



Modelling and environmentally sound management of brine discharges 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 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 that is based on very limited laboratory data on dilutions at the level of maximum rise. However, examination of more recent laboratory data and the parametric application of CorJet, a jet integral model within the CORMIX expert system suggest that flatter discharge angles of about 30° to 45° above horizontal may have considerable design advantages. These relate to better dilution levels at the impingement location, especially if bottom slope on port height are taken into account, better offshore transport of the mixed effluent during weak ambient current conditions, and the ability to locate in more shallow water near-shore.

Keywords: Brine disposal; Negatively buoyant jets; Mixing; Density

1. Introduction

Seawater desalination contributes positively to the environment (e.g. reducing exploitation of non-renewable drinking water sources) and to humanity, but at the same time may cause negative local impacts on the environment. Besides the impacts regarding energy consumption and land use, the major impact is related to the marine environment, especially to coastal water

quality [1]. Seawater desalination plants carry a number of waste products into the coastal ocean [2]. The most direct product is a concentrated salt brine discharge (Fig. 1) that may also have an elevated turbidity and temperature (latter most notable for plants with thermal desalination techniques such as multistage flash (MSF)). Other waste products relate to chemicals used for biofouling control (e.g. chlorine), scale control (antiscalants), foam reduction, and corrosion inhibition. Depending on the physical and ecological characteristics of the receiving waters, these

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Fig. 1. Al Ghubrah desalination plant (largest in Oman, production capacity 191,000 m³/d): Brine waste discharge through an open channel at the beach into the Gulf of Oman (photo: H.H. Al-Barwani).

substances can have a harmful impact on the local environment. Especially vulnerable are areas such as mangrove forests, salt marshes, coral reefs, or generally, low energy intertidal areas, while exposed rocky coasts with high energy wave action may be less susceptible [3]. Enclosed seas, like the gulf or the red-sea have limited water exchange capacities and are generally shallow and less energetic, thus more sensitive to effluent discharges. Potential impacts on local fisheries or tourism resources with considerable economic consequences are some of the conflict points that arise when planning desalination plants. In particular, increased plant capacities raise the impact concentrations of effluent constituents to levels that can become harmful to the marine environment.

Genthner [4] notes that there is increased public concern and scientific awareness on the environmental impact of desalination plants. For example, objections in the USA regarding environmental impacts have already become key

issues for project permits, often considerably influencing plant commissioning and design [5]. The necessity of sound environmental impact studies and public involvement will further increase because several countries define new regulatory strategies on protection and conservation of the marine environment [6]. From a regulatory viewpoint, many countries (e.g. USA or European Union countries) restrict the levels of aquatic pollutants both at the discharge point (“effluent standards”, e.g. chlorine, 7.5 µg/L, US-EPA) as well as within the receiving water (“ambient standards”). The former encourage source control principles and treatment and recycling technologies. The latter demand for the consideration of the ambient response often associated with the concept of the “mixing zone”, an allocated impact zone in which the numerical water quality standards can be exceeded [7]. In order to meet these regulations, optimized high efficiency mixing designs are needed for the brine effluent discharges (Fig. 2(b)), which need

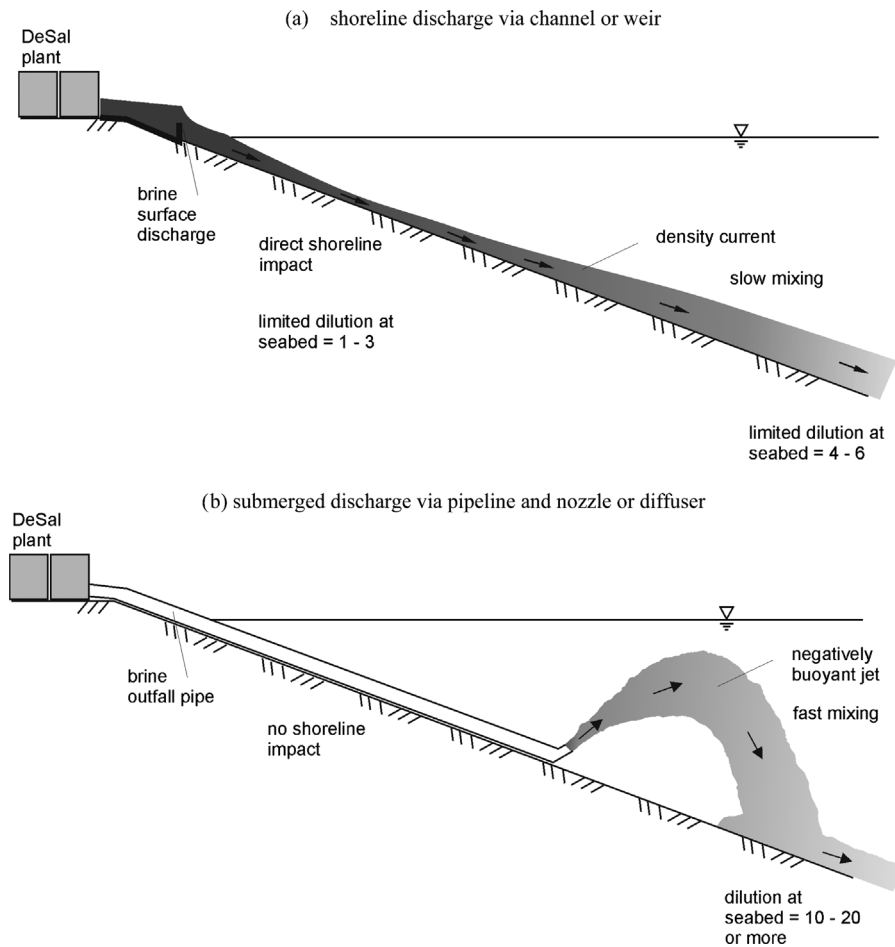


Fig. 2. Discharge strategies for negatively buoyant effluents [8]. (a) Shoreline discharge via channel or weir, (b) submerged discharge via pipeline and nozzle or diffuser.

to be embedded in a sustainable concentrate management plan. Together these technologies can be considered as concentrate management technologies.

However, discharge designs are often not optimized regarding environmental impacts nor operational needs. In addition, regulations often lack clear guidance regarding the control of ambient standards or environmental impact studies [7]. Consequently it can be observed that the majority of discharges, especially in the Middle East North African (MENA) region, are surface discharges directly at the coastline (Fig. 2(a))

with very low mixing capacities. Similar design deficiencies also apply for intakes, that can be harmful to fish or other species. In addition, there is a potential for recirculation to the plant intake, reducing overall system efficiency especially for larger plants or plant complexes.

Scientifically validated and efficient planning tools in the form of predictive models and expert system design guides are needed to assist desalination plant designers and plant managers in designing and operating the intake-treatment-outfall scheme so that environmental impacts on the marine environment can be controlled and

minimized. The preliminary results of the development of such tools are presented as follows.

2. State of the art — previous works

The high salt concentration and the residual concentrations of added process chemicals of the discharge water may harmfully impact organisms near the outfall that cannot tolerate either high concentration levels or fluctuations in levels of these substances. In general there is little systematic information available on the impacts of desalination plants on the marine environment. Even less data is available to quantify such impacts for regulatory or design purposes. This is similar to other discharge regulations where specification of where in the water body the environmental quality standards apply are missing [7]. Only an at least basic knowledge of the resulting concentration distributions allows for an impact assessment and design optimization.

The concentration distribution depends on the siting of the outfall, the amount of mixing and the transport capacities of the prevailing currents. The former two are major design parameters, whereas the latter can only be influenced indirectly via an appropriate siting.

Problem complexities are related to the mixing calculation. Due to their high salinity, the discharges from desalination plants are more dense than seawater. Even brine with elevated temperature from plants with thermal desalination processes is significantly denser than seawater. If discharged directly the effluent sinks to the bottom, and spreading horizontally following the slope of the sea bathymetry. Mixing is very low during that spreading process thus causing potential adverse impacts to benthic communities, besides the impacts on other biota, including plankton, fish, and marine mammals. The problem becomes even more complex for discharges from cogenerating plants consisting on a thermal electric power plant and a desalination plant with thermal desalination technologies, where the

desalination brine is generally blended with the cooling water discharge before entering the sea. In these cases (depending on the cooling water flow) the resulting plume may be always or intermittent positive buoyant or with neglectable density difference.

Occurring density differences depend on salinity but also temperature differences and are dominating the mixing processes. Common technological measures to reduce density differences and to control concentration distributions are outfalls with efficient mixing devices as shown in Fig. 2(b). High mixing efficiencies can be attained with submerged high-velocity discharges located offshore that produce a negatively buoyant jet. Obviously, a surface discharge directly at the shoreline 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. In difference to buoyant discharges (i.e. treated domestic wastewater) there have been very few systematic studies of negative buoyant brine discharges and discharge configurations, let alone any consistent design recommendation.

The earliest study by Zeitoun et al. [9] experimentally investigated 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 [10], Roberts and Toms [11] and Roberts et al. [12] 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” [12] for brine discharge installations. This is rather surprising given the considerable uncertainty of the crude dilution measurement technique of Zeitoun et al. [9] with highly variable and erratic results as noted

by these authors themselves and later by Roberts and Toms [11]. In more recent experiments, Cipollina et al. [13] 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. Furthermore all studies predict only near-field (initial mixing until impingement with boundary) characteristics and do not include the intermediate field (boundary interaction and density current development) or far-field characteristics (density currents and passive mixing and transport) of the brine. For the far-field related impacts the discharge region sea currents and salinity distributions need to be predicted in addition. Further complexities to near and far-field regions are related to very shallow water conditions (e.g. Arabian Gulf is only 40 m deep but some 250 km wide and 1000 km long) and extremely high evaporation rates.

Although there are several massive developments in this scientific area there are still substantial deficits in the basic understanding and in practical implementation, especially for negatively buoyant effluents and their complex interactions with boundaries and their unknown interplay. Given the paucity of reliable experimental data (notably dilution measurements) for the entire negatively buoyant jet including sloping bottom interaction, existing design recommendations [16] are considered preliminary. To further corroborate them, a vigorous program of experimental studies using modern field-revolving techniques, such as laser induced fluorescence (LIF) and particle-image-velocimetry (PIV), supported by detailed computational fluid dynamics (CFD) modeling, is called for in several laboratories. This appears to be crucial in view of ongoing design and siting activities for numerous new desalination plants all around the globe.

A commonly used model for wastewater discharges is CORMIX (Cornell Mixing Zone Expert System, see www.cormix.info) which is used

worldwide in engineering and research projects especially for planning and design purposes belonging the near-field characteristics of mainly positive discharges into water bodies. Its major application area is for discharges from wastewater sources or from industrial treatment plants, including cooling water discharges. The model has been extensively validated and is equipped with a wide range of extensive pre- and post-processing routines for data preparation, result visualization and design recommendation [14,15]. Thus the model already allows for design purposes for positive buoyant effluents from cogeneration plants with large cooling water flows (approx. above 50 m³/s). Special preliminary extensions of CORMIX have been built for negative buoyant brine discharges under an EPRI (Electric Power Research Institute, USA) contract in the early 1990's [17] and for sediment density currents from dredging operations under a U.S. Army Corps of Engineers contract [18]. However, these versions have not undergone extensive validation, do not contain appropriate pre- and post-processing, and are missing design optimization guidelines. Currently, no flexible and widely validated predictive tool exists to deal with the special geometrical aspects of such brine discharges, encompassing both the initial negatively-buoyant free jets and the final bottom-hugging density current plumes.

In the following a preliminary parametric study of the submerged negatively buoyant jet discharging over a flat or sloping bottom and covering the entire range of angles from 0° to 90° above horizontal is given. The CORMIX submodel CorJet [15], 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 overall trajectory shape as key indicators for discharge design and siting strategies. Finally recommendations

are given for the subsequent modeling of the intermediate and far-field regions and the brine discharge assessment.

3. Brine discharge model

Fig. 3 shows the side view of a negatively buoyant jet discharging into a receiving water body with a local ambient water depth H_{ao} and a sloping bottom with inclination angle θ_B . The port geometry is given by its diameter D , its height above bottom h_o , and its inclination angle θ_o 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_o and density $\rho_o > \rho_a$. This gives the following flux variables, the volume flux (discharge) Q_o , momentum flux M_o , and buoyancy flux J_o , respectively,

$$Q_o = U_o D^2 \pi / 4, \quad M_o = U_o Q_o, \quad J_o = g'_o Q_o \quad (1)$$

in which $g'_o = g(\rho_a - \rho_o)/\rho_a < 0$ 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 [19,20]

$$L_Q = Q_o / M_o^{1/2}, \quad L_M = M_o^{3/4} / |J_o|^{1/2} \quad (2)$$

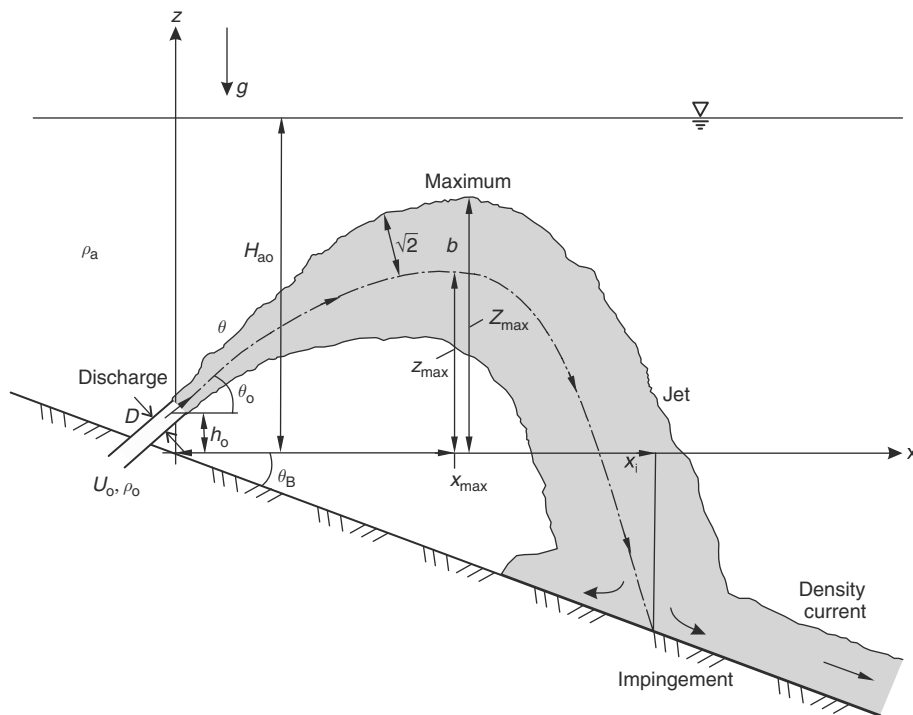


Fig. 3. Schematic side view of negatively buoyant jet discharging into stagnant ambient with sloping bottom [16].

A related non-dimensional parameter is the jet densimetric Froude number F_o

$$F_o = U_o / \sqrt{|g'_0| D} \quad (3)$$

that is simply proportional to the length scale ratio, $L_M/L_Q = (\pi/4)^{-1/4} F_o$. Thus, for high Froude number discharges, $F_o \gg 1$, L_Q ceases to be a dynamically important parameter, as is well known for many other jet configurations [15]. Detailed studies by Zhang and Baddour [21] for a vertical negatively buoyant jet have shown that the dilution at the maximum level becomes independent of Froude number when $F_o \geq 10$. For smaller Froude numbers the initial dilution becomes lower. A high Froude number discharge, $F_o > 10$, is assumed in the following so that L_M is the unique length scale for displaying jet properties.

The jet integral model CorJet [15] 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 non-equilibrium buoyant jet flows, in stagnant or flowing environments, with or without density stratification, respectively, generally with good comparison to experimental results [15]. 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. 4 as a function of discharge angle θ_o . The geometric properties (Fig. 4(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. 3.

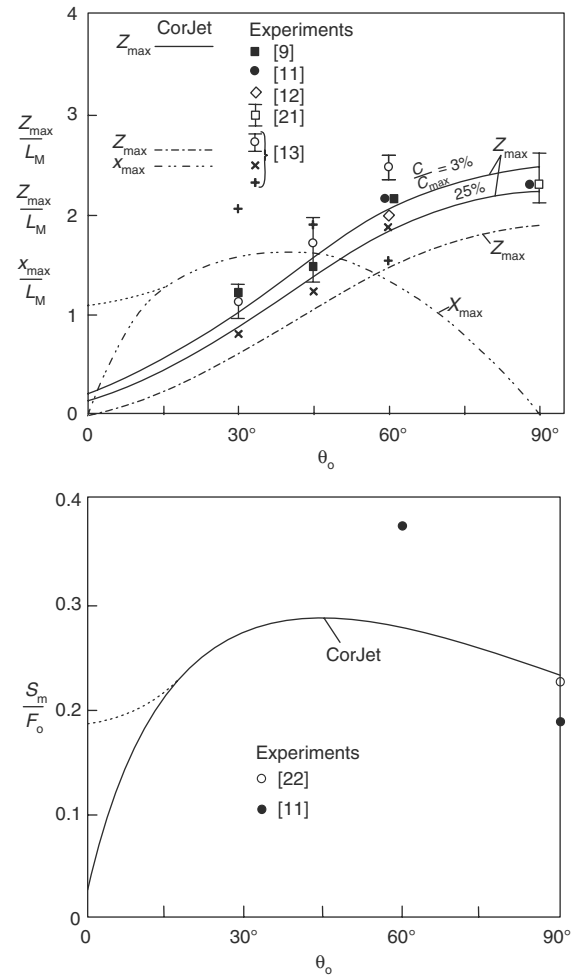


Fig. 4. Jet properties at maximum level of rise. Comparison of CorJet model with experimental data. (a) Geometric properties, (b) Minimum centerline dilution, both as a function of discharge angle θ_o [16].

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, $h_o = 0$) 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 [15]. All the data sources [11–13,19,21] are in reasonable agreement with this range of predictions, the only exception being Cipollina et al.'s [13] data for $\theta_o = 60^\circ$. The data by Roberts and Toms have been corrected for their reported port height h_o . Also note that Zhang and Baddour gives a wide range $Z_{\max} = 1.7$ to 3.2 (not included in Fig. 4(a)) for a summary of several earlier investigations for the vertical ($\theta_o = 90^\circ$) jet that scatters widely about the model predictions [15]. The only data reported on the centerline position of the trajectory maximum are the recent ones by Cipollina et al. [13], once again with reasonable agreement. (The dotted line for x_{\max} for $\theta_o \rightarrow 0^\circ$ 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} ; Fig. 3).

The normalized minimum (centerline) dilution S_m/F_o at the maximum rise level are compared in Fig. 4(b). The CorJet prediction indicates a flat maximum $S_m/F_o \approx 0.28$ to 0.29 over the angle range $\theta_o = 30^\circ$ to 60° . For a vertical discharge, the predicted values $S_m/F_o = 0.24$ are in reasonable agreement with 0.23 reported by Abraham [22] and 0.19 by Roberts and Toms [11]. For $\theta_o = 60^\circ$, however, Roberts and Tom's data point shows a rather strong increase to $S_m/F_o = 0.38$, much more than is predicted by CorJet. Not included in Fig. 2(b) are the data by Zeitoun et al. [9] that would lie yet much higher ($S_m/F_o = 0.55$, 0.42, and 0.36 for $\theta_o = 60^\circ$, 45° and 30° , respectively), but appear erroneous in hindsight as has been commented in the introduction.

The conditions at the impingement point for a discharge over flat bottom ($\theta_B = 0^\circ$) are summarized in Fig. 5. The location of impingement x_i/L_M (Fig. 5(a)) is well predicted by CorJet when compared to the data of Roberts et al. [12]

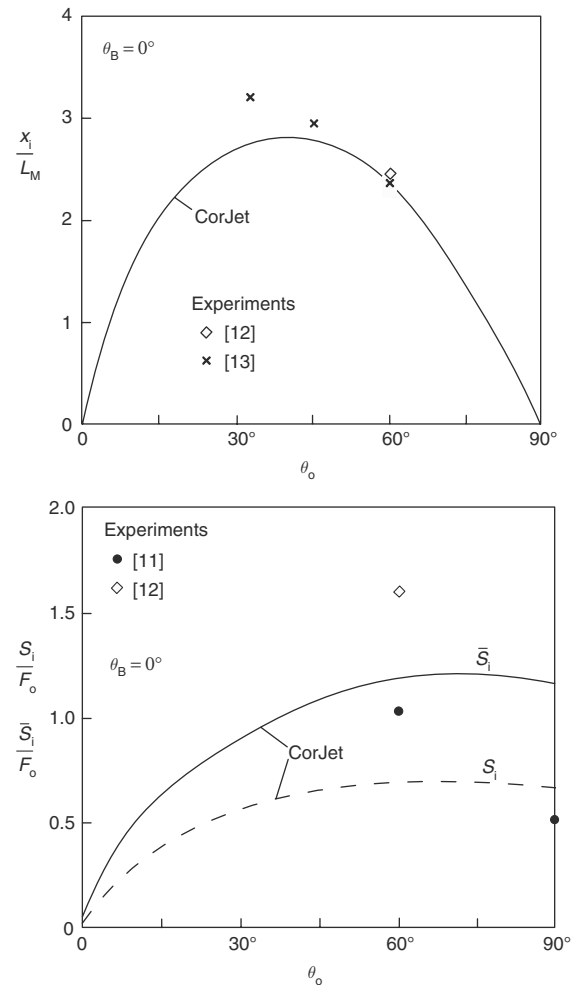


Fig. 5. Jet properties at the impingement point for zero offshore slope ($\theta_B = 0^\circ$). (a) Location x_i/L_M , (b) Dilution levels, both as a function of discharge angle θ_o [14].

and Cipollina et al. [13]. Two predicted values for the dilution impingement dilutions are plotted in Fig. 5(b) the minimum dilution S_i at the level $z = 0$ and the corresponding bulk (flux averaged) dilution $\bar{S}_i \cong 1.7 S_i$ [15]. Since the impingement process represents an additional mixing mechanism, actual observed dilutions should probably lie between these limits. The observations shown in Fig. 5(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. [12] using an LIF visualization for dilution measurements. Unfortunately, the recent study of Cipollina et al. [13] 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 set-up (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 [15] 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.

4. Brine discharge design

The CorJet model is applied over the entire range of discharge angles $0^\circ \leq \theta_o \leq 90^\circ$ and for different offshore bathymetries, θ_B from 0° to 30° , in order to evaluate possible design improvements. Fig. 6 shows the normalized centerline trajectories, z/L_M versus x/L_M , and their intersections with the possible bottom slopes. The discharge range θ_o from 30° to 45° provides the largest offshore impingement location, x_i/L_M .

The dilutions at the maximum rise level, S_m/F_o , have already been given in Fig. 4(b). CorJet predicts an optimal value of 45° , but a wide flat plateau between 30° and 60° . Important from the viewpoint of environmental impacts is the dilution at the impingement point (e.g. for exposure of benthic organisms). Fig. 7

gives the predicted bulk dilution \bar{S}_i/F_o 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_o from 60° to 75° , for moderate slopes (10° to 20°) the maximum is found at about 45° to 60° , while for strong slopes (30°) this shifts to a discharge angle between 30° to 45° . Rather flat plateau values apply in all of these cases. Note that increasing discharge heights h_o have a qualitatively similar effect as increasing offshore slopes!

These results, together with several other siting factors, lead to the conclusion that the discharge angle range of 30° to 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. 4(b)). (2) It provides high dilutions at the impingement point (Fig. 7), 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. 6) and, because of the flatter impingement angle, provides more offshore momentum for the ensuing bottom density current.

It provides considerably flatter trajectories (Fig. 6), thus allowing the discharge to be located more near-shore in smaller water depth (Fig. 3).

Even under these simple conditions the following design procedure can already be recommended for a discharge with given plant flowrate Q_o and discharge density ρ_o (hence, given g'_o and J_o) located on an offshore slope with angle θ_B :

- (1) Choose a sufficiently high Froude number design, $F_o \geq 10$, with the recommended range $F_o = 20$ to 25 . (Note that higher values imply larger pumping head losses.) With $U_o = Q_o/(D^2\pi/4)$ in Eq. 3, the required port diameter is computed as $D = \left[(4/\pi) Q_o / (F_o |g'_o|^{1/2}) \right]^{2/5}$ as well as the values M_o Eq. (1) and L_M Eq. (2).

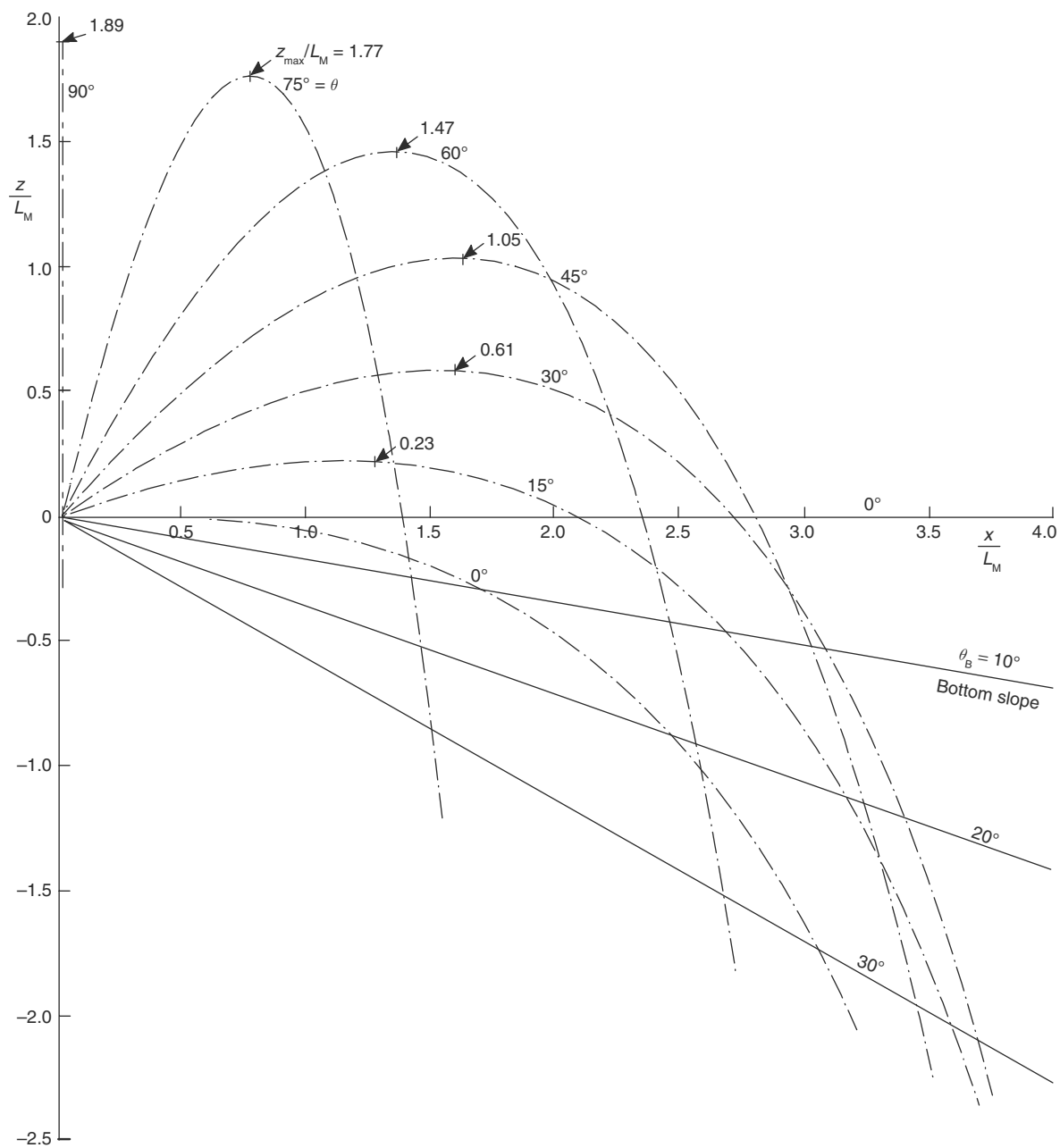


Fig. 6. *Jet trajectories*: Negatively buoyant jet behavior for complete range of discharge angles $0^\circ \leq \theta_o \leq 90^\circ$ and with variable offshore slopes θ_B from 0° to 30° . A zero discharge height, $h_o = 0$, is assumed [16].

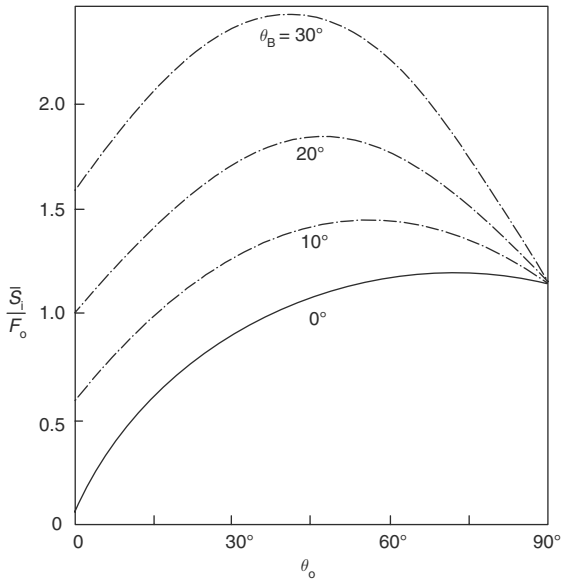


Fig. 7. Bulk dilutions as a function of discharge angle θ_o : Negatively buoyant jet behavior for complete range of discharge angles $0^\circ \leq \theta_o \leq 90^\circ$ and with variable off-shore slopes θ_B from 0° to 30° . A zero discharge height, $h_o = 0$, is assumed [16].

- (2) Choose a discharge angle $\theta_o = 45^\circ$ for weaker bottom slopes ($\theta_B \leq 15^\circ$) or $\theta_o = 30^\circ$ for stronger slopes. (see step (5) for consideration of port height.)
- (3) Evaluate jet geometry using Fig. 4(a) and 6, respectively.
- (4) Select the offshore location for the discharge in terms of a local water depth H_{ao} (Fig. 3) that guarantees that the upper jet boundary $Z_{\max} \leq 0.75 H_{ao}$, in order to prevent dynamic surface interference.
- (5) Choose a port height $h_o = 0.5$ to 1.0 m. (In a second iteration, the effect of the port height can be considered as an added slope angle when using Fig. 6 in steps (3) and (4)).
- (6) Evaluate the concentration of key effluent parameters at the impingement point using Fig. 7 and compare with applicable environmental criteria or regulations. If the dilution effect is insufficient, a design iteration is necessary.

The above procedure and illustrations apply to a discharge into stationary, non-flowing 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 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 [16]. The CorJet model can be used embedded within the CORMIX expert system [23] that 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 [17], or for sediment currents [18], that includes the dynamics of the downward propagating density current can be used for a complete environmental impact evaluation for the near and intermediate field regions.

5. Conclusions

Sea water desalination plants discharge a concentrated brine effluent into coastal waters. Modern, large capacity plants require submerged discharges, in 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 that is based on very limited laboratory data on dilutions at the level of maximum rise. However, examination of more recent laboratory data and the parametric application of CorJet, a jet integral model within the CORMIX expert system, suggest that flatter discharge angles of about 30° to 45° above horizontal may have considerable design advantages. These relate to better dilution levels at the impingement location, especially if bottom slope on port height are taken into account, better

offshore transport of the mixed effluent during weak ambient current conditions, and the ability to locate in more shallow water near-shore.

However 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. The summary of state of the art design methodologies for brine discharges shows that there is a further need for more experiments that describe the jet evolution and mixing in better resolution. To further corroborate them, a vigorous program of experimental studies using modern field-revolving techniques, such as LIF and PIV, supported by detailed 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.

Furthermore a detailed study of the impingement zone and the far-field mixing is necessary. Even after strong initial jet mixing the heavy effluent generally sinks on the seabed and develops a density current. Depending on topographical features (i.e. channels, submarine valleys or depressions) the density current is strongly limited in its spatial extents resulting in weak mixing and strong benthic impacts. In addition velocities at the sea-floor are small and vertical mixing inhibited by the strong density gradient. The extension of existing models promises better capabilities for future brine discharge assessments.

In addition alternative concentrate management technologies (e.g. recycling or substitution of substances, or treatment of effluents) need to be examined. A summary of experiments, design alternatives and technologies could be given in a design manual for the standardization of concentrate management technologies including optimized outfall-intake designs for desalination plants to mitigate the image of desalination technologies being non-sustainable and expensive technologies regarding the natural sources.

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