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Desalination brine disposal by means of negatively buoyant jets

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ABSTRACT

Desalination plants commonly discharge large quantities of brine wastes into the adjacent coastal waters causing potentially harmful environmental impacts. To increase the effluent dilution prior to impingement on the sea floor, disposal by means of upwards inclined dense (negatively buoyant) jets can be applied. This paper presents an overview of experimental results on inclined negatively buoyant jets, focusing on the impact dilution achieved and illustrating its dependence on the jet inclination and the source characteristics, expressed by the densimetric Froude number F_o. It is shown that, in a stagnant ambient, the impact dilution for a certain discharge angle is well linearly correlated to F_o (for F_o, larger than about 20) and increases with the angle but is not very sensitive to it in the practical range between 30° and 75°. Typical dilutions attained are of the order of 50. The effect of ambient flow is also briefly discussed.

Keywords: Desalination; Brine disposal; Negatively buoyant jets; Dense jets; Dilution

1. Introduction

Freshwater scarcity in many arid coastal areas or islands has led to a rapid increase of seawater desalination plants worldwide in recent years. It is estimated that the present combined production capacity of all seawater desalination plants worldwide exceeds 30 million m^3/d and it is expected to double in the next decade. The majority of plants, especially in the Mediterranean region, employ reverse osmosis technology [1]. As a consequence of the desalination process, large quantities of brine effluents are being discharged into coastal waters through many types of outfall systems. Such effluents contain high salt concentrations as well as traces of chemicals, such as chlorine, antiscalants, antifoaming additives, coagulants and metals from corrosion; therefore, they may potentially cause harmful impacts on the benthic marine flora and fauna. A review of relevant environmental impacts is given by Lattemann and Höpner [2]. In areas of high concentration of desalination plants, such as the Persian/Arabic Gulf, the brine effluents may become a major source of land-based marine pollution. Particularly vulnerable are areas with coral reefs, mangrove forests, salt marshes and shallow sandy coasts. An inexpensive way to reduce such impact is to take advantage of the efficient mixing and dilution processes that take place in submerged jets, issuing either through single ports or through multiport diffusers. Since the brine effluents are normally heavier than ambient waters due to the high salt

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content, it is preferable to discharge the jets inclined upwards so as to increase their trajectory and consequent dilution prior to their impingement on the sea bottom.

The use of inclined dense jets for desalination brine disposal has been advanced since the early 1970s and considerable research has been carried out concerning both their geometrical and dilution characteristics. From the environmental point of view, of major importance is the dilution at the impingement point as it determines the highest concentration of any contained harmful substance on the sea floor. Of equal importance may also be the maximum height of rise of the jet: hitting the free surface is generally undesirable for aesthetic reasons and because surface interference modifies the trajectory and may reduce the dilution that would be attained otherwise. This paper presents an overview and comparison of results of relevant experimental studies, illustrating the importance of the discharge angle and the source characteristics and leading to some conclusions concerning the design of brine disposal schemes.

2. Theoretical considerations

In the simplest form, the problem considered concerns the discharge of an effluent of density, ρ_o, through a nozzle of diameter D, with velocity U_o, into a quiescent ambient of density ρ_a ($\rho_a < \rho_o$), at an angle θ_o to the horizontal (Fig. 1). Initially, the jet moves upwards, due to its initial momentum and discharge orientation, until it reaches a terminal height. At that point, the vertical component of jet momentum vanishes and the jet starts to move downwards due to its negative buoyancy until it hits the bottom where it spreads as a density (gravity) current. A photo of such a jet in a laboratory tank is shown in Fig. 2.

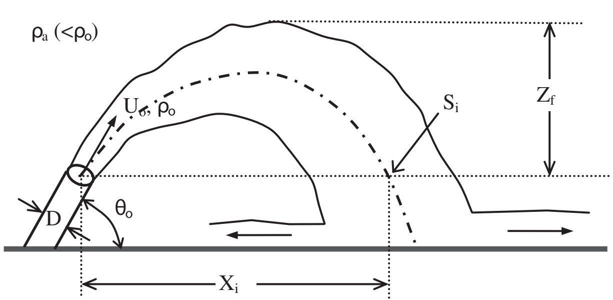

Fig. 1. Problem schematic and notation.

The most important geometrical characteristics of the jet are the terminal height of rise (Z_f) and the return distance (X_i), i.e. the distance where the jet returns to the source elevation, for a horizontal or nearly horizontal bottom, which is practically the distance at which the jet impinges on the bottom. It can be shown [2] that the behaviour of the jet is governed by the non-dimensional initial densimetric Froude number, defined as $F_o = U_o/(g'D)^{1/2}$, where g' is the reduced acceleration of gravity, i.e. $g' = g\cdot(\rho_o - \rho_a)/\rho_o$. If F_o is sufficiently large (larger than about 20), it can also be shown through dimensional analysis [3,4] that the trajectory of the jet, if normalized by dividing the horizontal and vertical coordinates by (DF_o), depends solely on the angle θ_o. Therefore, the maximum height of rise (Z_f) may be expressed in the form:

$$Z_f/(DF_o) = const(\theta_o) \tag{1}$$

Likewise the dilution S, defined as the ratio of initial concentration at the source to the local concentration, normalized by F_o, is also a function of only θ_o. In particular, the minimum impact dilution S_i (strictly, the dilution at the return point) is:

$$S_i/F_o = const(\theta_o) \tag{2}$$

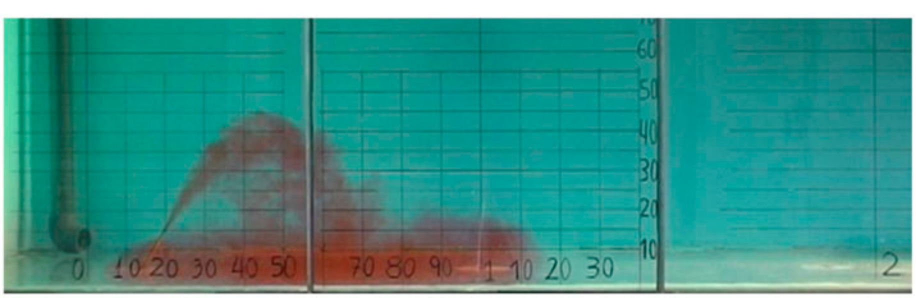

Fig. 2. Photo of a 60˚ inclined negatively buoyant jet in a laboratory tank (from Papakonstantis [5]).

3. Overview of relevant research

3.1. Stagnant ambient

Inclined negatively buoyant jets issuing in calm ambient were first studied by Zeitoun et al. [6]. They presented experimental results for the geometry and the dilution; the latter obtained by extracting certain volumes of fluid from the jet and measuring the dye concentration. As reported, the measurements yielded erratic results; nevertheless, they concluded that the jet inclined at $\theta_o = 60^\circ$ gives the longest path and, consequently, the maximum dilution at the return point. The 60˚ inclined dense jet was considered as an optimal design thereafter and was further studied experimentally by Roberts and Toms [7] and by Roberts et al. [3]. Their results concern the terminal height of rise of the upper boundary, the minimum (centreline) dilution at the terminal height, the distance to the centreline point of impact on the bottom and the respective dilution. Dilutions at the impact point for several jet discharge angles were presented by Nemlioglu and Roberts [8]. Cipollina et al. [9] provided experimental results based on visual trajectory measurements regarding geometrical characteristics of jets discharged at angles 30˚, 60˚ and mostly 45˚ at relatively high F_o (larger than 30). These concern the terminal height of the rise of the upper (outer) boundary, the maximum height of the centreline (jet axis) and the horizontal distance to the centreline maximum height and to the centreline point where the jet returns at the source elevation. Kikkert et al. [10] presented experimental measurements obtained by light attenuation (LA) technique and a semi-analytical model for the geometrical characteristics and dilution for discharge angles up to 60˚. They provided results for the integrated dilution in the transverse direction for the angles 15˚, 30˚, 45˚ and 60˚, according to which the normalized dilution at terminal rise is about the same for $30^\circ \leq \theta_o \leq 60^\circ$. This is contrary to the earlier results of Zeitoun et al. [6], but is supported by model predictions and other experimental studies (Papakonstantis [5]). Jirka [11] carried out a parametric study based on an integral model and concluded that smaller angles, in the range between 30˚ and 45˚, may be better than 60˚ in terms of impact dilution if the bottom slope and port height are taken into account. Papakonstantis et al. [4] studied the geometrical characteristics of jets inclined at 45˚, 60˚, 75˚, 80˚, 85˚ and 90˚, whereas Papakonstantis et al. [12] presented concentration measurements obtained by a micro-conductivity probe and dilution results at the terminal height and at the return point for $\theta_o = 45^\circ$, 60˚ and 75˚; they concluded that the effect of angle in that range was minor. Shao and Law [13] reported experimental results on 30˚ and 45˚ jets through Laser Induced Fluorescence (LIF) and Particle Image Velocimetry (PIV) techniques and discussed the influence of boundary proximity on the development of the jet and the dilutions; they found out that the effect of the boundary is significant for the angle of 30˚ when the height of the source from the bottom is less than about 0.2 (DF_o). Lai and Lee [14] studied jets at angles 15˚, 30˚, 38˚, 45˚, 52˚ and 60˚ mainly with LIF technique and also applied a Lagrangian model to compare and interpret the data. Their results concern the terminal rise height and the respective dilution as well as the dilution at the impact; they found out that the latter is not sensitive to the discharge angle for $38^\circ \leq \theta_o \leq 60^\circ$. Finally, Oliver et al. [15] presented experimental measurements of jet geometry and dilutions in comparison to a proposed integral model.

Besides the experimental research, mathematical modelling of negatively buoyant jets has also received considerable attention. Application of commercial software packages which have been originally developed for positively buoyant jets has shown limited success so far, as reviewed by Palomar et al. [16]. This is due to fundamental differences in the behaviour of negatively buoyant jets, in which buoyancy is opposite to the initial vertical momentum. More recent approaches which involve modifications of traditional formulations or radically different assumptions seem more promising [17] but need further testing. Thus, experimental results are still the basis for quantitative estimates of jet characteristics.

3.2. Effect of current

The effect of ambient flow has been studied to a lesser extent. In that case, an additional non-dimensional parameter besides F_o needs to be taken into account, namely the ratio of the ambient velocity (U_a) to the initial jet velocity (U_o), denoted as $U_r = U_a/U_o$. In most cases, this velocity ratio is combined with the Froude number as a product ($U_r F_o$). Also, the angle φ of the current to the initial plane of the jet (axis) may have some influence on the evolution of the jet.

The earliest study was conducted by Pincince and List [18] for a 60˚ inclined jet in a co-flowing current, whereas Tong and Stolzenbach [19] studied vertical jets and proposed the following expression for the impact dilution:

$$S_i/F_o = c_1 (U_r F_o)^{n1} \quad (3)$$

with $c_1 = 2$ and $n_1 = 1/3$. A much more extensive study by Roberts and Toms [7] included vertical and 60˚ inclined jets and various angles, φ. According to their data, an equation in the form of (3) is valid for $\varphi = 90^\circ$, with $c_1 = 2$ and a larger exponent, $n_1 = 1/2$. They also found out that the dilution increases as φ increases from 0° (opposing current) to 180° (co-flowing current). More recently, Gungor and Roberts [20] focused on vertical jets in relatively weak ambient flows ($0 < U_rF_o < 2$) and determined the values $c_1 = 2.3$ and $n_1 = 1/2$.

Concerning the height of rise, both Roberts and Toms [7] and Tong and Stolzenbach [19] proposed expressions in the form of Eq. (4), based on their experimental results:

$$Z_f/(DF_o) = c_2(U_rF_o)^{n2} \tag{4}$$

Lindberg [21] concluded that the ambient current has no appreciable effect on the jet's geometry for $U_rF_o <$ 0.7, whereas Roberts and Toms [7] suggested that for $U_rF_o > 2$, the normalized height of rise is independent of this parameter. Gungor and Roberts [20] confirmed the validity of Eq. (4) for vertical jets in an ambient flow provided that $U_rF_o > 0.7$ and determined the values $c_2 = 2.5$ and $n_2 = -1/3$.

In general, the presence of ambient flow is favourable: Simple calculations using the above equations show that the ambient current leads to a decrease in the height of rise and increase in dilution at the return point. Therefore, stagnant water conditions should be considered as "worst case" scenario for design purposes.

4. Summary and discussion of experimental results

Table 1 summarizes experimental results reported by various researchers for the maximum height of rise of (the outer boundary of) a negatively buoyant jet in a quiescent ambient for various discharge angles. It is observed that, in most cases, the results of different studies are close to each other. As evident from Fig. 3, the normalized maximum height of rise increases almost linearly with increasing jet inclination up to 75°. However, data from several studies show that the height for the vertical jet ($\theta_o = 90°$) is considerably less than that for 75° and even lesser than that for $\theta_o = 60°$ (Papakonstantis et al. [4]); this is due to the fact that the vertical jet falls on itself, thus impeding the rise. Therefore, it seems that the maximum possible height of rise is attained for θ_o near 75°.

Table 2 presents the results of experimental measurements of minimum (axial) dilutions at the return point of negatively buoyant jets issuing at various angles. The variation of the normalized dilution with the discharge angle is also depicted in Fig. 4. It is seen that there is considerable dispersion between the results of different studies, partly due to the different experimental set-ups and methods and also possibly due to the difficulty in locating the exact measurement point. The values of S_i/F_o appear to increase slightly with increasing angle, although it is noted that in the three studies that measured dilutions for both 60° and 75°, those two values were almost the same. With the exception of the angle of 15°, the values of S_i/F_o are in the range 1.2–1.7; since the usual range of densimetric Froude number recommended in practice is between 20 and 30 [3,11], it follows that the expected (minimum) dilutions will be of the order of 30–50.

The actual dilution at the impingement point on the bottom will generally be higher than the respective value at the return point and will depend on the bottom slope and the height of the port (source) above the bottom. Thus, while the highest dilution at the return point is achieved in the range of θ_o from 60° to 75°, according to Jirka [11], the maximum dilution at the impingement point for moderate bottom slopes shifts to the range of 45°–60° and may be to even smaller angles for steep slopes and/or large port discharge heights. Recent measurements by Nikiforakis

Table 1
Summary of experimental results for the normalized maximum height of rise (Z_f/DF_o)

Study	15°	30°	45°	60°	75°	90°
Papakonstantis et al. [4]			1.58	2.14	2.48	1.91
Lai and Lee [14]	0.44	0.95	1.58	2.08		
Shao and Law [13]		1.05	1.47			
Roberts et al. [3]				2.20		
Cipollina et al. [9]		1.08	1.61	2.32		
Kikkert et al. (LA) [10]	0.52	1.00	1.60	2.05	2.56	
Oliver et al. [15]	0.62	1.15	1.65	2.19	2.50	
Average	0.53	1.05	1.58	2.16	2.51	2.00*

*Average of 12 experimental studies reviewed in Papakonstantis et al. [4].

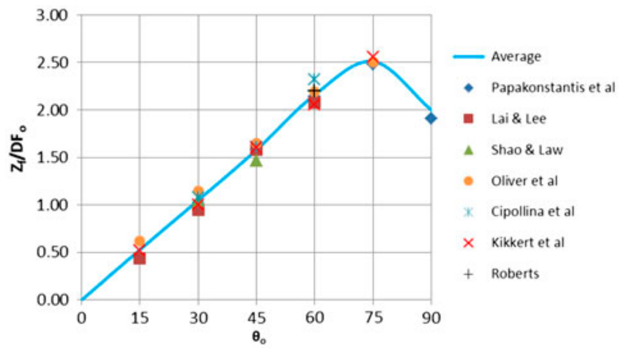

Fig. 3. Variation of normalized rise height with discharge angle.

Table 2
Summary of experimental results for the normalized minimum return point dilution (S_i/F_o)

Study	15°	30°	45°	60°	75°
Papakonstantis et al. [12]			1.55	1.68	1.67
Lai and Lee [14]	0.43	0.82	1.09	1.07	
Shao and Law [13]		1.45	1.26		
Roberts et al. [3]				1.60	
Nemlioglu and Roberts [8]	1.40	1.90	1.70	1.70	1.80
Oliver et al. [15]	0.49	0.84	1.22	1.56	1.54
Average	0.77	1.25	1.36	1.52	1.67

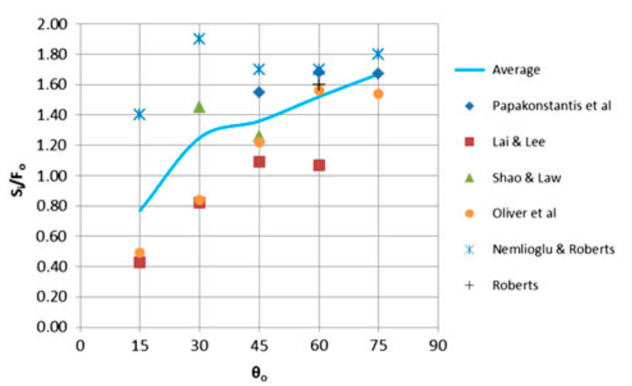

Fig. 4. Variation of normalized return point dilution with discharge angle.

et al. [22] on a 5° slope show the minimum impact dilution ratios S_i/F_o are equal to 2.1 and 2.3 for $\theta_o = 45°$ and 60°, respectively, i.e. considerably higher than the values given in Table 2 for the return point dilution.

Assuming a typical value of initial seawater salinity, 3.5% and double brine salinity, i.e. 7.0%, a dilution of the order of 35 at the impact point implies an excess salinity of about 0.1%, i.e. 1 ppt. This is low enough so as to be tolerated by many marine species, for example, the *Posidonia oceanica*, which is abundant in the Mediterranean Sea [23]. Note that this dilution value, which is easily achievable according to the above, is the minimum at the jet axis at impact, so it is the worst condition to be expected in the vicinity of the outfall.

5. Conclusions

It may be concluded from the above review that upwards inclined negatively buoyant jets are efficient means of reducing impacts on the marine environment due to desalination brine disposal. Their most important characteristic is the dilution at the impact point as it determines the highest concentration of any contained harmful substance on the sea floor. However, the terminal height of rise also needs to be considered so as to locate the source at sufficient depth to avoid the jet hitting the free surface. In general, the presence of ambient flow reduces the terminal height and increases the impact dilution; therefore, the design should be based on stagnant conditions. Available experimental results show that the height of rise increases considerably with increasing discharge angle up to 75°, whereas the minimum return point dilution increases to a lesser degree. Therefore, in deep waters, it is advisable to employ high inclination angles, 60–75°; in shallow areas, use of smaller angles, 30–45°, can also give satisfactory results. In all cases, of major importance is the choice of the port diameter and discharge velocity which determine the initial densimetric Froude number as the dilution is directly proportional to it.

Symbols

c_1, c_2	—	constants
D	—	jet source diameter
g	—	acceleration of gravity
F	—	densimetric Froude number
n_1, n_2	—	constants
S	—	dilution
U	—	velocity
U_r	—	ratio of the ambient velocity to the initial jet velocity
Z_f	—	maximum height of rise
θ_o	—	discharge angle (to the horizontal)
ρ	—	density

Subscripts

a	—	ambient value
i	—	value at impact or return point
o	—	initial value (at the source)

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