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Design and Modeling of Brine Discharge from Desalination Plants

[1]*Jamel Orfi and* [2]*Hesham Fouli*

[1]Department of Mechanical Engineering, King Saud University, P.O. Box 800, Riyadh 11421, KSA
[2]Department of Civil Engineering, King Saud University, P.O. Box 800, Riyadh 11421, KSA

Abstract: The present work discusses aspects of brine discharge in the form of negatively buoyant jets intocalm and non-flowing receiving water.The study is important for the assessment of brine discharges from desalination plants and how they may adversely affect the aquatic environment. A critical literature review shows that such a problem can have three regimes depending on the values of the water depth(H), the discharging nozzle diameter (D) and the densimetric Froude number of the outflow (F).The majority of the previous studies are concerned with the fully submerged jets where the jet trajectory does not hit the water surface. The situation with shallow waters, however, is still not well studied. Preliminary laboratory experimentswith two brine densities, two nozzle diameters and two discharges were performed and their results analyzed. The kinematic, dynamic and geometric properties of the brine jets are compared with previous studies.

Key words: Brine disposal・Buoyant jets・Stratified flow・Environmental quality of desalination plants

INTRODUCTION

Arid regions such as the Gulf Countries including Saudi Arabia suffer from potable water scarcity. This situation has become critical during the last decades due to the important developments in various sectors; particularly the industrial one. Desalination has been identified as an appropriate solution to meet such water demand deficits. Large desalination plants have been constructed to cover these deficits.Desalination technologies, however, suffer from several limitations including high energy consumption and negative environmental impacts associated with the concentrated brine discharged back to sea. Several physical phenomena control the brine discharge into the receiving seawater. The main ones are: dispersion, diffusion, convection and buoyancy. Depending on the relative magnitude of the physical phenomena involved, three regions can be distinguished characterizing the discharge process. The first region, known as the near field region, is situated in the vicinity of the outflow systems. The second region, known as the far field region, is determined by ambient transport mechanisms such as ambient diffusion and advection. An intermediate field separating the near and far fields can also be considered. The investigations concerned with the near field region aim essentially at analyzing the local dynamics and initial dilution of brine plumes at the outflow ports of the desalination plants while those of the far field focus on predicting the final status and position of the plume as it is transported by density driven flows and tidal currents [1].

Several review works have been published describing the three regions and outlining the main findings of previous studies on the fundamentals and practical aspects of brine discharge in those regions [1-5]. Missimer *et al*. [2] focused specifically on concentrated brines discharged from sea water reverse osmosis (SWRO) desalination plants by addressing two important aspects; namely the design of intakes and outfalls and the assessment and reduction of environmental impacts.The studies conducted on the brine discharge subject were generally performed using theoretical (analytical and numerical) models and not too many of them were concerned with experimental, field monitoring and laboratory investigations. Chung *et al*. [6] reviewed the main aspects of brine discharge and management methods from a thermodynamic perspective and zero liquid discharge concept. They analyzed two different ways of managing highly saline brines.

There are various theoretical models proposed and applied for brine discharge problems. Al-Sanea and Orfi [7] presented numerical results for predicting brine and

Corresponding Author: Jamel Orfi, Department of Mechanical Engineering, King Saud University, P.O. Box 800, Riyadh 11421, KSA.

heat dispersion into shallow coastal waters resulting from effluent discharge from an existing desalination/power plant situated on the Arabian Gulf. Other numerical studies have also been conducted to address various aspects of the brine discharge. Examples of these studies can be found in [8, 9]. Palomar *et al*. [10] presented the main theoretical models used to simulate the negatively buoyant jets arising from near field brine discharges. The considered models are *Cormix*, *Visual*, *Plumes* and *Visjet.* Palomar *et al*.[10] analyzed the main assumptions, the capabilities and limitations of those models. They outlined specific conclusions on those models for the cases of single port and multiport jet charges. They reported that several errors have been detected when dealing with the effect of the ambient current direction. Besides, they noticed that some models do not agree with the experimental results. In a review paper, Palomar *et al*.[11] performed comparison and validation tests of those commercial models for the near field region of dense single port jets discharging into both stagnant and dynamic environments. Similarly, Loya-Fernandez *et al*. [12] compared four near field mixing zone models using measurements of brine discharge from a SWRO plant in Spain.

One of the earliest studies on jets behaviors in stagnant fluids with various angles ranging from 30°to 90° above the horizontal is the study of Zeitoun *et al*. [13]. They reported, based on dilution measurements at the maximum rise level of the jet trajectory, that there is an optimum angle of 60° providing the longest trajectory for entrainment and hence the highest dilution. This finding was not shared by Bleninger and Jerka [14] who suggested angles between 30 and 45° that would be design advantageous. Such suggestions were based on the examination of laboratory data and the use of *Cormix*, a jet integral model. Bleninger and Jerka [14] proposed a design procedure applied to discharge into stationary ambient conditions corresponding to negatively jet configurations.

Papakonstantis *et al*.[15] performed experimental tests on inclined turbulent round jets with negative buoyancy discharging in a stationary homogenous fluid. The results obtained from extensive visualization experiments concern essentially a wide range of Froude number and discharge angles (from45° to 90° to horizontal) on the geometrical characteristics of the jets such as the initial and final terminal rise heights. Fair comparisons with the previous results of Zeitoun *et al*. [13] and others have been presented. On another side, Shao and Law [16] noticed that the recommended angle of jet inclination with the bottom (sea bed) is 60° for maximum mixing efficiency. They also concluded that the controlling parameter for the bed influence appeared to be the parameter Z_o/L_M and not Z_o/D as commonly given; Z_o is the distance between the center of the nozzle and the bottom, D is the nozzle diameter and L_M is a jet-plume characteristic length scale. Besides, for 30°, the bed influence became significant when $Z_o/L_M< 0.2$. On the other hand, for60°-inclined dense jets of desalination brine discharges to achieve maximum mixing efficiency,they resulted in a relatively high terminal rise. Therefore, this may be too large for discharges into shallow waters. Shao and Law [16] proposed an experimental investigation on the mixing behavior of dense jets with smaller angles of discharge of 30° to 45° in calm ambient. The obtained results concern two sets based on the geometrical bed proximity (nozzle close or far to side); their results show that the terminal rise height, horizontal distance of the return point and centerline peak location were found to correlate with the Froude number.

The works of Abessi and Roberts [17, 18] are also of interest and importance in clarifying the behavior of dense jet discharges mainly in shallow waters. Abessi and Roberts [17] conducted extensive experiments with nozzles oriented at 30°, 45° and 60°to the horizontal. They identified three flow regimes depending on the value of the dimensionless number DF/H, where D, F and H refer to the nozzle diameter, the Froude number and the water depth respectively. Those regimes are: deep water, surface contact and shallow water. Abessi and Roberts [17] tabulated the obtained values of (DF/H) for transition between the three regimes for nozzle angles of 30°, 45° and 60°. These values show general agreement for angles of 30° and 45° with those of Jiang *et al*. [19]. The presented experimental results of Abessi and Roberts [17] highlighted the complexity of the physical phenomena for the case of shallow water regime. In fact, for the deep water regime, the obtained results agreed fairly with previous published results on fully submerged jets. As DF/H increases (the water depth decreases), the situation becomes more complicated due to the strong interaction of the jet with the water surface.

Based on the above discussed studies on brine discharge problems, one can mention that they concern to a certain limit the case of fully submerged jets for which the results agree in general when describing the main physical phenomena. However, lesser works have been conducted for the cases of shallow waters when the jets can clink to the water surface. The present work discusses results on preliminary laboratory tests on concentrated jets into calm and pure water.

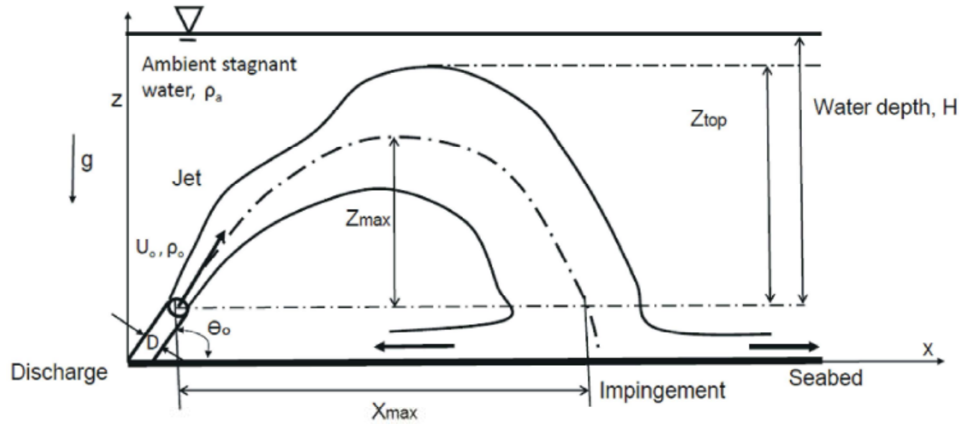

Fig. 1: Schematic side view of negatively buoyant jet discharging into stagnant ambient water

Table 1: Main flux variables for negatively buoyant jets discharging into calm ambient water

Discharge volume flux, Q_o	Momentum flux, M_o	Buoyancy flux, J_o
$Q_o = U_o \pi D^2/4$	$M_o = U_o Q_o$	$J_o = Q_o g(\rho_o - \rho_\alpha)/\rho_o$

Table 2: Main flux variables for negatively buoyant jets discharging into calm ambient water

Discharge length scale, L_Q	Momentum length scale, L_M (jet/plume transition)	Jet densimetric Froude number, F_o
$L_Q = Q_O / M_O^{0.5}$	$L_M = M_O^{0.75} / \lvert M_O \rvert^{0.5}$	$F_O = U_O / (\frac{gD(\rho_O - \rho_a)}{\rho_a})^{0.5}$

Theoretical Background: The discharge phenomenon can be described as follows [14, 17]. The discharged jet with high initial velocity first rises to a maximum level then falls under the negative gravity effect to impinge on the sea bed bottom. The impingement phenomenon has forward, lateral and reverse spreading. For the case of shallow water, the jet can clink the water surface and will spread forward and downward.

Fig. 1 depicts the side view of a negatively buoyant jet discharging into calm receiving water which has depth of H and density of ρ_a. The discharge is characterized by an initial jet velocity U_o and a brine density $\rho_o > \rho_a$. The nozzle has a diameter D and an inclination to the horizontal □$_o$. Therefore, the main flux variables can be evaluated as listed in Table 1.

Three other quantities can also be obtained: a) two length scales; L_Q and L_M characterizing the geometric and mixing characteristics of the turbulent jet and b) the densimetricFroude number; F_o that resembles the traditional open-channel Froude number classifying different flow regimes but using reduced gravity; i.e. $g' = g(\Delta\rho/\rho_a)$. These quantities are defined [14,17] as listed in Table 2.

It is of interest to note that the ratio of L_Q to L_M is related to only Froude number F_o as shown by Eq. 1 [14, 17].

$$\frac{L_Q}{L_M} = Q_o J_o^{0.5} M_o^{-\frac{5}{4}} = (\pi/4)^{0.25}/F \qquad \text{Eq. 1}$$

Design of Experiments and Modeling: Experiments were carried out in the Hydraulics Laboratory of the Civil Engineering Department at King Saud University. Fig.2 shows a schematic diagram of the setup. The setup consists of an elevated steel feed tank for brine storage. The feed tank is 1.50 m long, 0.76 m wide and 0.45 m deep. Brine is discharged intoa receiving fresh water tank that is 1.97 m long, 1.38 m wide and 0.52 m deep. The receiving tank wasplaced at a lower level below the feed tank, such that the brine would flow under the differential head between the water free surfaces in both tanks thougha PVC plastic pipe approximately 3.10 m long. The supply pipe had a valve at the upstream end to start the brine discharge once the salt concentration was adjusted and another valve at the downstream to stop the experiment as steady quasi-steady state was reached. The experiments last for relatively short durations of less than one minute that the water surface fluctuations in both tanks were insignificant.

A vertical pipe attached to a funnel at its upper end was connectedto the supply pipe between the two tanks for the injection of dye to observe and track brine discharge into the receiving tank. An orifice meter was

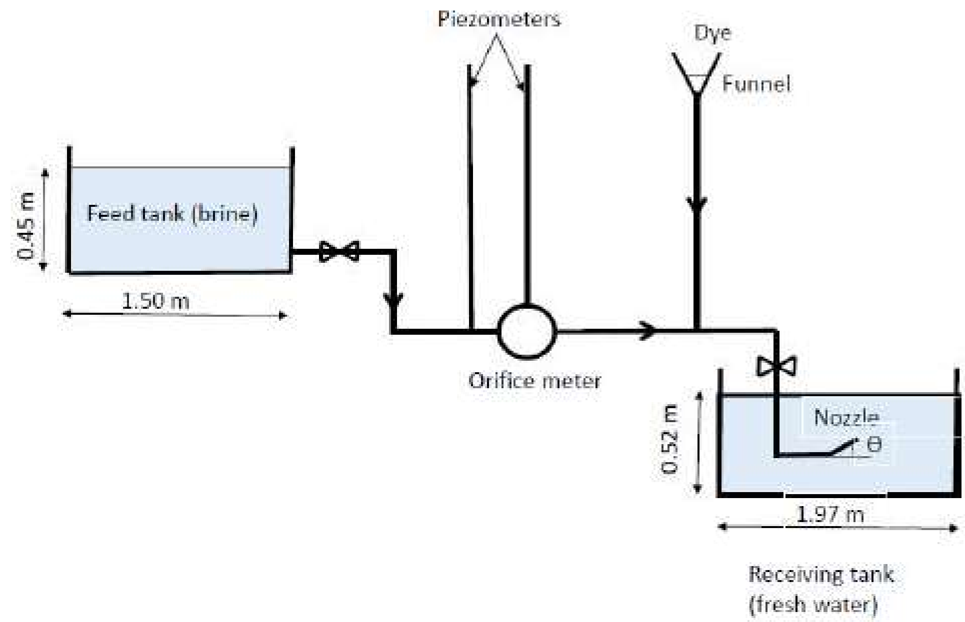

Fig. 2: Schematicside view of the experimental setup

Table 3: List of experiments and their parameters

Experiment No.	Brine density (kg/m^3)	Nozzle diameter (mm)	Brine discharge (l/s)
1	1017.14	4	0.075
2		4	0.18
3		12	0.075
4		12	0.18
5	1036.73	4	0.075
6		4	0.18
7		12	0.075
8		12	0.18

also connected to the supply pipe between the two tanks to measure the brine flow rate. Twovertical piezometers were attached to the orifice meter at standard spacing to calibrate the meter. Calibration was done prior to running the experiments using a pump and weighing different volumes of discharged water from the feed tank and measuring the elapsed times during the discharge using different valve openings. The rating curve between the differential head of the two piezometers and the valve opening was used to estimate the discharges during the experiments. A 5 cm-squares grid was fixed on the glass wall of the receiving tank and the experiments were video-recorded for adequate durations that allowed full development of the jet trajectories; these durations were in the order of 15 s approximately. The videos were then digitized to obtain individual images that were processed to obtain the geometric properties of the jets.

Experiments were performed using two different densities of brine; namely 1017.135 and 1036.731 kg/m^3. The density of brine was calculated using optimized density function of temperature and salinity [20].Two nozzle diameters of 4 mm and 12 mm were used. The water surfaces in both tanks were kept constant by adding equal amounts of brine at the same concentration replacing the discharged brine after each experiment. Likewise, similar amounts of water were removed from the receiving tank to maintain the same surface water level. A combination of 8 experiments wasobtained as presented in Table 3.The angle of inclination was approximately 58° in Exp. 1 – 4 and 69° in Exp. 5 - 8.

RESULTS AND DISCUSSION

Fig. 3a and 3b show sample snapshots from Exp. 1 and 2, respectively. It is seen that the jet hits the free surface and divides into two opposite surface density currents. This indicates it is following the shallow water regime. As the momentum of the current ceases with distance, buoyancy dominates and the effluent falls down towards the tank base.

It is notable though that the upstream extent of the surface current in Exp. 2 did not extend upstream of the nozzle x-location (Fig. 3b). However, in Exp. 1 (Fig. 3a) the nose of the upstream current extended to the x-location of the bottom bend. This is significantly different from Exp. 2 and may be attributed to the smaller discharge in Exp. 1.

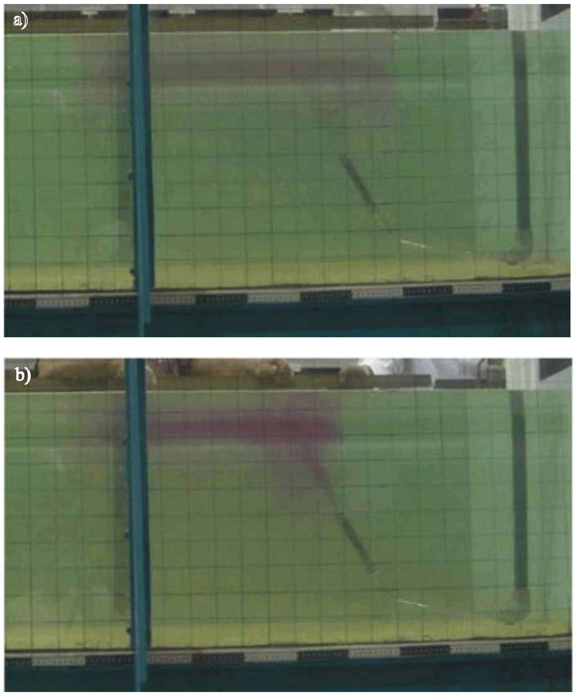

Fig. 3: Snapshots of the jet trajectory from: a) Exp. 1 &b) Exp. 2 (shallow regime)

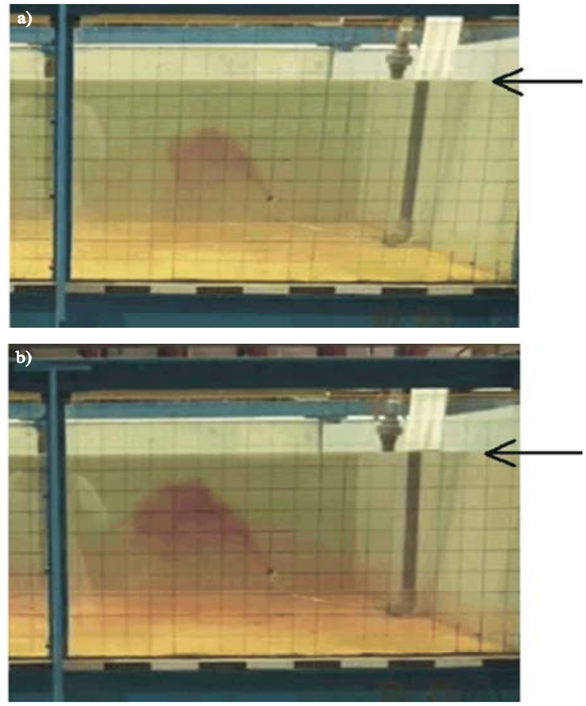

Fig. 4: Snapshotsof the jet trajectoryfrom: a) Exp. 7 &b) Exp. 8 (submerged regime)

Table 4: Kinematic and dynamic properties of the brine discharge jets in the different experiments

Experiment No.	U_o (m/s)	g' (m/s^2)	F_o	R_e	M_o (m^4/s^2)	J_o(m^4/s^3)(x10^{-5})	L_Q (m)	L_M (m)
1	5.97	0.193	215	20,252	4.48x10^{-4}	1.45	0.0035	0.81
2	14.32		516	48,605	2.58x10^{-3}	3.47	0.0035	1.94
3	0.66		14	6,751	4.97x10^{-5}	1.45	0.0106	0.16
4	1.59		33	16,202	2.86x10^{-4}	3.47	0.0106	0.37
5	5.97	0.386	152	16,723	4.48x10^{-4}	2.89	0.0035	0.57
6	14.32		365	40,135	2.58x10^{-3}	6.94	0.0035	1.37
7	0.66		10	5,574	4.97x10^{-5}	2.89	0.0106	0.11
8	1.59		23	13,378	2.86x10^{-4}	6.94	0.0106	0.26

The higher momentum in Exp. 2 due to the larger discharge probably causes most of the flow to move downstream.

Fig. 4a and 4b show sample snapshots from Exp. 7 and Exp. 8, respectively. It is seen that the jet does not reach the free surface and falls back to the floor resembling submerged jet regime. It is also clear that the higher momentum in Exp. 8 led to higher rise of the jet climax point (compare the side arrows at the free surface level on the grid).

Table 4 lists the different parameters governing the kinematics and dynamics of the brine discharge jet in the different experiments. It is obvious that the effect of larger diameter nozzle of 12 mm in Exp. 3, 4 and 7, 8 is significant in reducing and the jet velocity and hence Froude no., which is further reduced by the effect of larger g' for denser brine in Exp. 7, 8.

Table 5 lists the geometric properties of the jets as extracted from the images at the times of full development of the trajectories; i.e. the longest horizontal extents upstream and downstream.

The properties in Tables 4 and 5 were used to estimate the non-dimensional parameters: DF_o /H and X_{max}/dF_o and they are presented in Table 6.

By comparing our results of X_{max}/dF_oin Table 6 to those in Table 7 reproduced from [19], it can be seen that our values are smaller. This is due to our larger inclination angles of 58°and 69° compared to 30° and 45° in Table 7. It is also probably the reason that in our experiments surface backflow upstream current was observed that did not occur in [19].

Table 5: Geometric properties of the fully developed trajectories of the jets in the different experiments (the nozzle mouth is assumed at the origin – see Fig. 1)

Experiment No.	Regime type	X_{max} (cm) (downstream)	X_{max} (cm) (upstream)	Z_{top} (cm)	H (cm)
1	shallow	49.3	-9.9	---	17.5
2	shallow	44.3	-0.8	---	17.5
3	submerged	26.9	---	20	28
4	shallow	20.0	2.5	---	28
5	shallow	44.0	-13.0	---	17.5
6	shallow	34.0	0.0	---	17.5
7	submerged	18.0	---	17.5	28
8	submerged	20.0	---	24	28

Table 6: Values of dF_o/H and X_{max}/dF_o

Experiment No.	DF_o/H	X_{max}/dF_o (downstream)	X_{max}/dF_o (upstream)
1	4.91	0.57	-0.12
2	11.79	0.21	0.00
3	0.59	1.63	---
4	1.42	0.50	0.06
5	3.47	0.72	-0.21
6	8.34	0.23	0.00
7	0.42	1.54	---
8	1.00	0.71	---

Table 7: Comparison of experimental coefficients (reproduced from [19]); x_r herein corresponds to X_{max} downstream in our study; Present study in this Table refers to [19]

	Return point horizontal displacement coefficient	
	x_r/DF	
Study	30°	45°
Present study	2.98	3.0
Lai and Lee (2012)	3.18	3.34
Papakonstantis et al. (2011)	—	3.16
Shao and Law (2010)	3.00	2.83
Kikkert et al. (2007)	3.14 (light attenuation)	3.26 (light attenuation)
Nemlioglu and Roberts (2006)	3.3	3.2
Cipollina et al. (2005)	3.03	2.82

Our values of DF_o/H in Table 6 range from 0.42 to 11.79 which is much bigger than those reported in [17] as larger than 0.64 for 60° inclined jets.

CONCLUSIONS AND RECOMMENDATIONS

Experiments of brine discharge into calm fresh water were studied for two brine densities and two nozzle diameters. The experiments revealed shallow water and submerged jet regimes. Because of the large jet inclination angles, the shallow water regime experiments featured upstream surface backflow density current. The extents of the downstream surface density currents were smaller compared to other experiments of previous studies. These results could be used by coast authorities and environment agencies for the environmental quality assessment of desalination plants.

It is recommended to expand on the current set of experiments by investigation the effect of higher brine densities and other H/D ratios to draw some trends for the brine discharge properties in the different regimes. The presented results may be used for verification of numerical studies of the topic.

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