Improved Discharge Configurations for Brine Effluents from Desalination Plants

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Abstract: Sea water desalination plants discharge a concentrated brine effluent into coastal waters. Modern, large capacity plants require submerged discharges, in the form of a negatively buoyant jet, that ensure a high dilution in order to minimize harmful impacts on the marine environment. Existing design practice favors a steep discharge angle of 60° above horizontal, a practice based on limited and outdated laboratory data for dilutions at the level of maximum rise. Examination of more recent laboratory data and the parametric application of a jet integral model suggest that flatter discharge angles of about 30–45° above horizontal may have considerable design advantages. These relate to better dilution levels at the impingement location, especially if bottom slope and port height are taken into account, there is better offshore transport of the mixed effluent during weak ambient current conditions, and there is the ability to locate in more shallow water near shore.

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Introduction

An increasing population combined with a growing industrial and agricultural production drives up worldwide water consumption. In arid zones and other water-scarce areas this consumptive demand is increasingly being met through sea water desalination plants. In 2004, the total world installed capacity for sea water distillation was about 22 million m^3/day. Of that, 75% was situated in the Middle East region. Also noteworthy are the increasingly larger plant sizes for individual installations, such as the Al-Jubail, Saudi Arabia plant with 1.1 million m^3/day capacity, or the projected Sydney, Australia plant with 0.5 million m^3/day.

Sea water desalination plants carry, dependent on the process involved (e.g., distillation plants or reverse osmosis), different waste products in the coastal marine environment (Lattemann and Höpner 2003). The most direct effluent is a concentrated salt brine that may also have an elevated temperature. Other waste products relate to chemicals used for biofouling control, scale control, foam reduction, and corrosion inhibition. Depending on the physical and ecological characteristics of the receiving marine waters these substances can have a harmful impact, in particular for large effluent flow rates.

The most common existing discharge practice, especially for smaller plants of old vintage, is a surface discharge directly at the shoreline. Obviously, this design produces very little initial mixing and leads to high concentrations in the negatively buoyant plume that will progress at the bottom of the receiving water.

Much better mixing efficiencies can be attained with submerged high-velocity discharges located further offshore that produce a negatively buoyant jet. There have been very few systematic studies of this discharge configurations, let alone any consistent design recommendations. The earliest study by Zeitoun et al. (1970) investigated experimentally jets in stagnant fluids with angles of 30, 45, 60, and 90° above the horizontal. Based on dilution measurements at the maximum rise level of the jet trajectory these authors concluded that the 60° inclination provided the highest dilution. This suggestion of an apparent "optimal angle of 60°" has been adopted in further experimental studies by Pincince and List (1973), Roberts and Toms (1987), and Roberts et al. (1997) who investigated jet trajectories and mixing under both stagnant and flowing conditions. Based on these results, the 60° design has apparently "been adopted as the de facto standard" (Roberts et al. 1997) for brine discharge installations. This is rather surprising given the considerable uncertainty of the crude dilution measurement technique of Zeitoun et al. with highly variable and erratic results as noted by these authors themselves and later by Roberts and Toms. In more recent experiments, Cipollina et al. (2005) have investigated the 30, 45, and 60° configuration. Unfortunately, their measurements were limited to the jet trajectory, and did not include dilution values that are critical for environmental impact evaluations.

In this technical note a preliminary parametric study of the submerged negatively buoyant jet discharging over a flat or sloping bottom and covering the entire range of angles form 0 to 90° above horizontal is given. A numerical jet integral model is first compared to the limited existing experimental data on jet trajectory and dilutions, all for flat bottom. The model is then applied for the jet behavior over a variable bottom slope using the conditions at the point of jet impingement on the bottom slope as well as the overall trajectory shape as key indicators for discharge design and siting strategies.

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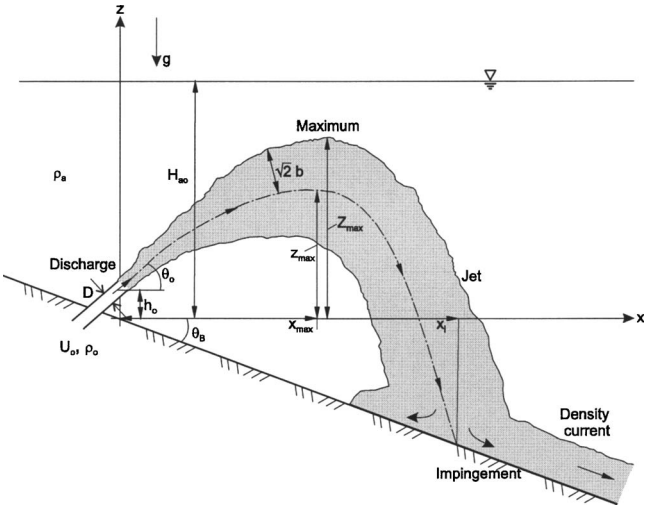

Fig. 1. Schematic side view of negatively buoyant jet discharging into stagnant ambient with sloping bottom

Model Application and Validation

Fig. 1 shows the side view of a negatively buoyant jet discharging into a receiving water body with a local ambient water depth H_{a0} and a sloping bottom with inclination angle θ_B. The port geometry is given by its diameter D, its height above bottom h_0, and its inclination angle θ_0 above the horizontal, pointing offshore. The receiving water is unstratified with a constant density ρ_a and stagnant. The jet has a discharge velocity U_0 and density $\rho_0 > \rho_a$. This gives the following flux variables, the volume flux (discharge) Q_0, momentum flux M_0, and buoyancy flux J_0, respectively

$$Q_0 = U_0 D^2 \pi/4, \quad M_0 = U_0 Q_0, \quad J_0 = g_0' Q_0 \tag{1}$$

in which $g_0' = g(\rho_a - \rho_0)/\rho_a < 0$ is the buoyant acceleration.

The turbulent jet that results from this high velocity discharge first rises to a maximum level and then falls downward under the influence of the negative buoyancy until it impinges on the sloping bottom. Impingement is a complex three-dimensional process, with forward, lateral, and partially reverse spreading, until a density current is formed that propagates downslope.

The geometric and mixing characteristics of the turbulent buoyant jet can be determined by two length scales: the discharge length scale L_Q and the momentum (jet/plume transition) length scale L_M (Wright 1977; Jirka and Doneker 1991)

$$L_Q = Q_0/M_0^{1/2}, \quad L_M = M_0^{3/4}/|J_0|^{1/2} \tag{2}$$

A related nondimensional parameter is the jet densimetric Froude number F_0

$$\mathsf{F}_0 = U_0/\sqrt{|g_0'|D} \tag{3}$$

that is simply proportional to the length scale ratio, $L_M/L_Q = (\pi/4)^{-1/4}\mathsf{F}_0$. Thus, for high Froude number discharges, $\mathsf{F}_0 \gg 1$, L_Q ceases to be a dynamically important parameter, as is well known for many other jet configurations (Jirka 2004). Detailed studies by Zhang and Baddour (1998) for a vertical negatively buoyant jet have shown that the dilution at the maximum level becomes independent of the Froude number when $\mathsf{F}_0 \geq 10$. For smaller Froude numbers the initial dilution becomes lower. A high Froude number discharge, $\mathsf{F}_0 > 10$, is assumed in the following so that L_M is the unique length scale for displaying jet properties.

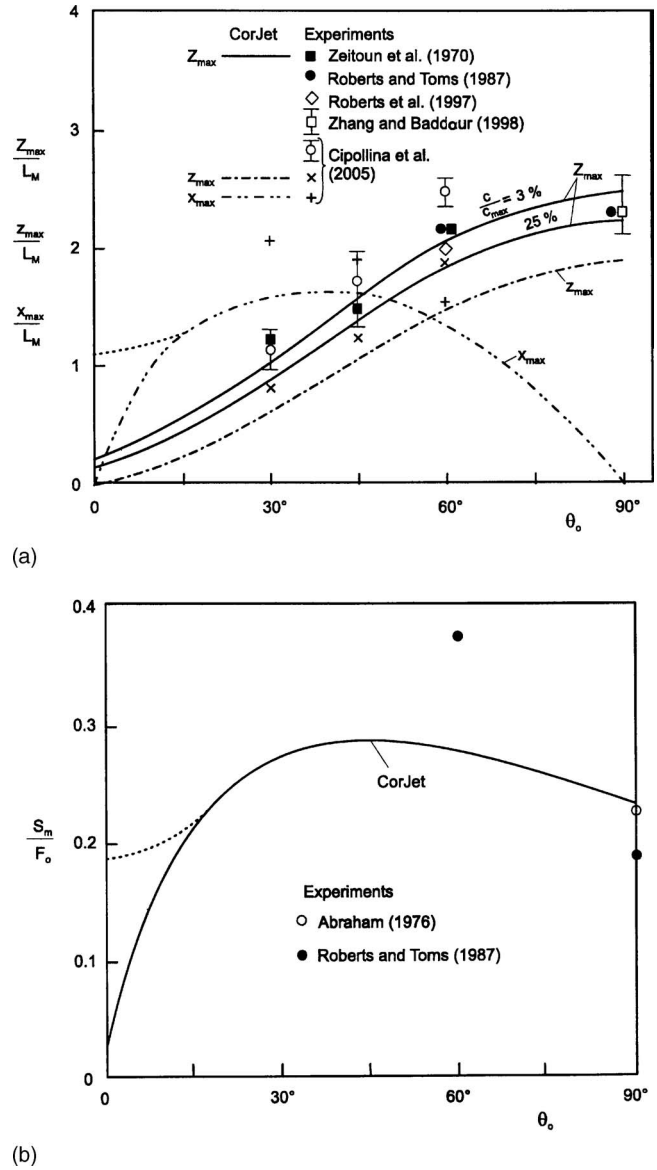

Fig. 2. Jet properties at maximum level of rise. Comparison of CorJet model with experimental data: (a) geometric properties; (b) minimum centerline dilution, both as function of discharge angle θ_0.

The jet integral model CorJet (Jirka 2004) is used in this investigation. CorJet uses a flux conserving integral formulation with an entrainment closure approach that includes the different shear mechanisms leading to turbulent jet/plume entrainment. The model has been extensively validated for the five asymptotic self-similar stages of jet/plume flows as well as for a wide variety of nonequilibrium buoyant jet flows, in stagnant or flowing environments, with or without density stratification, respectively, generally with good comparison to experimental results (Jirka 2004). This prior validation also includes several types of negatively buoyant discharges with or without crossflow. Of the many jet integral models that can be found in the literature, CorJet is clearly the most thoroughly validated one.

Available experimental data of the negatively buoyant jet for the conditions at the maximum level of rise and CorJet predictions are summarized in Fig. 2 as a function of discharge angle

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θ_0. The geometric properties [Fig. 2(a)] relate to the point of the centerline trajectory maximum (x_{max}, z_{max}) as well as the maximum of the upper jet boundary (Z_{max}), as defined in Fig. 1. Most of the experimental data reported concern Z_{max} that is usually taken from visual (photographic) observations. This involves considerable judgment and error due to the type and amount of dye used, the illumination level, and the sensitivity of the recording method. These parameters vary between experiments in an unknown manner. CorJet predictions (always with zero port height, $h_0=0$) are given using two criteria for the "visual boundary," a local concentration level $c/c_{max}=3$ and 25%, respectively, where c_{max} is the centerline concentration at the maximum level. The 25% value corresponds to a jet width $\sqrt{2}b$ where b is the $1/e=37\%$ jet width for the standard Gaussian profile (Jirka 2004). All the data sources (Zeitoun et al. 1970; Roberts and Toms 1987; Roberts et al. 1997; Zhang and Baddour 1998; Cipollina et al. 2005) are in reasonable agreement with this range of predictions, the only exception being Cipollina et al.'s data for $\theta_0=60°$. The data by Roberts and Toms have been corrected for their reported port height h_0. Also note that Zhang and Baddour give a wide range $Z_{max}=1.7-3.2$ [not included in Fig. 2(a)] for a summary of several earlier investigations for the vertical $(\theta_0=90°)$ jet that scatters widely about the model predictions (see also Jirka 2004). The only data reported on the centerline position of the trajectory maximum are the recent ones by Cipollina et al., once again with reasonable agreement. (The dotted line for x_{max} for $\theta_0 \to 0°$ indicates the fact that for small discharge angles the horizontal location of the jet boundary maximum Z_{max} differs greatly from that of z_{max}; see Fig. 1).

The normalized minimum (centerline) dilution S_m/F_0 at the maximum rise level is compared in Fig. 2(b). The CorJet prediction indicates a flat maximum $S_m/\mathsf{F}_0 \approx 0.28-0.29$ over the angle range $\theta_0=30-60°$. For a vertical discharge, the predicted values $S_m/\mathsf{F}_0=0.24$ are in reasonable agreement with 0.23 reported by Abraham (1967) and 0.19 by Roberts and Toms. For $\theta_0=60°$, however, Roberts and Tom's data point shows a rather strong increase to $S_m/\mathsf{F}_0=0.38$, much more than is predicted by CorJet. Not included in Fig. 2(b) are the data by Zeitoun et al. that would lie much higher ($S_m/\mathsf{F}_0=0.55$, 0.42, and 0.36 for $\theta_0=60$, 45, and 30°, respectively), but appear erroneous in hindsight as has been commented on in the "Introduction."

The conditions at the impingement point for a discharge over flat bottom $(\theta_B=0°)$ are summarized in Fig. 3. The location of impingement x_i/L_M [Fig. 3(a)] is well predicted by CorJet when compared to the data of Roberts et al. and Cipollina et al. Two predicted values for the dilution impingement dilutions are plotted in Fig. 3(b): the minimum dilution S_i at the level $z=0$ and the corresponding bulk (flux averaged) dilution $\bar{S}_i \cong 1.7S_i$ (Jirka 2004). Since the impingement process represents an additional mixing mechanism, actual observed dilutions should probably lie between these limits. The observations shown in Fig. 3(b) generally support that expectation, even though there is considerable inconsistency between that for 60° by Roberts and Toms using a suction technique and by Roberts et al. using a laser-induced fluorescence (LIF) visualization for dilution measurements. Unfortunately, the recent study of Cipollina et al. did not include dilution measurements.

In summary, the CorJet model appears reasonably validated with available experimental data sources. The inconsistency among different experimental studies is larger than the disagreement with the numerical model. Deficiencies in the experimental setup (e.g., flat bottom with possible recirculation effects after impingement; limited tank sizes) and in the measurement techniques (e.g., ambiguities in visual determinations; incomplete suction sampling in view of jet fluctuations) are the source of these inconsistencies. Considering the other validation cases (trajectories and dilutions) for negatively buoyant jets with or without crossflow that have been reported in Jirka (2004) it is therefore concluded that CorJet can be used as a tool for a preliminary parametric study of negatively buoyant jet discharge configurations covering a wider range of possible site conditions.

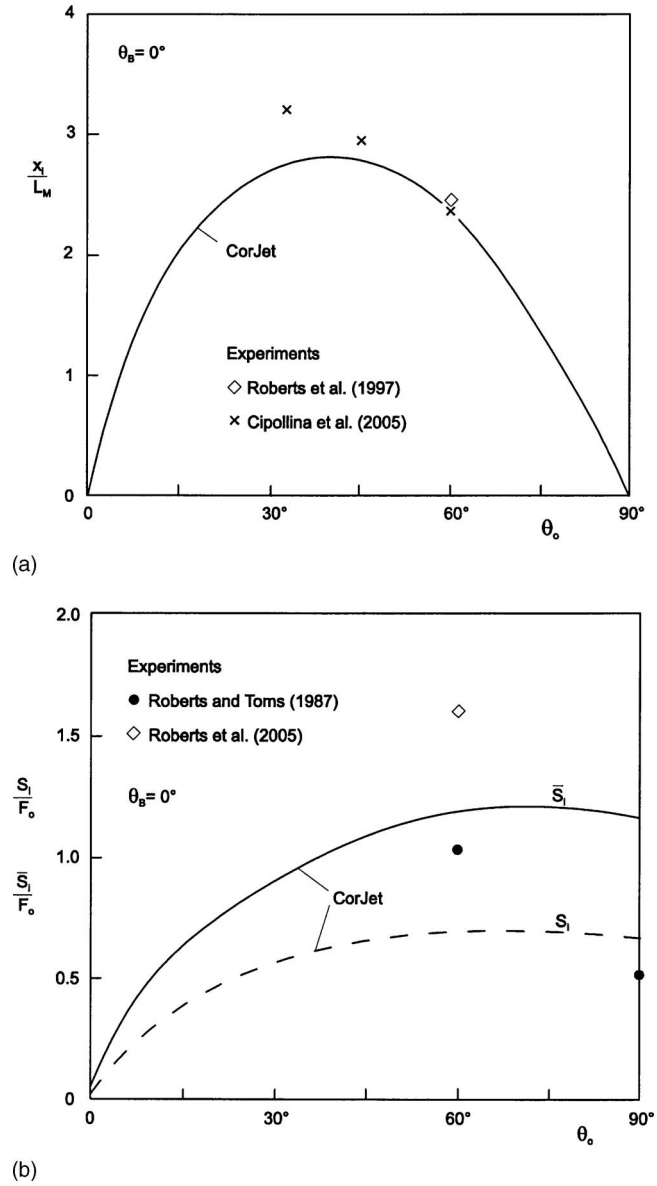

Fig. 3. Jet properties at impingement point for zero offshore slope $(\theta_B=0°)$: (a) location x_i/L_M; (b) dilution levels, both as function of discharge angle θ_0

Toward Design Optimization

The CorJet model is applied over the entire range of discharge angles $0° \leqslant \theta_0 \leqslant 90°$ and for different offshore bathymetries, θ_B from 0 to 30°, in order to evaluate possible design improvements. Fig. 4(a) shows the normalized centerline trajectories, z/L_M versus x/L_M, and their intersections with the possible bottom slopes.

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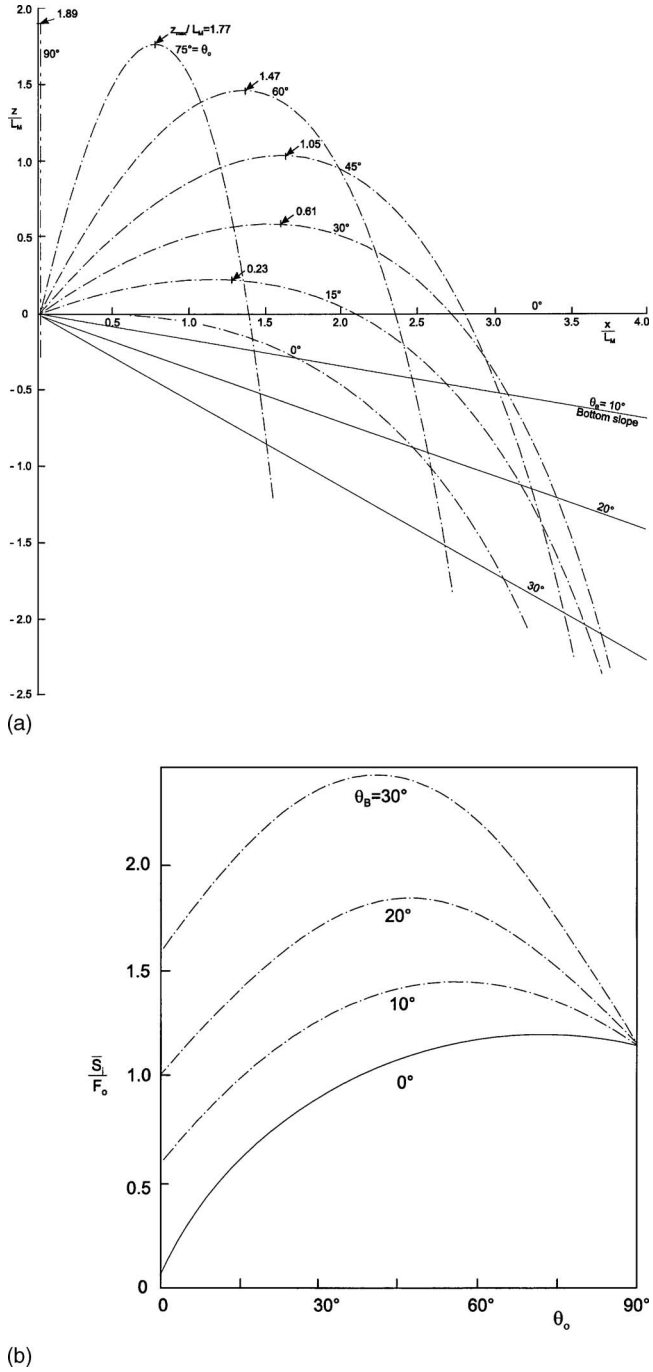

Fig. 4. Negatively buoyant jet behavior for complete range of discharge angles $0° \leqslant \theta_0 \leqslant 90°$ and with variable offshore slopes θ_B from 0 to 30°. A zero discharge height, $h_0=0$, is assumed: (a) jet trajectories; (b) bulk dilutions as function of discharge angle θ_0.

The discharge range θ_0 from 30 to 45° provides the largest offshore impingement location, x_i/L_M.

The dilutions at the maximum rise level, S_m/F_0, have already been given in Fig. 2(b). CorJet predicts an optimal value of 45°, but a wide flat plateau between 30 and 60°. From the viewpoint of environmental impacts the dilution at the impingement point is important (e.g., for exposure of benthic organisms). Fig. 4(b) gives the predicted bulk dilution $\bar{S}_i/\mathsf{F}_0$ as a useful measure for that impact. For a flat bottom (and with zero discharge height) the maximum dilution is attained in the range θ_0 from 60 to 75°, for moderate slopes (10–20°) the maximum is found at about 45–60°, while for strong slopes (30°) this shifts to a discharge angle between 30 and 45°. Rather flat plateau values apply in all of these cases. Note that increasing discharge heights h_0 have a qualitatively similar effect to increasing offshore slopes!

These results, together with several other siting factors, lead to the conclusion that the discharge angle range of 30–45° appears preferable for negatively buoyant jet discharges located in a near-shore environment. This is for the following reasons: (1) it produces the highest dilutions at the point of maximum rise [Fig. 2(b)]; (2) it provides high dilutions at the impingement point [Fig. 4(b)], especially so if sufficient offshore slope is given or, equivalently, if the discharge port is raised above the bottom; (3) it locates the jet impingement region further offshore [Fig. 4(a)] and, because of the flatter impingement angle, provides more offshore momentum for the ensuing bottom density current; and (4) it provides considerably flatter trajectories [Fig. 4(a)], thus allowing the discharge to be located more near shore in shallower water depth (see Fig. 1).

The following design procedure is recommended for a discharge with given plant flowrate Q_0 and discharge density ρ_0 (hence, given g_0' and J_0) located on an offshore slope with angle θ_B:

1. Choose a sufficiently high Froude number design, $\mathsf{F}_0 \geqslant 10$, with the recommended range $\mathsf{F}_0=20-25$. (Note that higher values imply larger pumping head losses.) With $U_0=Q_0/(D^2\pi/4)$ in Eq. (3), the required port diameter is computed as $D=[(4/\pi)Q_0/(\mathsf{F}_0|g_0'|^{1/2})]^{2/5}$ as well as the values of M_0 [Eq. (1)] and L_M [Eq. (2)];
2. Choose a discharge angle $\theta_0=45°$ for weaker bottom slopes ($\theta_B \leqslant 15°$) or $\theta_0=30°$ for stronger slopes (see step 5 for consideration of port height);
3. Evaluate jet geometry using Figs. 2(a) and 4(a), respectively;
4. Select the offshore location for the discharge in terms of a local water depth H_{a0} (Fig. 1) which guarantees that the upper jet boundary $Z_{\max} \leqslant 0.75\ H_{a0}$, in order to prevent dynamic surface interference;
5. Choose a port height $h_0=0.5-1.0$ m. [In a second iteration, the effect of the port height can be considered as an added slope angle when using Fig. 4(a) in steps 3 and 4]; and
6. Evaluate the concentration of key effluent parameters at the impingement point using Fig. 4(b) and compare them with applicable environmental criteria or regulations. If the dilution effect is insufficient, a design iteraction is necessary.

The above procedure and illustrations apply to a discharge into stationary, nonflowing ambient conditions that are typically the most limiting for dilution. Detailed application of the CorJet model is needed for cases of flowing environment, leading to more complex three-dimensional trajectories. Furthermore, in the case of large volume discharges it may be necessary to distribute the flow over several ports, i.e., a multiport diffuser, a situation that can also be predicted by CorJet (Jirka 2006). The CorJet model can be used embedded within the CORMIX expert system (Jirka et al. 1996) which allows for the prediction of not only the buoyant jet phase, but also of other mixing processes, such as the formation of the bottom density currents, boundary interactions, and transitions to far-field mixing. A special version DCORMIX for brine discharges from desalination plants (Del Bene et al. 1994), or for sediment currents (Doneker et al. 2004), which includes the dynamics of the downward propagating density current, can be used for a complete environmental impact evaluation.

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Given the paucity of reliable experimental data (notably dilution measurements) for the entire negatively buoyant jet including sloping bottom interaction, the above recommendations are considered preliminary. To further corroborate them, a vigorous program of experimental studies using modern field-resolving techniques, such as LIF and particle image velocimetry (PIV), supported by detailed computational fluid mechanics (CFD) modeling, is called for in several laboratories. This appears crucial in view of ongoing design and siting activities for numerous new desalination plants all around the globe.

Notation

The following symbols are used in this technical note:

b = jet width;
D = port diameter;
F_0 = jet densimetric Froude number [Eq. (3)];
g = gravitational acceleration;
g_0' = buoyant acceleration at discharge;
H_{a0} = ambient water depth at discharge;
h_0 = height of discharge port;
J_0 = discharge buoyancy flux;
L_M = momentum length scale [Eq. (2)];
L_Q = discharge length scale [Eq. (2)];
M_0 = discharge momentum flux;
Q_0 = discharge flowrate;
S_i = minimum dilution at bottom impingement;
$\bar{S}_i$ = average dilution at bottom impingement;
S_m = minimum dilution at maximum rise level;
U_0 = port discharge velocity;
x_i = horizontal position of impingement point;
x, z = horizontal, vertical coordinates;
$x_{\max}, z_{\max}$ = horizontal, vertical position of maximum rise;
$Z_{\max}$ = maximum vertical position of upper jet boundary;
θ_B = angle of bottom slope;
θ_0 = port discharge angle above horizontal;
ρ_a = ambient density; and
ρ_0 = discharge density.

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