoyant jets are discharged horizontally, a discharge with large buoyancy will be quickly deflected into a vertical trajectory and behave similar to a vertical discharge. However, a nonbuoyant jet would have no tendency to be deflected in the vertical and thus it can be anticipated that the dilution for horizontal jets with low buoyancy may be more sensitive to the choice of entrainment coefficient. This can be seen in the results given in Figs. 10 and 11. Both models correctly predict dilution for high buoyancy discharges. The original model again exhibits a tendency to over-predict dilution for low buoyancy discharges whereas the adjusted model is only somewhat more consistent. This is probably due to the fact that the nearly horizontal jet travels through previously discharged spreading fluid and thus while the mixing rate may be correctly computed in the model, the entrainment of ambient fluid may be less due to re-entrainment of previously discharged jet fluid.

Simulations were also run for the diffuser discharge data presented in Wright, et al (1982). Since the maximum height of rise was always less than 20 times the port spacing, all UDKHDEN simulations were run considering only the discharges from one side of the diffuser, while the data consisted of separate data sets with discharges from either one or both sides. It is not possible to distinguish between the nature of the results for either data set as indicated in Figs. 12 and 13 and thus this tends to confirm the conclusions regarding whether or not to consider the total discharge (both sides) or only that from one side. Both the original and adjusted UDKHDEN models behave similarly to the results discussed above for horizontal round buoyant jets (i.e. good at small values of l_M/l_b' and over-predict dilution at high values) and the general conclusions formed above are also applicable to diffuser discharges. It is also seen that the original model predicts somewhat higher dilutions than the adjusted model and this is taken to indicate that the two-dimensional aspect of the flow is not important in the simulations.

Buoyant Jets in Unstratified Crossflows

These comparisons are necessary to establish appropriate values for the entrainment coefficient A7 which describes the aspiration induced by the crossflow. Again, it is only realistic to assume that round and two-dimensional jets would exhibit different values for the coefficient (and also possibly that the coefficient will depend upon the relative buoyancy, but the data and the model construct are insufficient to resolve this issue). Consequently, a similar alteration of the numerical code was implemented such that a different value for A7 could be utilized for a round buoyant jet and a fully merged row of jets.

The data sets available to analyze the round jet in a crossflow are much more extensive than for a diffuser discharge. For this purpose, the data of Fan (1967) were employed. One difficulty in interpreting results is that Fan measured the minimum dilution on the vertical symmetry axis in most cases. In two experiments, he measured the complete concentration field and found that there was an off-centerline concentration maximum on the order of 50-75 percent greater than the value measured in the symmetry plane. Clearly the profiles used in the numerical simulation cannot be used to directly estimate the minimum centerline dilution from the predicted average dilution presented in the model output and there is no convenient way to resolve this dilemma. Given this, it was decided to simply assume that the average dilution would be equal to the minimum centerline dilution as they must be fairly similar and the comparison of UDKHDEN predictions and experimental observations is thus direct. Fan also formulated a numerical model in which it was necessary to include a pressure drag term in the momentum balance in order to properly deflect the jet in the downstream direction. In order avoid this issue, only a comparison of the model predictions for strongly deflected jets was made and the comparison was made at given downstream distances so that the issue of vertical jet location was not relevant. However, it is noted that an inspection of predicted trajectories versus observations indicated that the predicted jet rose too rapidly compared to the observations after the entrainment coefficient was adjusted to properly predict dilution. Further adjustments to the model would be required in order to properly compute the predicted jet trajectory, but past experience has indicated that it is very difficult to optimize the various coefficients so that both trajectories and dilutions are computed properly.

A comparison of predicted dilutions (both with the original model and with the adjusted model) versus observed dilutions for several of Fan's experiments is provided in Figs. 14-16. It is seen that the predicted dilution by the original model is too large by an amount that cannot be attributed solely to questions of profile assumptions. In order to obtain more qualitatively consistent predictions, the entrainment coefficient A7 was reduced down from its original value of 11.5 to 3.0. The comparison of the predictions with this adjusted model is presented in the same figures and the agreement is seen to be much better. Although other experimental runs were simulated, the indicated results are typical and it appears that general agreement of the model predictions with Fan's data has been obtained.

The extension of the model to two-dimensional discharges in a crossflow is full of considerable uncertainty. The discussion by Roberts (1979) regarding the general nature of the wastewater field under these circumstances should be reviewed to obtain a qualitative understanding of the nature of the flow field. In particular, at high ambient velocities (more specifically high values of U_a^3/B), the discharge attaches to the bottom and does not behave as a free jet. Further downstream the flow may detach from the lower boundary but this is at least partially dependent upon diffuser end effects and is not explicitly modeled by any current integral model. In spite of these difficulties, simulations were run with the original value of A7 at 11.5 (for fully merged jets only, i.e. A7 = 3.0 for nonmerged jets) and compared to the data for tee-risers from the physical hydraulic model for the proposed San Francisco wastewater discharge as reported by Isaacson, et al (1978). Since two jets issue from each riser in close proximity to each other, it was felt that these would quickly coalesce into a single discharge as they were swept downstream (this is consistent with the visual impression of the flow) so the discharge input into the model was twice the value for an individual port. A comparison of the predicted results with the data is presented in Fig. 17 and a fairly good agreement with the individual experiments is obtained in most cases. Average dilutions are presented in the report, but do not correspond to the conventional definitions. The computed average dilutions, however are probably at most only 10-20 percent higher than would be obtained with the ratio S_{avg}/S_{min} determined from Bühler's data and thus the comparison presented is reasonable. It should be noted that the individual jets have not been merged for a considerable distance before the free surface is encountered (in fact, two of the results are completely independent of the two dimensional entrainment coefficient), so it is not clear that this data set is the most appropriate one for the determination of the aspiration entrainment coefficient for two-dimensional flows. At the same time, it is not clear that the entrainment relation is appropriate for the case of strong crossflows and so any conclusions at this point are questionable. Note also that the original model predicts significantly higher dilution than the observed values and this must be mainly due to the high value of A7 in the original model. Simulation results are clearly inappropriate for those cases and these results serve to confirm the general conclusions obtained for single round buoyant jets.

Buoyant Jets in Stratified Crossflows

The best experimental data for a comparison of the model predictions are those of Wright (1977) for round buoyant jets and Roberts, et al (1989) for diffuser discharges. Again, it is noted that no model adjustments are required to extend the results to stratified receiving fluids other than the decision to interpret the dilution at the maximum height of rise rather than at the trapping level as demonstrated for nonflowing receiving fluids. It becomes somewhat more important to identify the downstream location that the dilution is measured since both the results by Wright and Roberts indicate a fair amount of additional dilution (say up to a factor of two increase in dilution) as one goes downstream from the point of maximum rise. UDKHDEN, however, only provides simulation outputs up to the point where the maximum height of rise is reached. so a strict comparison of dilution versus distance is not generally possible. In the data by Wright, dilutions are presented just downstream from the maximum rise point and these are compared directly. It is presumed that the average dilution is only somewhat greater than the minimum dilution, perhaps 10 percent or so, but this is not known from direct measurements. The data presented by Roberts are given at various downstream locations in several cases and these locations are not related to the location of the maximum rise point.

A comparison of a selection of data by Wright (1977) and the predictions is presented in Fig. 18 and the adjusted model appears to provide fairly realistic results. The predicted average dilution is very close to the observed minimum dilution, in close correspondence to the dilution versus distance comparison of predictions of data by Fan. Again, the original model predicts too large of dilutions and there is more scatter in the data. Since the horizontal plot axis does not include the effect of crossflow, it is difficult to distinguish this effect in the plot. However, from the previous results, it is realistic to expect that the individual data with only small differences between the two models correspond to weak crossflows while those with larger discrepancies are for stronger crossflows.

The model predictions for the conditions of several experiments by Roberts, et al (1989) are compared with the measured minimum dilutions in Fig. 19. The average dilutions reported were not defined in terms of the volume fluxes and the ratio S_{avg}/Smin is larger than 2.0 for most of these data; this is much higher than can be reasonably expected from other experimental results and is related to the specific definition of S_{avg}. Roberts (personal communication indicates that when S_{avg} is defined in a manner consistent with the definition employed in this investigation, a more appropriate ratio would be on the order of 1.15-1.20. Fig. 19 indicates that the dilution may be somewhat over-predicted at low crossflow velocities and under-predicted at the highest velocities, but that the adjusted model does predict the observed dilutions fairly well. Again, the original model predicts dilutions that are too large, a result that is consistent with previous findings.

An inspection of the numerical simulation results indicate that even with the smallest diffuser port spacing studied by Roberts (these are the results presented in Fig. 19), the jets are not computed to be fully merged at the maximum height of rise and therefore only the round aspiration entrainment coefficient (A7) is used in the simulations. This is somewhat surprising since Roberts indicates that nearly all flows were generally two-dimensional in nature.

Returning back to the San Francisco outfall comparisons, the few data that were used to estimate the two-dimensional value of A7 are somewhat questionable because they represent relatively strong crossflows with little merging between adjacent port discharges. Given these uncertainties in the laboratory data examined, a final attempt was made to investigate the numerical model simulation results by comparing to the data collected in a field study of the Alyeska ballast water outfall diffuser. Some of the details of the field study have been previously documented by Wright, et al (1988) and others. In brief, the ballast water diffuser is located at a depth of about 60 m and discharges ballast water from the holds of oil tankers after treatment at an onshore facility. The density difference is not nearly so great as for a typical ocean wastewater diffuser, but the flows were still strongly influenced by their buoyancy. Two sampling events, one in October, 1985 during a period of high stratification and another in March, 1986 with relatively weak stratification were conducted. For the present purpose, only the March data are considered since these would give the individual jets a sufficient vertical rise to allow them to be merged as much as possible. Wright, et al (1988) considers the October data and shows them to be reasonably well simulated by the original UDKHDEN model. However, these are for strong stratification and weak ambient currents so the situation is somewhat analogous to the simulations of individual jets in a stagnant stratified fluid and large discrepancies between the two models would not be expected.

Ambient currents are rather weak, on the order of 2-5 cm/s and the discharge rises nearly to the surface in most cases in the March data. The crossflow Froude number U_a^3/B has a maximum value of about 0.28 for these data. An investigation of the numerical results for this data indicated that the two dimensional crossflow aspiration coefficient is operational (the individual port discharges are merged before the maximum height of rise is reached) and the simulation results were sensitive to the choice of A7. These data were therefore examined in order to determine whether a more positive statement could be developed regarding the magnitude of this coefficient.

The ports on this diffuser are in the form of risers that alternately point 45° from either side of the diffuser axis. Again, the numerical model simulation cannot handle this specific of a geometry so the simulations were performed under the assumption of a single row of ports with a constant orientation. The results of the simulations with the two-dimensional A7 set equal to 11.5 yielded predicted dilutions that were sometimes over four times the observed values. These results indicate that the entrainment coefficient A7 is considerably too high. Therefore the value was reduced to 3.0 and the results presented in Fig. 20. Also presented are the predictions of the original model. Given the uncertainties in the field data and the approximations in the geometrical representation of the problem, this is probably the maximum effort justified in calibrating the model with this data set. While the original model generally predicts too high a dilution, the results with the adjusted model generally cluster about a line of perfect agreement between the predicted average and the observed minimum dilutions. A reasonable interpretation of these results is that the estimate of the two-dimensional crossflow entrainment is probably accurate plus or minus 50 percent.

Recommendations and Conclusions

The existing UDKHDEN model was verified against an extensive set of laboratory data and one set of field data. It was found to be lacking in the ability to reproduce observed dilutions in many circumstances. In particular, the entrainment coefficients utilized in the model were not set to even properly compute the limiting cases of round and two-dimensional jets and plumes. Furthermore, the model interpretation of dilution in a stratified fluid was found to be lacking, but it could be corrected by a different interpretation of the model output.

The model entrainment coefficients were initially adjusted so that the appropriate asymptotic solutions described above could be obtained. After making these adjustments, the model was then capable of predicting the correct dilutions in stagnant receiving fluids, both stratified and unstratified. The agreement between the model predictions and the experimental data is excellent indicating that the adjusted model is a reasonable tool for predicting plume dilution.

After completing the model analysis for stagnant fluids, a similar analysis was performed for flowing ambient fluids. It was found that predictions could be made to agree with various data sets, both in stratified and unstratified ambient fluids for single round buoyant jets if the crossflow entrainment coefficient was reduced by nearly a factor of four from that value used in the original model. However, jet trajectories were not well predicted because of the need to incorporate a pressure drag term in the model formulation.

When the model was extended to consider diffuser discharges in a crossflow, the available data sets were somewhat more limited. This resulted in the selection of a set of field data to estimate the value of the two-dimensional crossflow entrainment coefficient. Again, it was necessary to reduce the entrainment coefficient by nearly a factor of four in order to satisfactorily reproduce the data set.

When the adjusted model was compared against the only extensive data set on diffusers in a crossflow, it reproduced the data fairly well, but the choice of two-dimensional crossflow entrainment coefficient was irrelevant to this comparison and there was therefore no way to verify the magnitude of this coefficient in a meaningful way from the laboratory data investigated. However, the model was calibrated against a set of field data for which a fairly good reproduction of observations was possible with the adjusted model. The uncertainties in the quality of the field data do not allow definitive conclusions, but the change in the crossflow entrainment coefficient appears to be reasonable given the other simulation results and it is recommended that this modification be also made in the original model as well.

While the original UDKHDEN model could predict the observed dilutions fairly well for certain data sets and subsets of others, it generally failed to perform adequately over the spectrum of conditions analyzed. There appears to be no basis for confidence in its ability to perform adequately over a wide range of environmental applications because of these limitations.

References

Bühler, J. (1973) *Model Studies of Multiport Diffusers in Unstratified Stagnant of Flowing Receiving Water,* Ph.D. Dissertation, University of California, Berkeley, California.

Chen, C.J. and W. Rodi, (1976) *Vertical Turbulent Buoyant Jets- A review of Experimental Data,* Pergamon Press.

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger, and N.H. Brooks, (1979) *Mixing in Inland and Coastal Waters,* Academic Press

Fan, L.N. (1967) *Turbulent Buoyant Jets into Stratified or Flowing Ambient Fluids,* Report KH-R-15, W.M. Keck Laboratory, California Institute of Technology, Pasadena, California

Fox, D.G., (1970) *Forced Plume in a Stratified Fluid,* Journal of Geophysical Research, Vol. 75, No. 33, pp. 6818-6835.

Isaacson, M.S., R.C.Y. Koh, and N.H. Brooks, (1978) *Sectional Hydraulic Modeling Study of Plume Behavior: San Francisco Southwest Ocean Outfall Project,* Technical Memorandum 78-2, W.M. Keck Laboratory, California Institute of Technology, Pasadena, California

Isaacson, M.S., R.C.Y. Koh, and N.H. Brooks, (1983) *Plume Dilution for Diffusers with Multiport Risers,* Journal of Hydraulic Engineering, Vol. 109, No. HY2, pp. 199-220.

Liseth, P. (1976) *Wastewater Disposal by Submerged Manifolds,* Journal of Hydraulics Division, ASCE, Vol. 101, HY1, pp. 1-13.

Muellenhoff, W.P., A.M. Soldate, D.J. Baumgartner, M.J. Schuldt, L.R. Davis, and W.E. Frick, (1985) *Initial Mixing Characteristics of Municipal Ocean Discharges, Volume I: Procedures and Applications,* U.S. EPA publication EPA/600/3-85/073a.

Roberts, P.J.W., W.H. Snyder, and D.J. Baumgartner, (1989) *Ocean Outfalls III: Effect of Diffuser Design on Submerged Wastefield,* Journal of Hydraulic Engineering, Vol. 115, No. 1, pp. 49-70.

Roberts, P.J. W., (1979) *Line Plume and Ocean Outfall Dispersion,* Journal of Hydraulics Division, ASCE, Vol. 105, HY4, pp. 313-331.

Wong, D.R. (1984) *Buoyant Jet Entrainment in Stratified Fluids,* Ph.D. dissertation, The University of Michigan Ann Arbor, Michigan.

Wong, D.R. and S.J. Wright, (1988) *Submerged Turbulent Jets in Stagnant Linearly Stratified Fluids,* Journal of Hydraulic Research, Vol. 26, No. 2, pp. 199-223.

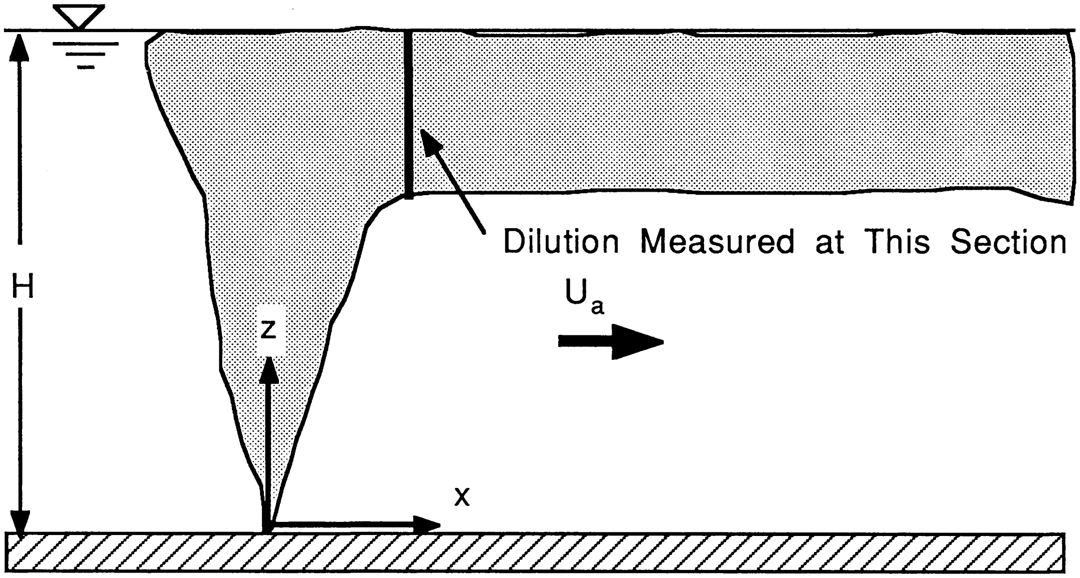
Wright. S.J., D.R. Wong, R.B. Wallace, and K.E. Zimmerman (1982) *Outfall Diffuser Behavior in Stratified Ambient Fluid,* Journal of Hydraulics Division, ASCE, Vol. 108, HY4, pp. 483-501.

Wright. S.J. (1985) *Discussion of Wastewater Field Thickness and Initial Dilution,* Journal of Hydraulic Engineering, Vol. 111, No. 5, pp. 891-896.

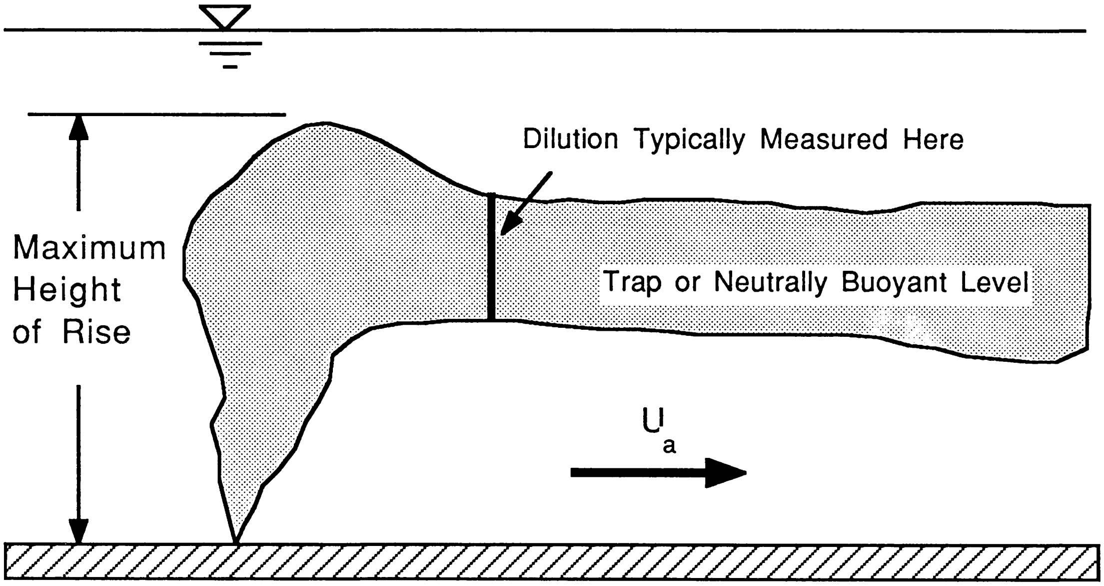
Wright, S.J. and J. Bühler, (1986) *Control of Buoyant Mixing by Far Field Spreading,* Proceedings, Symposium on Advancements in Aerodynamics, Fluid Mechanics, and Hydraulics, Minneapolis, Minnesota, pp. 736-743.

Wright, S.J. (1977) *Effects of Ambient Crossflows and Density Stratification on the Characteristics Behavior of Round Turbulent Buoyant Jets*, Report KH-R-36, W.M. Keck Laboratory, California Institute of Technology, Pasadena, California.

Wright, S.J., P.A. Mangarella, and J.M. , (1988) *Outfall Plume Dilution in Stratified Fluids,* Proceedings, International Symposium on Model-Prototype Correlation of Hydraulic Structures, pp. 148-157, Colorado Springs, Colorado.



Unstratified Crossflow



Stratified Crossflow

Fig. 1. Schematic of Buoyant Jet Discharge in Stratified Crossflow.

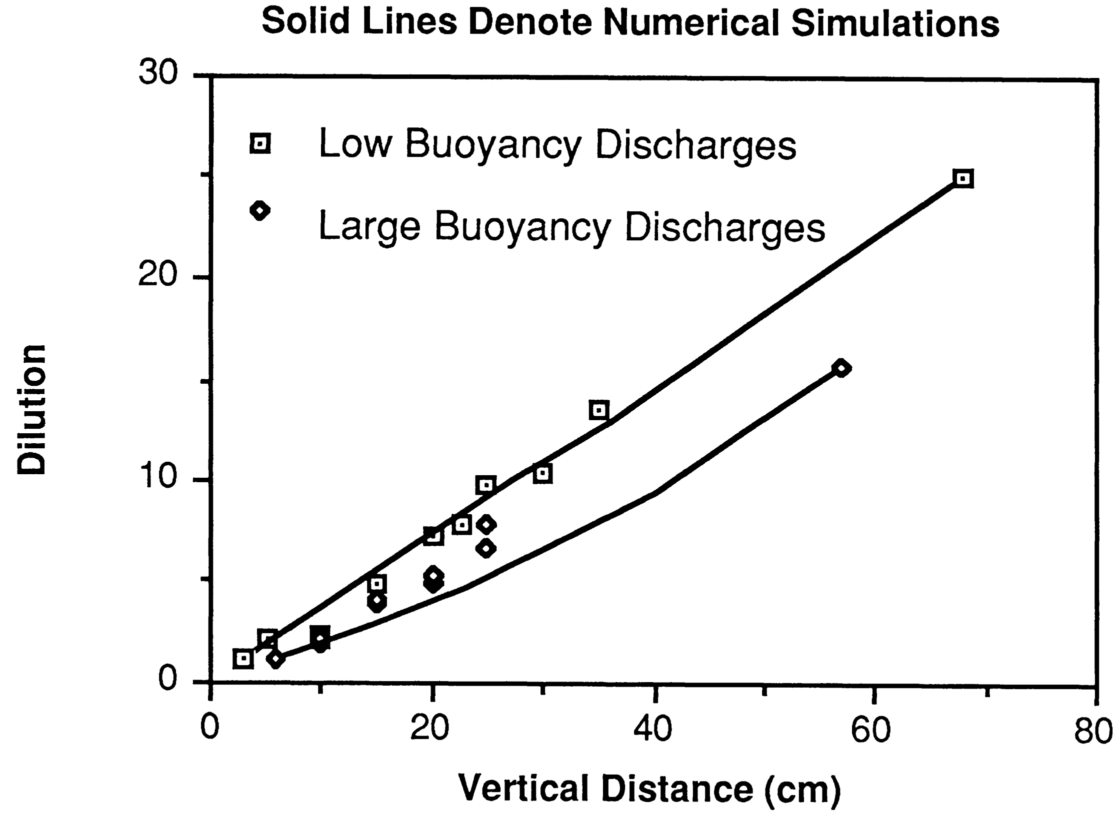


Fig. 3. Comparison Between Numerical Predictions of Adjusted UDKHDEN Model and Selected Data from Wong (1984).

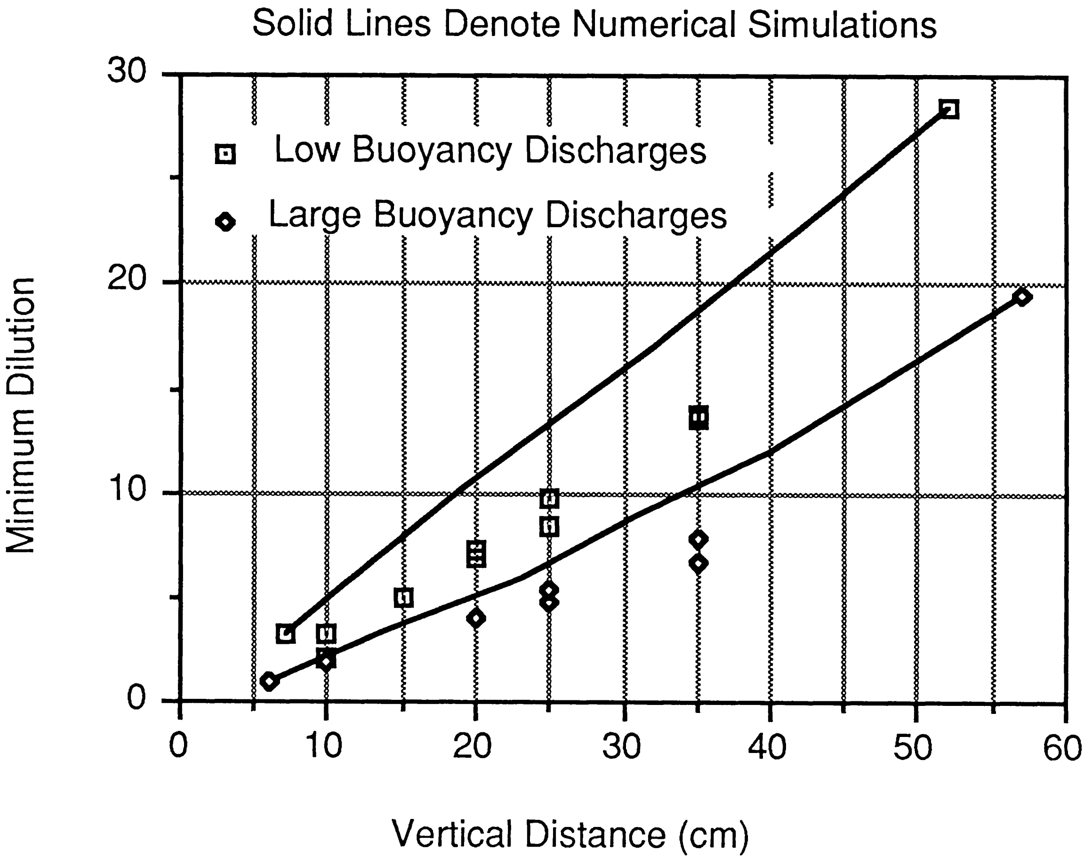


Fig. 2. Comparison Between Numerical Predictions of Original UDKHDEN Model and Selected Data from Wong (1984).

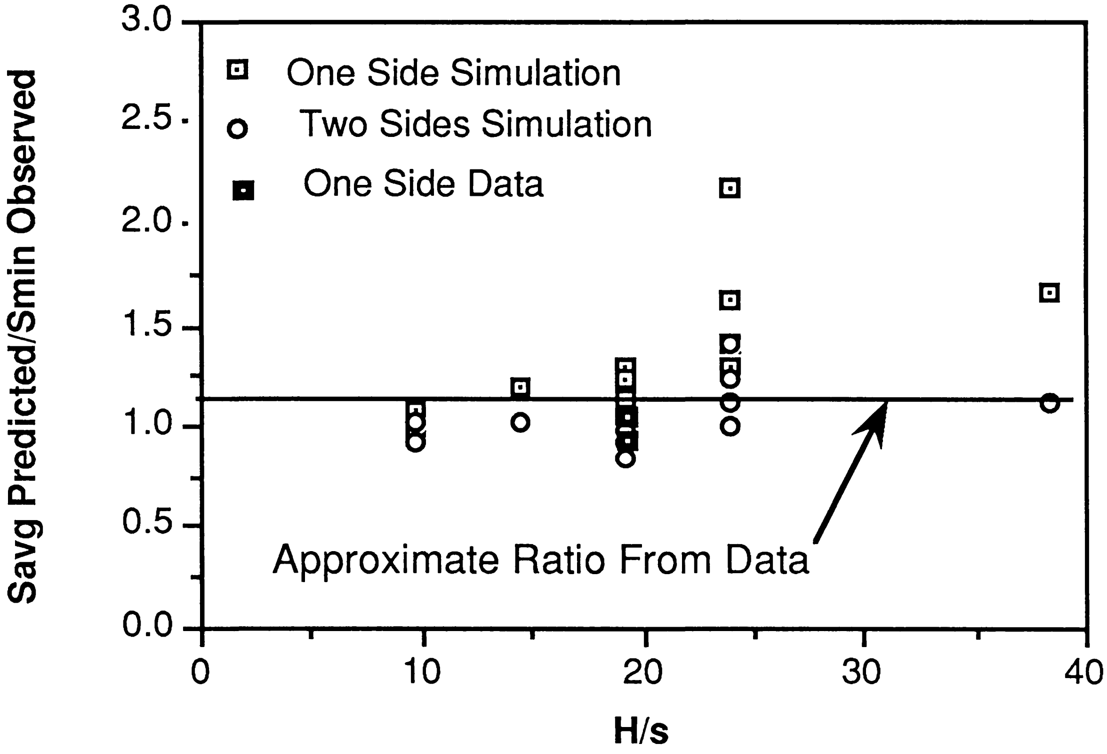


Fig. 4. Comparison Between Numerical Predictions of Adjusted UDKHDEN Model and Diffuser Data from Bühler (1983).

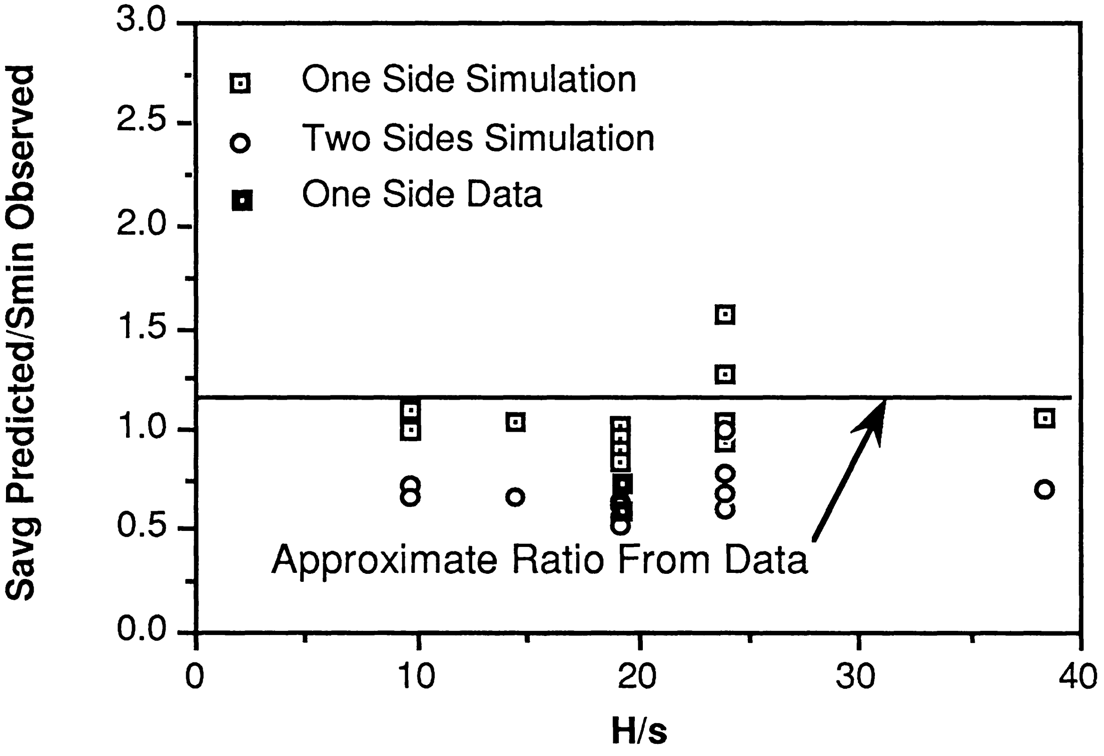


Fig. 5. Comparison Between Numerical Predictions of Original UDKHDEN Model and Diffuser Data from Bühler (1983).

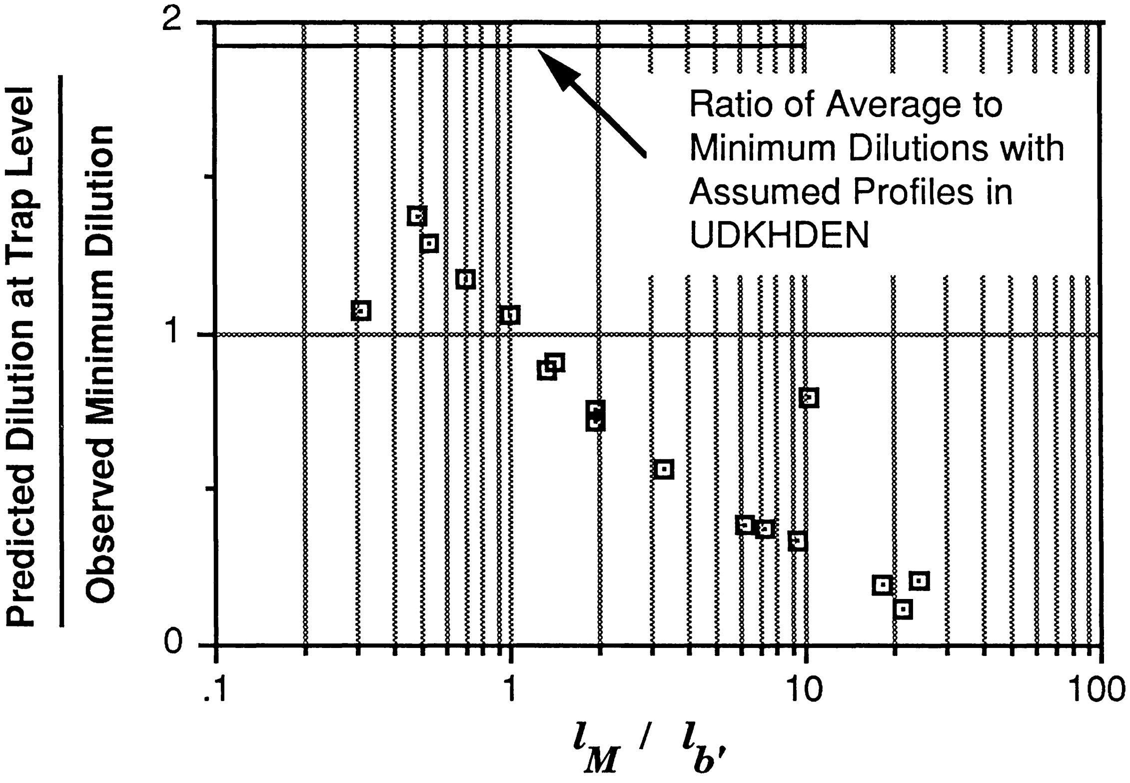


Fig. 6. Predictions of Original UDKHDEN model of Average Dilution at Trap Level with Measurements of Minimum Dilution from Wong (1984) for Round Buoyant Jets in a Stagnant Linearly Stratified Fluid.

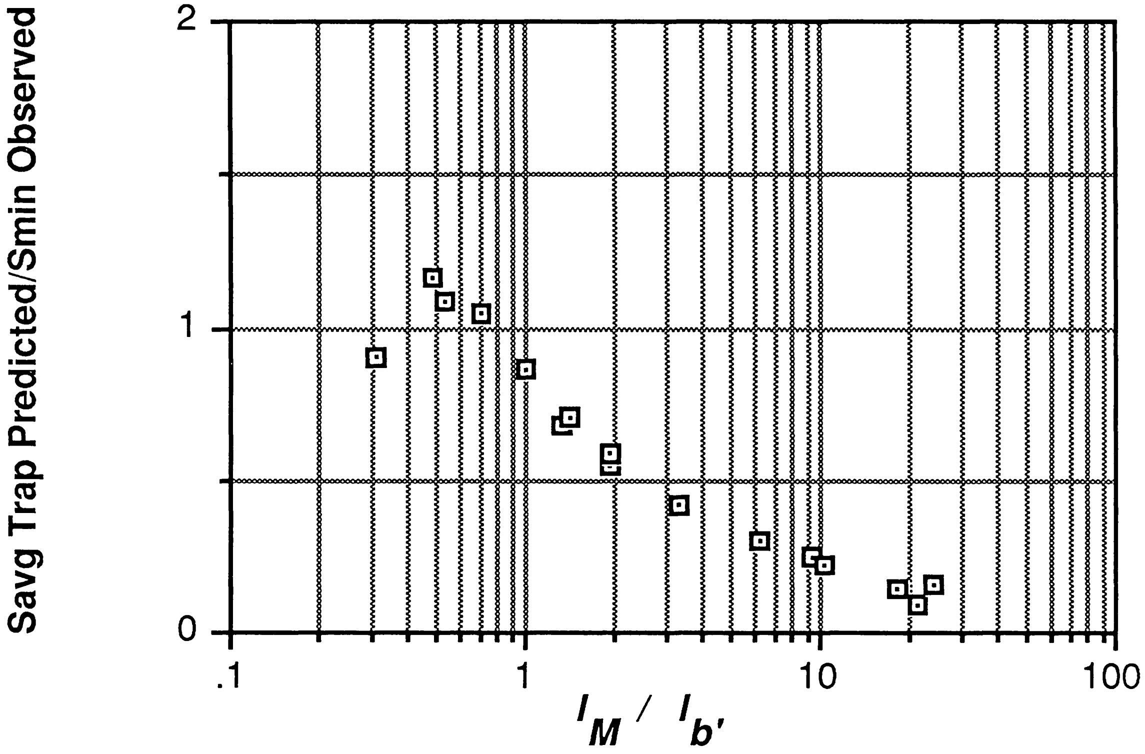


Fig. 7. Predictions of Adjusted UDKHDEN model of Average Dilution at Trap Level with Measurements of Minimum Dilution from Wong (1984) for Round Buoyant Jets in a Stagnant Linearly Stratified Fluid.

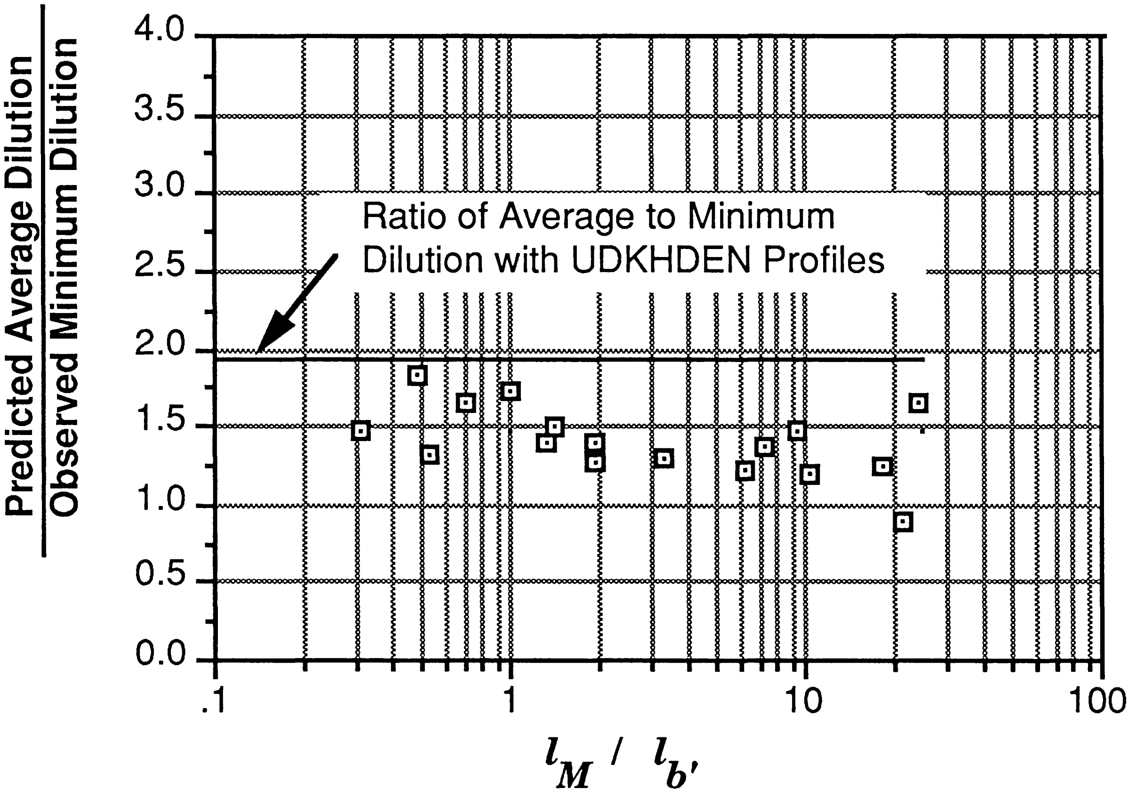


Fig. 8. Predictions of Original UDKHDEN model of Average Dilution at Maximum Height of Rise with Measurements of Minimum Dilution from Wong (1984) for Vertical Round Buoyant Jets in a Stagnant Linearly Stratified Fluid.

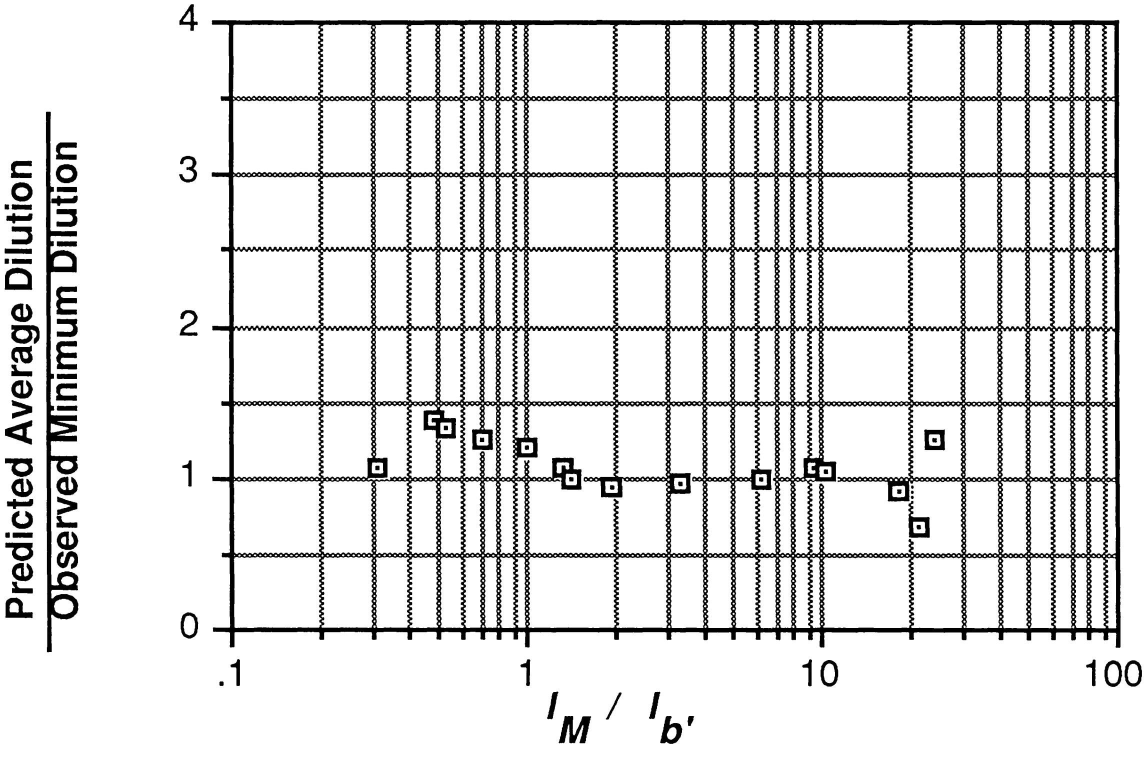


Fig. 9. Predictions of Adjusted UDKHDEN model of Average Dilution at Maximum Height of Rise with Measurements of Minimum Dilution from Wong (1984) for Vertical Round Buoyant Jets in a Stagnant Linearly Stratified Fluid.

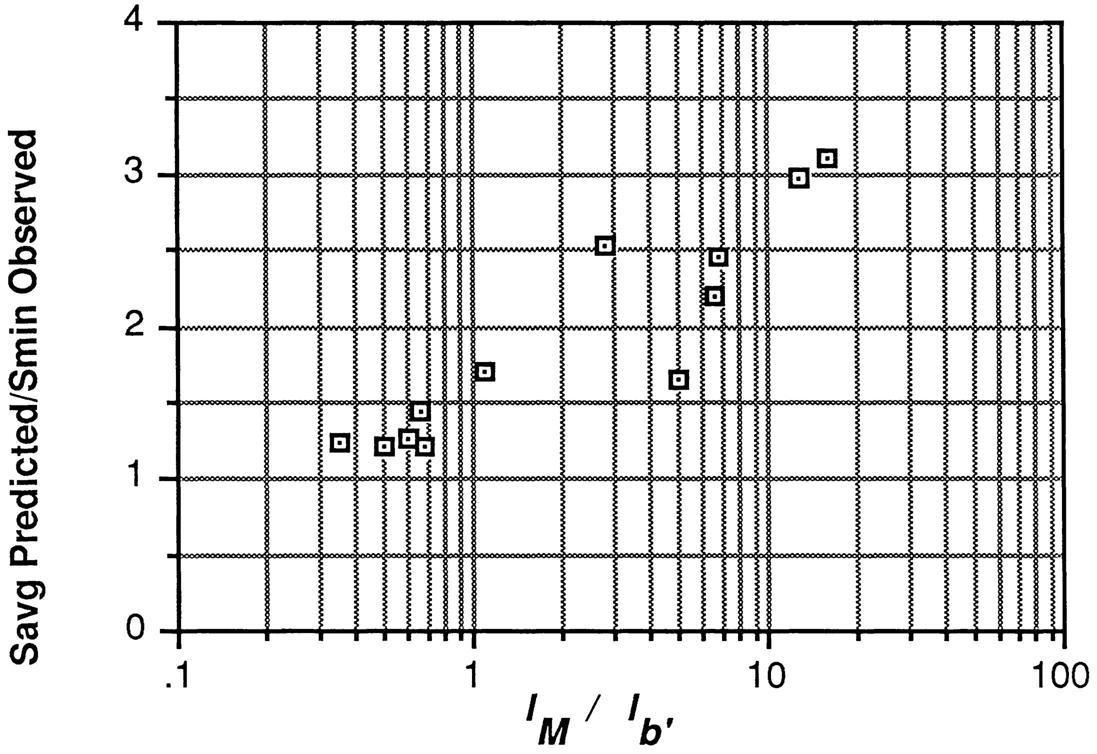


Fig. 10. Predictions of Original UDKHDEN model of Average Dilution at Maximum Height of Rise with Measurements of Minimum Dilution from Wong (1984) for Horizontal Round Buoyant Jets in a Stagnant Linearly Stratified Fluid.

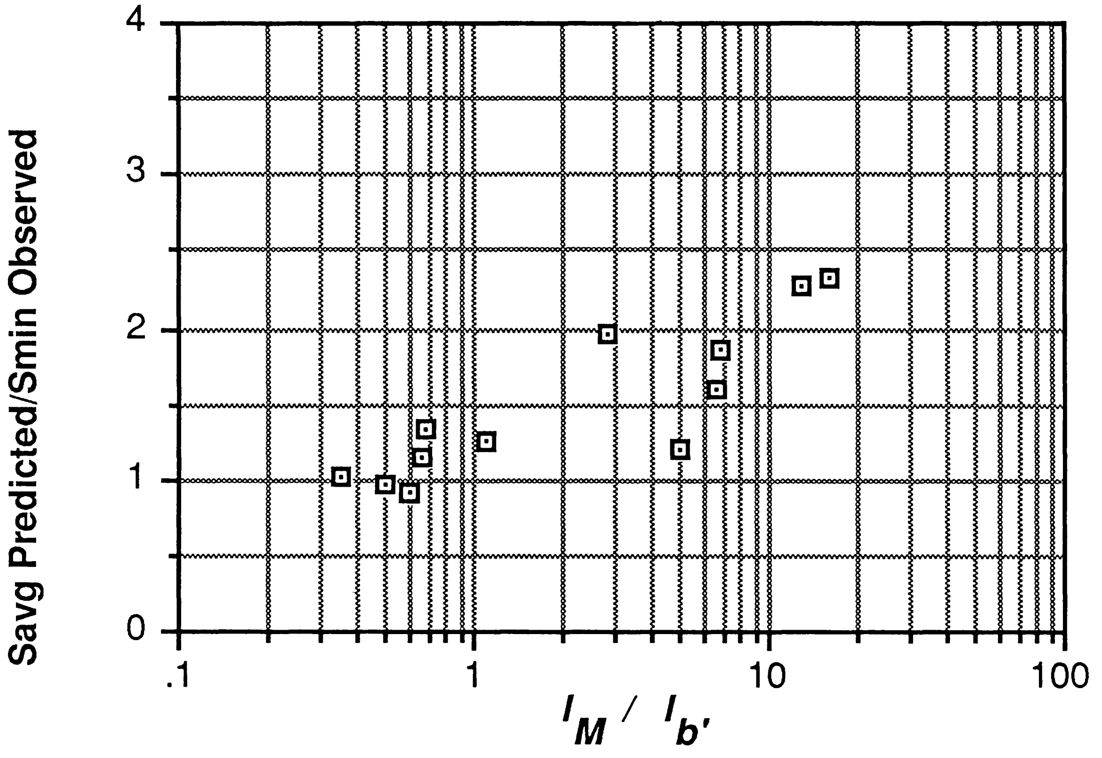


Fig. 11. Predictions of Adjusted UDKHDEN model of Average Dilution at Maximum Height of Rise with Measurements of Minimum Dilution from Wong (1984) for Horizontal Round Buoyant Jets in a Stagnant Linearly Stratified Fluid.

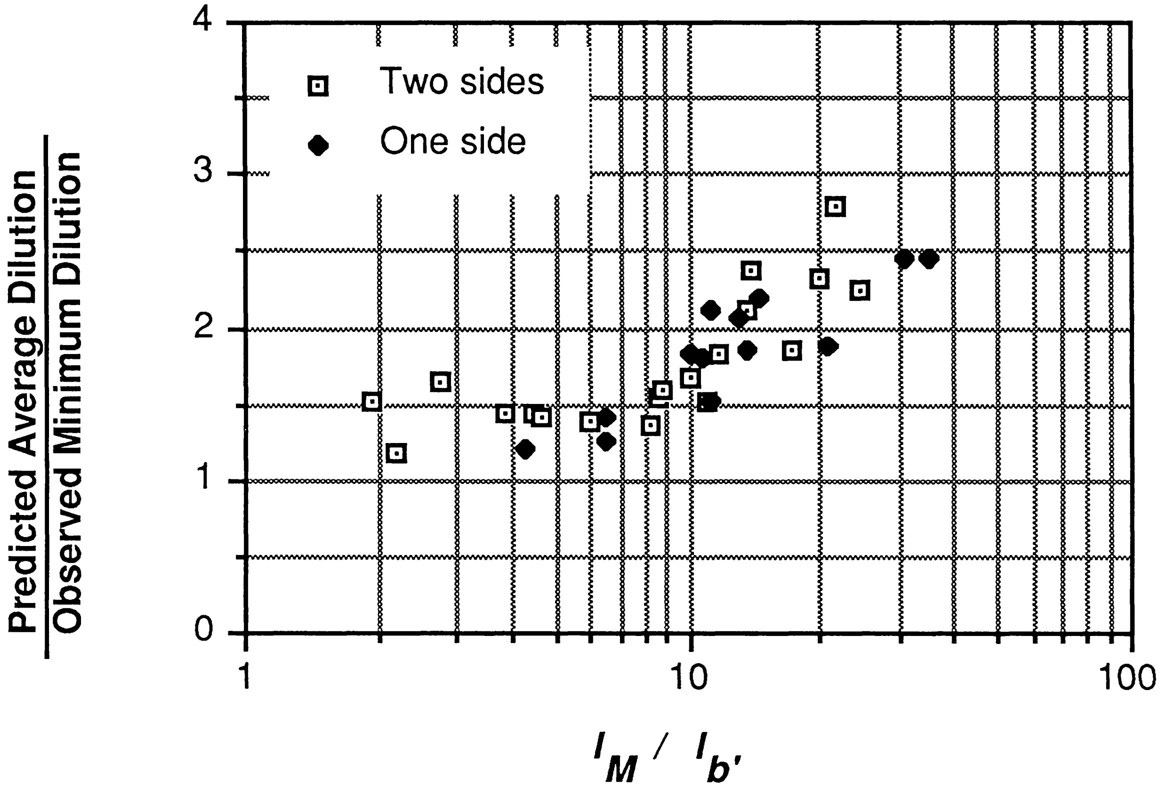


Fig. 12. Predictions of Adjusted UDKHDEN Model of Average Dilution at Maximum Height of Rise with Measurements of Minimum Dilution from Wright, et al (1982) for Diffuser Discharges in a Stagnant Linearly Stratified Fluid.

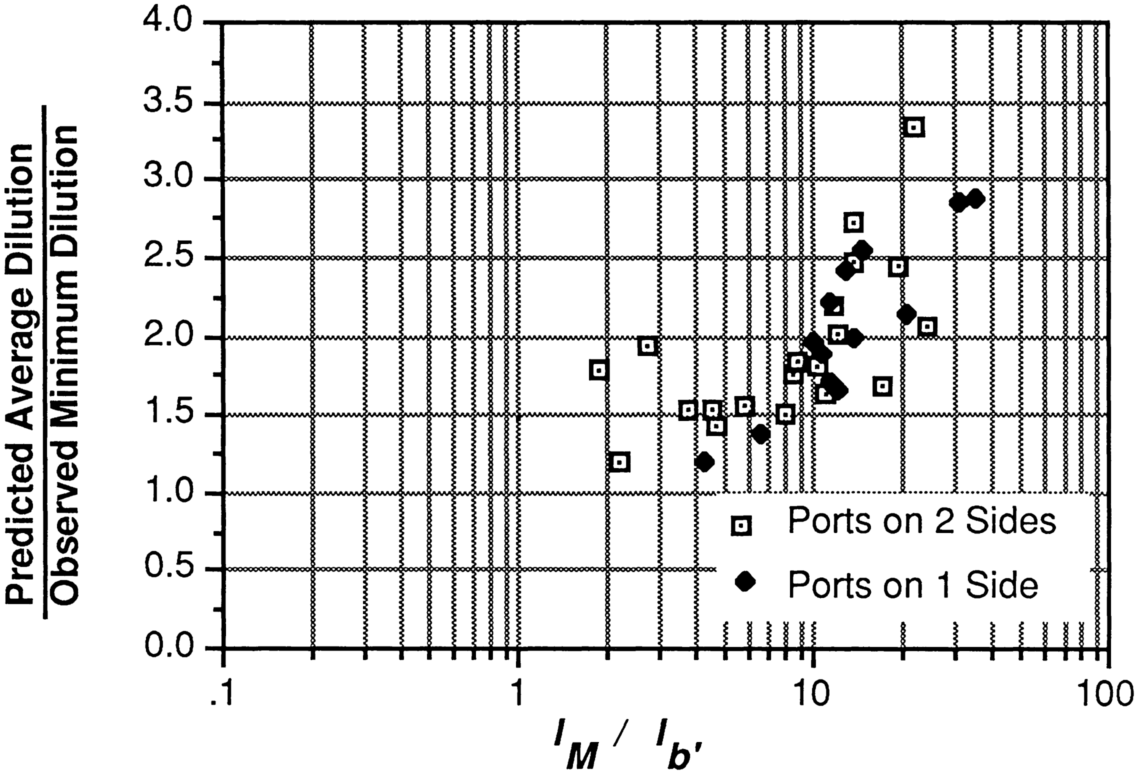


Fig. 13. Predictions of Original UDKHDEN Model of Average Dilution at Maximum Height of Rise with Measurements of Minimum Dilution from Wright, et al (1982) for Diffuser Discharges in a Stagnant Linearly Stratified Fluid.

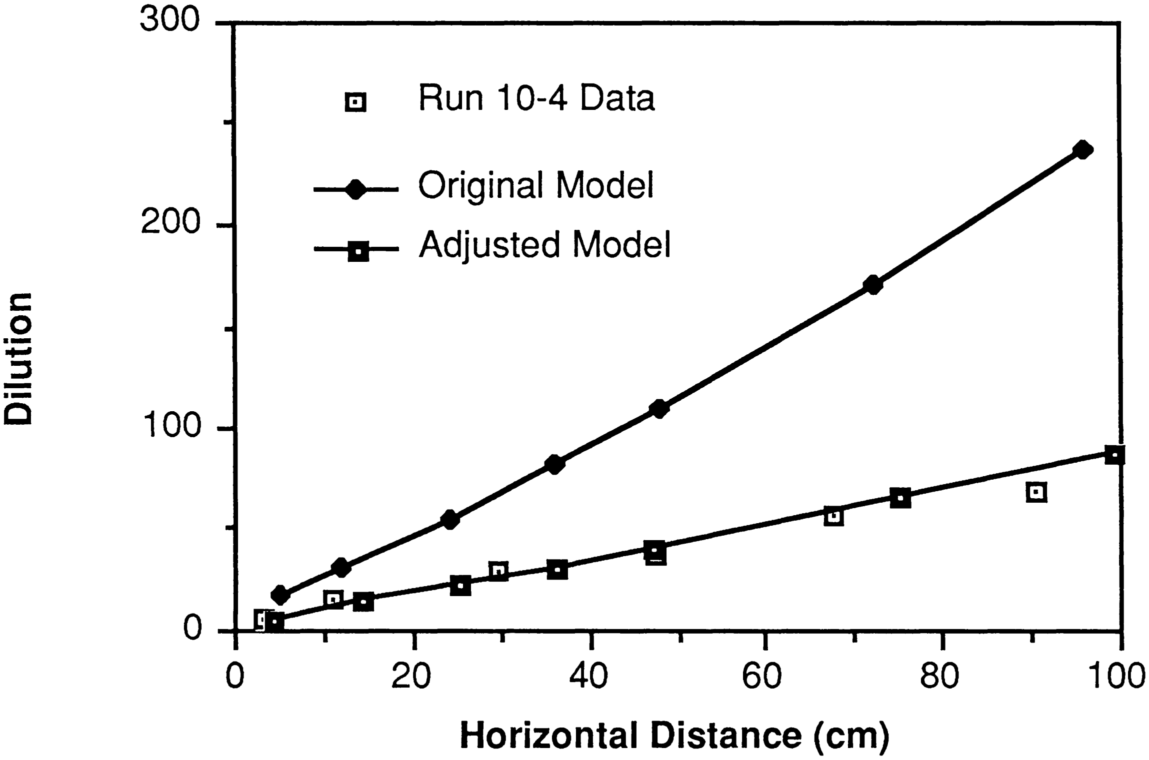


Fig. 14. Comparison of UDKHDEN Model Predictions (Both Original and Adjusted Models) for Run 10-4 from Fan (1967), Round Buoyant Jet in a Crossflow.

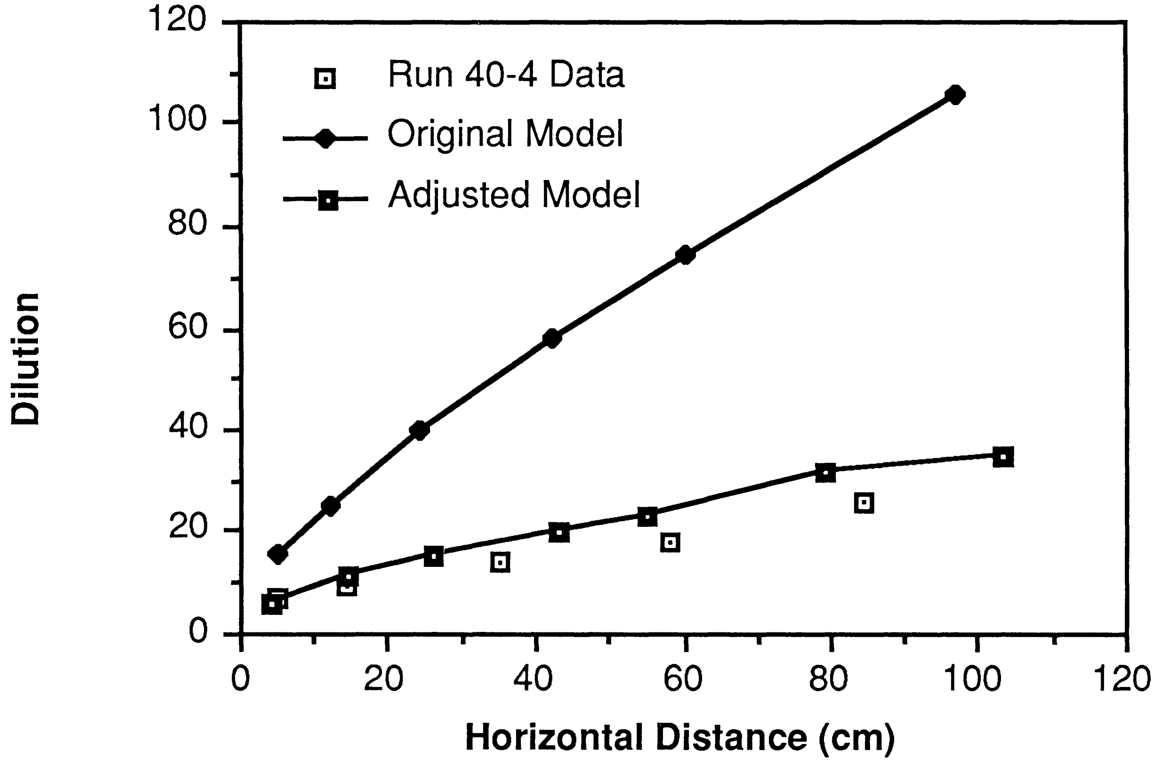


Fig. 15. Comparison of UDKHDEN Model Predictions (Both Original and Adjusted Models) for Run 40-4 from Fan (1967), Round Buoyant Jet in a Crossflow.

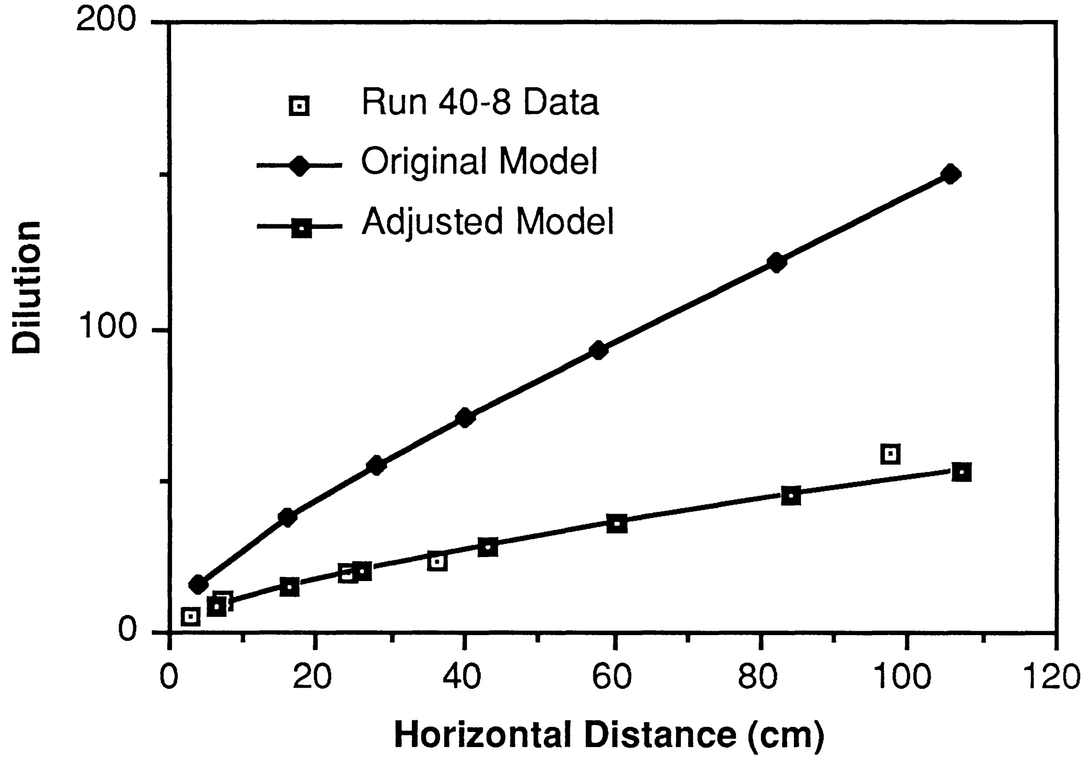


Fig. 16. Comparison of UDKHDEN Model Predictions (Both Original and Adjusted Models) for Run 40-8 from Fan (1967), Round Buoyant Jet in a Crossflow.

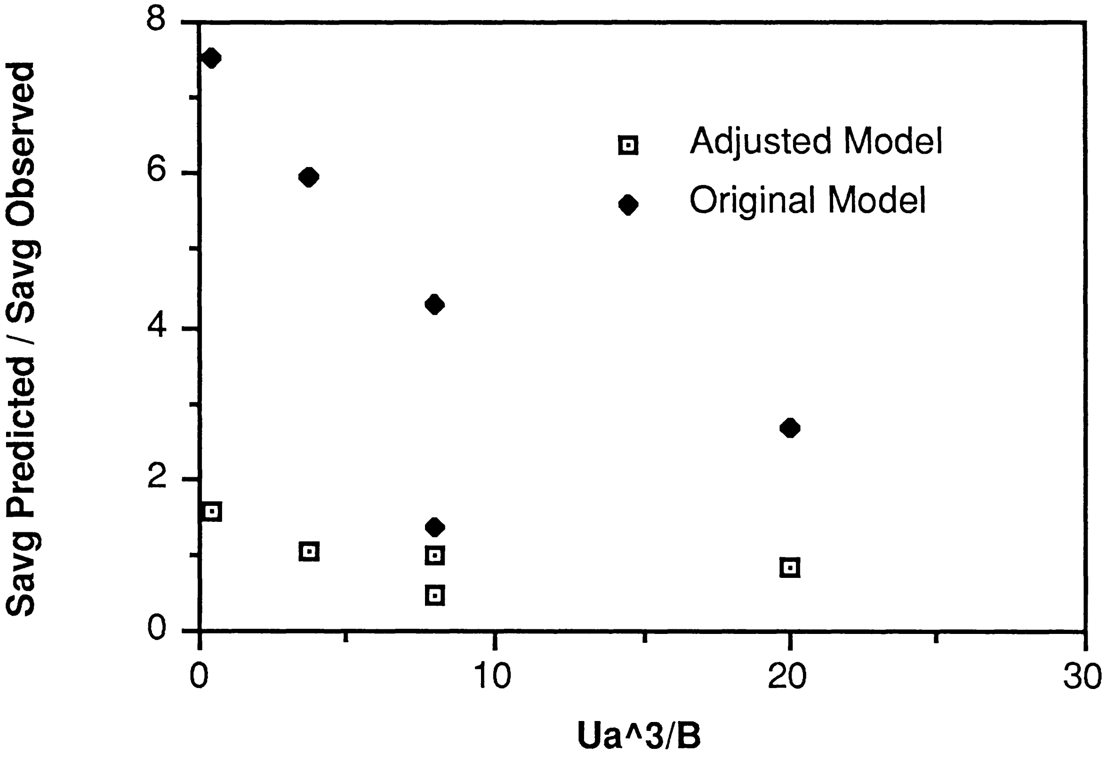


Fig. 17. Comparison of UDKHDEN Predictions of Average Dilution at Free Surface with Data from Isaacson, et al (1978) for Diffuser Discharges in an Unstratified Crossflow.

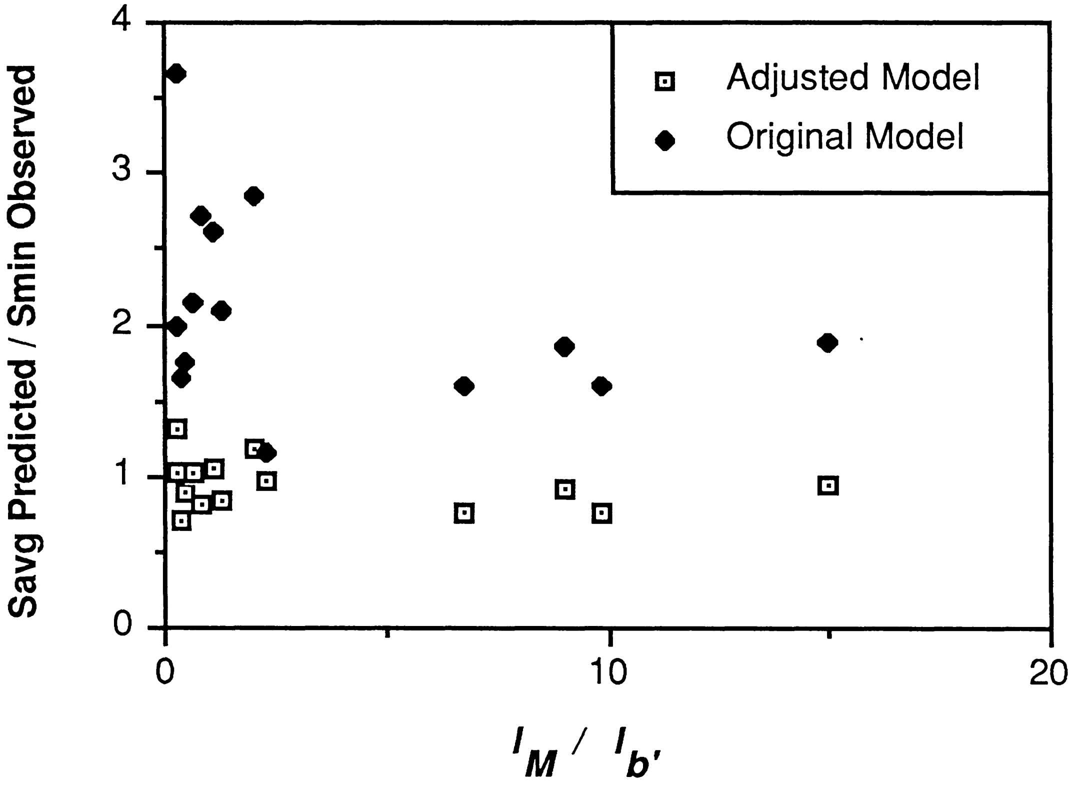


Fig. 18. Comparison of UDKHDEN Predictions of Average Dilution at Maximum Height of Rise with Data from Wright (1977) for Round Buoyant Jets in a Stratified Crossflow.

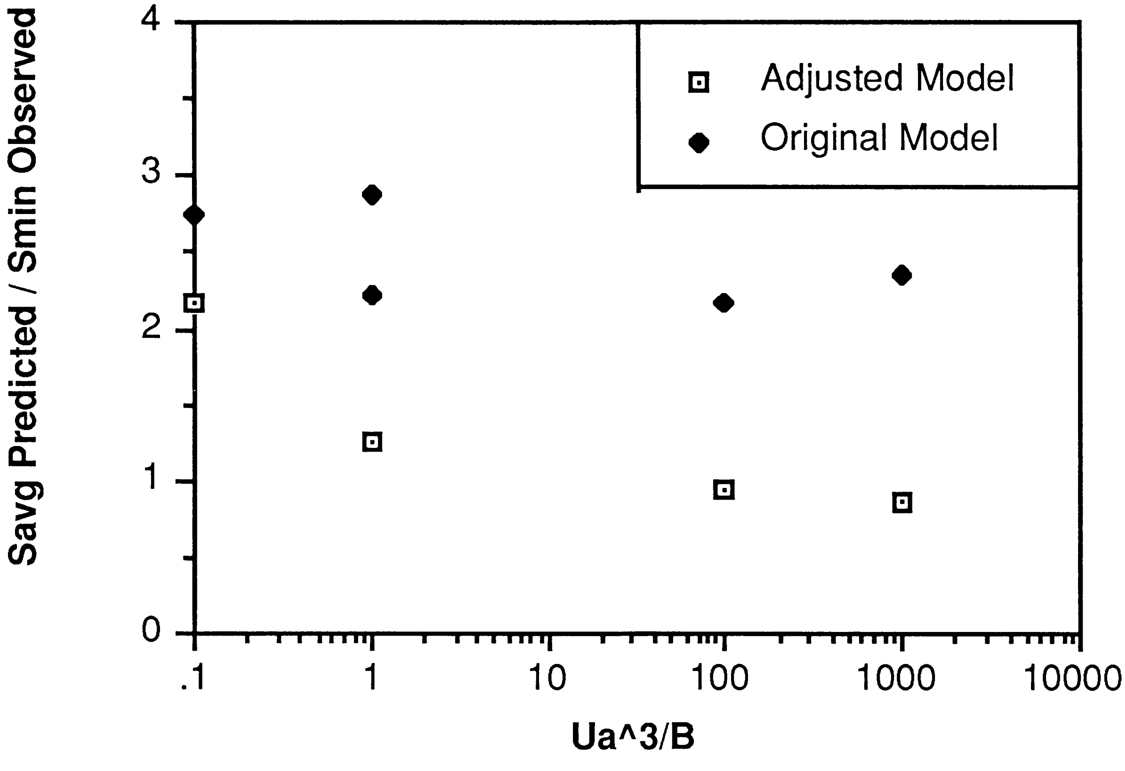


Fig. 19. Comparison of UDKHDEN Predictions of Average Dilution at Maximum Height of Rise with Data from Roberts, et al (1989) for Diffuser Discharges in an Stratified Crossflow.

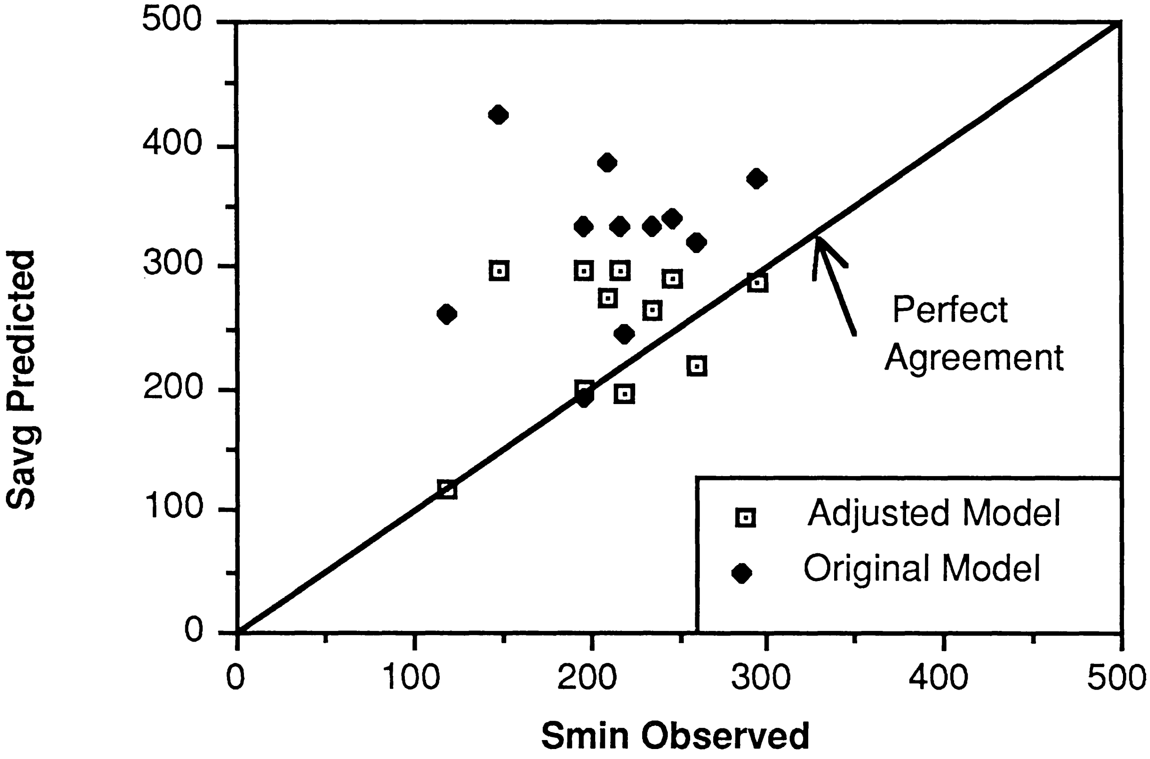


Fig. 20. Comparison of UDKHDEN Predictions of Average Dilution at Maximum Height of Rise with Data from Diffuser Discharges in an Stratified Crossflow, Field Data from Alyeska Ballast Water Diffuser.

AIIM SCANNER TEST CHART # 2

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Greek and Math Symbols

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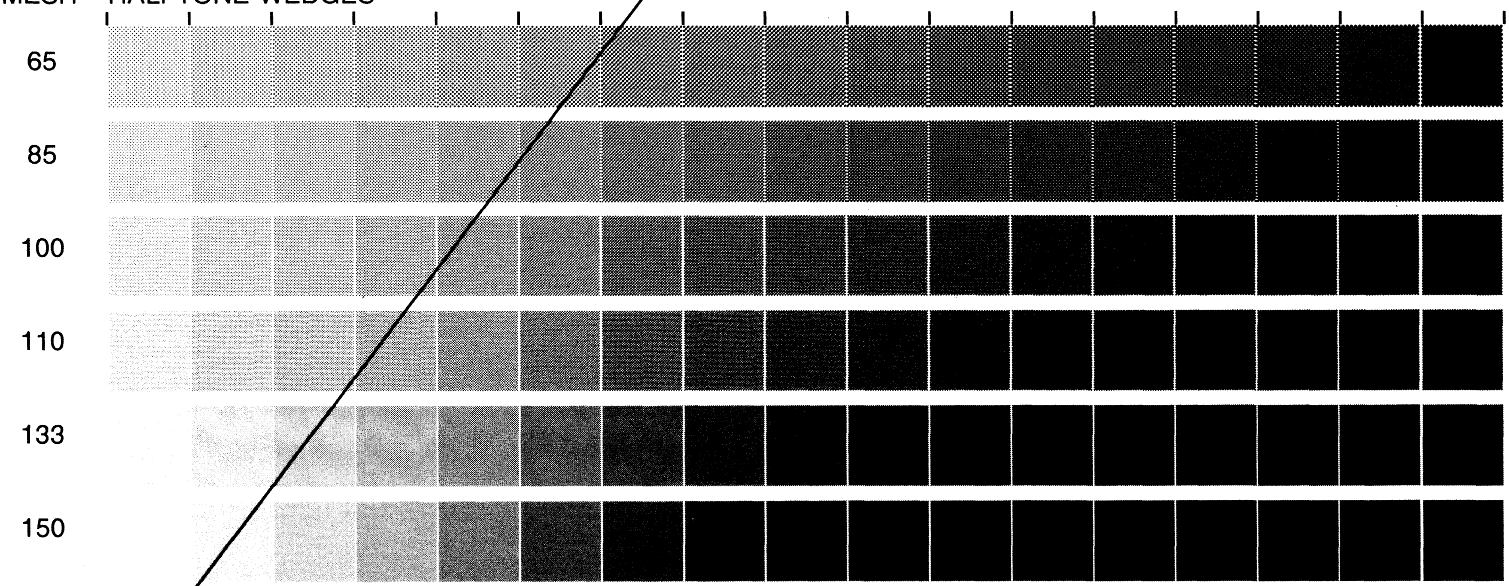
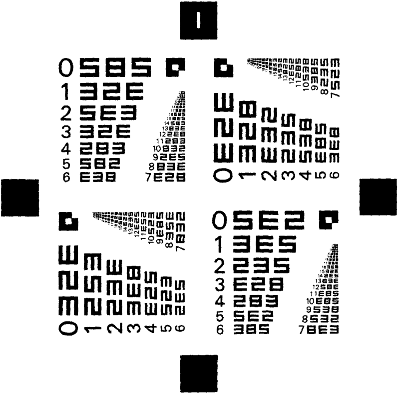
MESH HALFTONE WEDGES



RIT ALPHANUMERIC RESOLUTION TEST OBJECT, RT-1-71



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