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ARTICLE

Minimum return dilution method to regulate discharge of brine from desalination plants

Nadeem Ahmad and Raouf E. Baddour

Abstract: The mixing zone approach in regulating the discharge of brine and other toxic dense discharges has many limitations when applied in environmentally sensitive areas. A well-defined minimum return dilution is advocated in this study as an alternative method to regulate the disposal of brine and other toxic dense discharges. This study examined experimentally the development and dilution of turbulent vertical dense jets (or fountains) at small Froude numbers. The study complements an earlier larger Froude number investigation. The mean and fluctuating temperature fields were measured with fast responding thermocouples, and an emphasis was given to the minimum return dilution, which occurred just outside the edge of the discharge pipe. The study has revealed that at small Froude numbers ($Fr < 5$) the normalized minimum dilution, μ_{min}/Fr, decreased linearly with the Froude number and it became constant only at larger Froude numbers ($Fr > 7$). Simple design equations for the calculations of minimum return dilution and maximum excess temperature and salinity at the level of the source are provided for small and large Froude number regimes. This study also recognized the advantage of using a vertical discharge configuration (inclination $\theta = 90°$ with horizontal) as opposed to an inclined configuration ($0° \leq \theta < 90°$) when discharging brine into water environments. The inclined discharge configuration has the potential of producing higher concentrations of brine and temperature near the source when ambient currents are in a direction opposite to the discharge.

Key words: regulation, brine, fountain, dense jet, minimum dilution, mixing zone.

Résumé : L'approche de la zone de mélange pour régulariser la décharge de saumure et autres décharges toxiques denses présente plusieurs contraintes lorsqu'on l'applique à des régions à environnement sensible. Une dilution de retour minimale est présentée dans cette étude comme autre moyen de régulariser l'élimination de la saumure et des autres décharges toxiques denses. La présente étude a examiné le développement et la dilution de jets denses turbulents verticaux (ou fontaines) utilisant de petits nombres de Froude. L'étude complète une étude antérieure utilisant de plus grands nombres de Froude. La température moyenne et la fluctuation des températures ont été mesurées au moyen de thermocouples à réponse rapide et l'attention a porté sur la dilution de retour minimale, qui survenait tout juste à l'extérieur des rebords du tuyau de déversement. L'étude a révélé qu'en utilisant de petits nombre de Froude ($Fr < 5$), la dilution minimale normalisée, μ_{min}/Fr, diminuait de manière linéaire avec le nombre de Froude et ne devenait constante qu'à de grands nombres de Froude ($Fr > 7$). Des équations simples de conception pour calculer la dilution minimale de retour, la température maximale excédentaire et le niveau de salinité de la source sont fournies pour des régimes de petits et de grands nombres de Froude. La présente étude reconnaît également l'avantage d'utiliser une configuration de décharge verticale (inclination $\theta = 90°$ avec l'horizontal) par rapport à une configuration inclinée ($0° \leq \theta < 90°$) lors de la décharge de saumure dans les environnements aquatiques. La configuration en décharge inclinée risquait de produire de plus fortes concentrations en saumure et une température plus élevée près de la source lorsque des courants ambiants ont une direction opposée à celle de la décharge. [Traduit par la Rédaction]

Mots-clés : régularisation, saumure, fontaine, jet dense, dilution minimale, zone de mélange.

Introduction

Brine, which is warm salty water, is produced as a byproduct during various industrial and mining processes such as desalination, potash mining, and solution mining of salt domes. This paper is mainly concerned with a method to regulate the disposal of negatively-buoyant desalination brine. Figure 1 shows historic and forecast data on world desalination capacity (Global Water Intelligence Report 2006). Worldwide desalination has increased exponentially in the last decades. Worldwide desalination capacity has reached 64 million m^3/d in 2010 and is projected to reach 98 million m^3/d by the year 2015 (Global Water Intelligence Report 2006). Brine is usually disposed into the sea where high salinity and temperature of desalination brine have negative impacts on marine life (Jirka 2008). Extensive body of environmental research (Einav et al. 2002; NOAA 1978; Gacia et al. 2007; Matsumoto and Martin 2008; Talavera and Ruiz 2001; Pillard et al. 1999; Mabrook 1994) has shown that even a small increase of salinity may be harmful to marine life.

Submerged discharge methods for disposal of brine into the sea are nowadays considered the best practical solutions, as they have high diluting capabilities (Jirka 2008). Figure 2 shows a typical submerged brine diffuser system at the end of a long pipe line connected to a desalination plant. Two mixing zones can be identified in the area surrounding the discharge: (*i*) near-field mixing zone and (*ii*) far-field mixing zone. Near-field mixing zone is also known as the zone of immediate dilution (ZID), toxic dilution zone (TDZ), and acute mixing zone (AMZ). We define in this study the radius of the near-field mixing zone as the radius of the fountain at the level of the source ($z = 0$). For large Froude number fountains ($Fr > 7$), the radius of the fountain at the level of the

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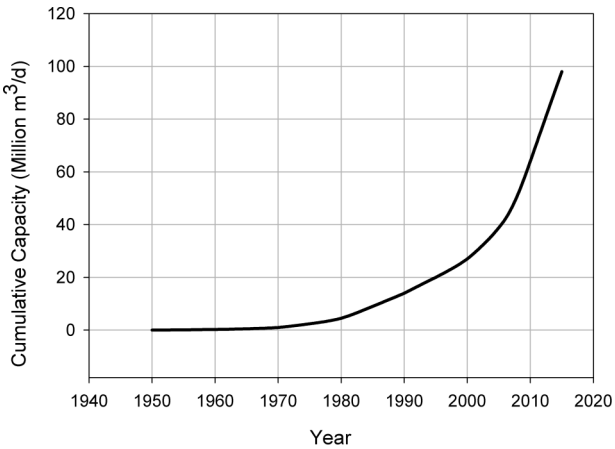
Fig. 1. Global desalination capacity.



source was about 1.40 r_0Fr, were r_0 is the radius of the source (Ahmad and Baddour 2012). Dilution in the near-field mixing zone depends mainly on the discharge Froude number, while the dilution in far-field mixing zone depends also on ambient currents, tides, and turbulence, which are often variable, uncertain or unpredictable. Near-field mixing zone is, therefore, important to designers and engineers, since dilution in this region can be modelled and controlled.

The first objective of this work was to analyse and report new dilution data obtained at the level of the source of low Froude number vertical fountains. These new dilution data complement earlier data obtained for larger Froude number fountains by Ahmad and Baddour (2012).The second and more important objective was to use the dilution data to develop a method based on minimum return dilution for regulating and monitoring brine discharges from desalination plants. The minimum return dilution method, which depends only on the discharge Froude number, can be used in practice as an alternative to the well-known mixing zone approach. The final objective of this work was to examine dilution data published in the literature on inclined fountains and compare the dilution of vertical and inclined fountains in the presence of co-currents and counter-currents.

Mixing zone and minimum return dilution methods

The concept of mixing zone is widely used in North America to regulate pollutant and toxic discharges. Mixing zones are stipulated to protect human health, aquatic habitat, and the water body as a whole (IMDs 2007). The allocation of a mixing zone around a discharge point of brine is an economical strategy. However, several governmental documents in North America (US EPA 1994; Rutherford et al. 1994; IMDs 2007; CCME 2008) recognize that the mixing zone approach may have limitations in case of brine discharges in sensitive areas, such as areas close to drinking water intakes, fish habitat, recreation, and sensitive biota. Disposal of brine in sensitive areas requires a minimal size of mixing zone. Moreover, mixing zones are not allowed for some dense effluents such as mining and oilfield brines, which contain toxic substances.

Under this background, it is proposed to apply the concept of minimum return dilution measured immediately outside the edge of a vertical source of brine as a method to regulate the discharge of brine in environmentally sensitive areas. This concept, illustrated in Fig. 3, can replace the less defined mixing zone approach and could help address more stringent end of pipe criteria for toxic discharges. The brine in Fig. 3 is discharged vertically upward through a riser forming a dense fountain. The brine rises in the fountain due to its initial momentum and then falls back and spreads on the seabed due to its negative buoyancy.

Methodology

Ahmad and Baddour (2012) conducted a hydraulic model investigation of a negatively buoyant vertical discharge by matching the field and laboratory densimetric Froude numbers. The discharge densimetric Froude number is defined as

$$Fr = \frac{U_0}{\sqrt{g_0' r_0}} \tag{1}$$

where U_0 is the discharge velocity, r_0 is the radius of discharge nozzle, $g_0' = g((\rho_0 - \rho_a)/\rho_a)$ is the discharge buoyancy (or effective gravity), g is the gravity, ρ_0 is the discharge density, and ρ_a is the ambient water density.

It is well understood that a well-defined dilution of brine takes place within the fountain. Dilution is principally responsible for the reduction of temperature and salinity within the finite volume of the fountain. Conserving heat and salt in the fountain, a simple definition for the dilution at any point is

$$\mu = \frac{\Delta T_0}{\Delta T} = \frac{\Delta S_0}{\Delta S} \tag{2}$$

where $\Delta T = T - T_a$ and $\Delta S = S - S_a$ are, respectively, the excess temperature and excess salinity of the brine above the ambient values T_a and S_a; ΔT_0 and ΔS_0 are the initial excess temperature and excess salinity at the point of discharge. According to eq. (2), the minimum dilution is associated with maximum temperature and salinity. And, as shown in Fig. 3, the minimum dilution at the level of the source occurs at the outer edge of the riser (Ahmad and Baddour 2012). This minimum value of dilution at $z = 0$ is referred to as minimum return dilution. It represents a worst case scenario for the dilution in calm water. The minimum return dilution provides a simple and reliable method to regulate and monitor the discharge of brine in sensitive areas. The minimum return dilution at the source of a vertical fountain is conservative and can be easily modeled in the laboratory and monitored in the field. The minimum return dilution at the source is essentially reducing regulatory mixing zones to the edge of the riser, and may therefore replace the less defined toxic dilution zone (TDZ) and more stringent end of pipe criteria.

For large Froude numbers, Ahmad and Baddour (2012) found the normalized minimum return dilution at the outer edge of the nozzle to be

$$\frac{\mu_{\min}}{Fr} = 0.581 \quad \text{for } Fr > 7 \tag{3}$$

This equation provides a simple modeling tool to design large Froude number vertical fountains of brine to comply with any required regulatory minimum return dilution at the source. This modeling tool will be extended in eq. (7) of this paper to low Froude number discharge conditions.

Note, salinity and temperature are only controlled by dilution in the immediate vicinity of the source. Accordingly, the maximum excess salinity, $\Delta S_{\max}$, and maximum excess temperature, $\Delta T_{\max}$, at the outer edge of the discharge pipe, relative to the ambient water, can be calculated using the following equations, which are obtained by conserving heat and salt in the vertical fountain (Ahmad and Baddour 2012)

$$\Delta S_{\max} = \frac{\Delta S_0}{\mu_{\min}} \tag{4}$$

Fig. 2. A typical submerged brine diffuser system showing a vertical dense fountain and mixing zones in calm water.

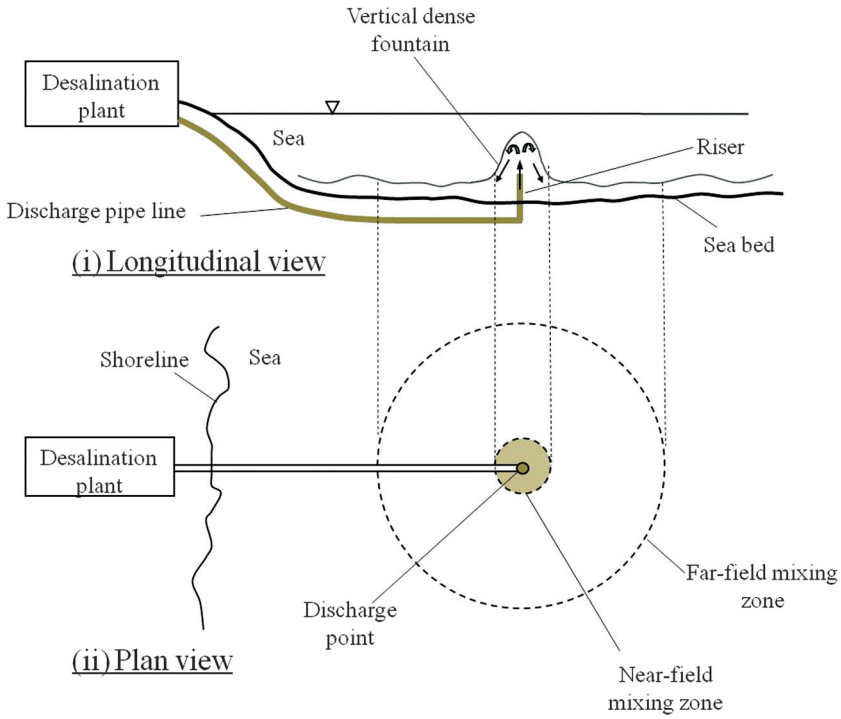
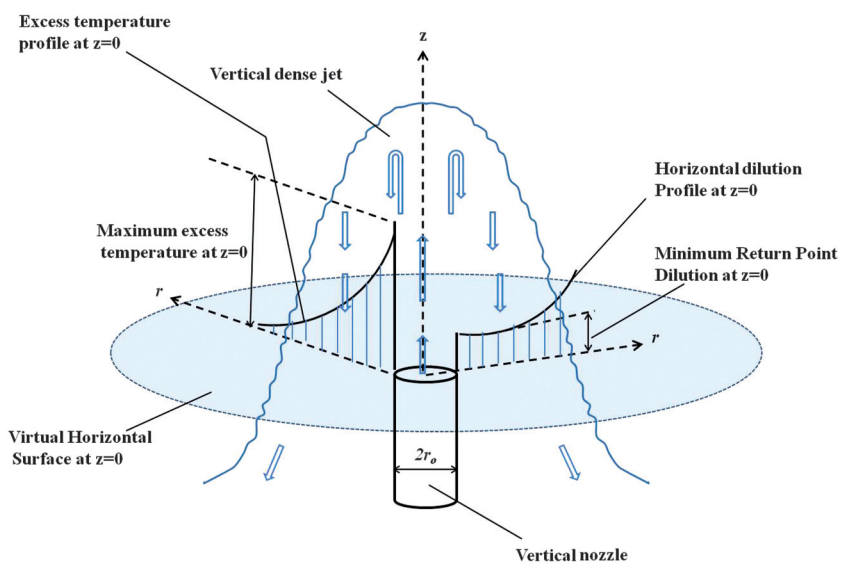


Fig. 3. Definition sketch of a vertical dense fountain illustrating the concept of minimum return dilution at the outer edge of the riser.



$$\Delta T_{\max} = \frac{\Delta T_0}{\mu_{\min}} \tag{5}$$

where ΔS_0 is the initial excess salinity and ΔT_0 is the initial excess temperature, both calculated at the point of discharge. Eliminating $\mu_{\min}$ using eq. (3), the maximum excess salinity and maximum excess temperature at the outer edge of the riser of a large Froude number fountain can be determined directly using the following equation

$$\frac{\Delta S_{\max}}{\Delta S_0} = \frac{\Delta T_{\max}}{\Delta T_0} = \frac{1.72}{Fr} \quad \text{for } Fr > 7 \tag{6}$$

Experiment

The present experimental study is extending the earlier work by Ahmad and Baddour (2012) to low Froude number fountains ($Fr < 7$). The low Froude number tests were performed in the same apparatus described by Ahmad and Baddour (2012). The thermocouples used in this study were 0.1 mm in diameter and their frequency response exceeded 10 Hz, which was adequate in capturing the turbulent temperature fluctuations inside the fountain.

Three series of experiments were conducted in this study. Only the two series of experiments (I and III) related to dilution measurements obtained at the level of the source of vertical fountains are reported in this paper. Table 1 summarizes the testing condi-

Table 1. Summary of experimental conditions.

Experiment series	Objective	Radius of nozzles r_o (mm)	Number of measuring points	Number of tests	Densimetric Froude No. *Fr*	Reynolds No. *Re*
I	Minimum dilution	17.25	4	18	0.96–6.7	2993–6232
III	Horizontal profiles	8.75	10	5	3.43–7.25	2253–4989

Note: T >15 °C.

tions of Experiment Series I and Series III. As seen in Table 1, turbulent flow conditions were maintained with discharge Reynolds numbers *Re* ranging from 2253 to 6232. The smallest Froude number *Fr* was 0.96 and the largest was 7.25. The two series of experiments related to the dilution at the level of the source are described in the following.

Experiment Series I was designed to establish the relationship between the minimum dilution and discharge Froude number. To improve accuracy, the minimum dilution was measured directly with four equally spaced thermocouples around the nozzle at the level of the source. To keep turbulent flow conditions at very low *Fr*, a larger diameter nozzle (r_0 = 17.25 mm) was used. A total of 18 tests were performed in Experiment Series I with *Fr* ranging between 0.96 and 6.7.

Experiment Series III was designed to gather detailed excess temperature profiles for low Froude number experiments on the horizontal surface (z = 0) and confirm the location of minimum return dilution. The required temperature data for this series were captured with a horizontal profiler made of 10 thermocouples deployed at z = 0. The horizontal thermocouple profiler was placed on one side of the edge of the nozzle and five experiments with different Froude numbers ranging from 3.43 to 7.25 were performed.

Furthermore, in all the experiments, a thermocouple was placed inside the nozzle and another one in the ambient water away from the fountain. These additional thermocouples continuously monitored the temperature of the discharge and ambient water.

Results and discussion

Horizontal profile analysis and minimum return dilution

The horizontal profiles obtained at the level of the source (z = 0) are analyzed in Figs. 4, 5,6, and 7. In Fig. 4, mean horizontal excess temperature profiles of low Froude number fountains are compared with corresponding profiles of high Froude number fountains by Ahmad and Baddour (2012). The mean horizontal excess temperature profiles have similar shapes at low and high Froude numbers with maximum values always occurring just outside the edge of the nozzle. In practice, we can assume, therefore, that the minimum return dilution occurs always at the outer edge of the nozzle. The data also suggest a reduction of fountain radius at the level of the source from $b_0 = 1.4\, r_0 Fr$ at high Froude number to $b_0 = 1.0\, r_0 Fr$ at low Froude number. The radius b_0 defines the impact zone of the fountain at the level of the source. Note, however, that the largest impact at the level of the source is always at $r - r_0 = 0$ (i.e., just outside the nozzle), where the excess temperature and excess salinity have maximum values (ΔT_{max}, ΔS_{max}) and where the dilution is minimum (μ_{min}). This behavior is clearly shown by the dilution profiles plotted in Fig. 5.

More detailed analyses of temperature fluctuations were carried out by determining the turbulent intermittency and turbulent intensity. The horizontal profiles of intermittency and turbulence intensity are presented in Figs. 6 and 7. The intermittency profiles in Fig. 6 indicate fluctuations of fountain radius between about 0.5 and 1.5 $r_0 Fr$. Visually, it was observed that the turbulent boundary of the fountain at the level of the source was more stable than the vertical front of the fountain. This observation would explain why the horizontal turbulent intensity profile in Fig. 7 does not have a pronounced peak value near the edge of the fountain. In comparison, a pronounced peak of turbulent intensity was found associated with the more unstable vertical front of the fountain.

Fig. 4. Horizontal excess temperature profiles at the level of the source (z = 0) for small and large Froude number fountains.

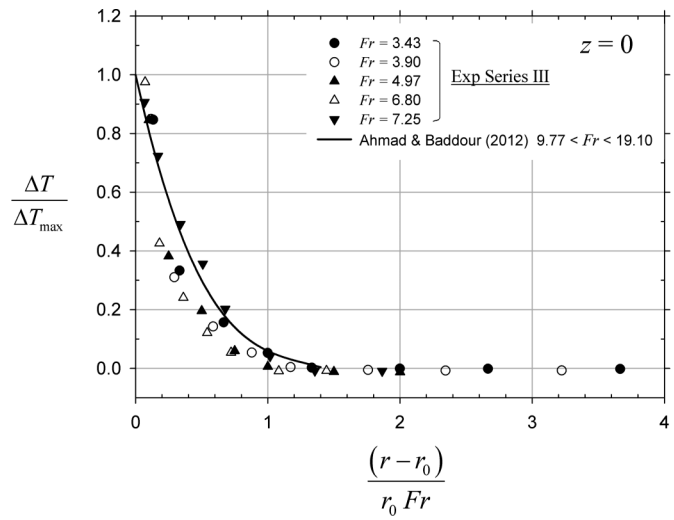
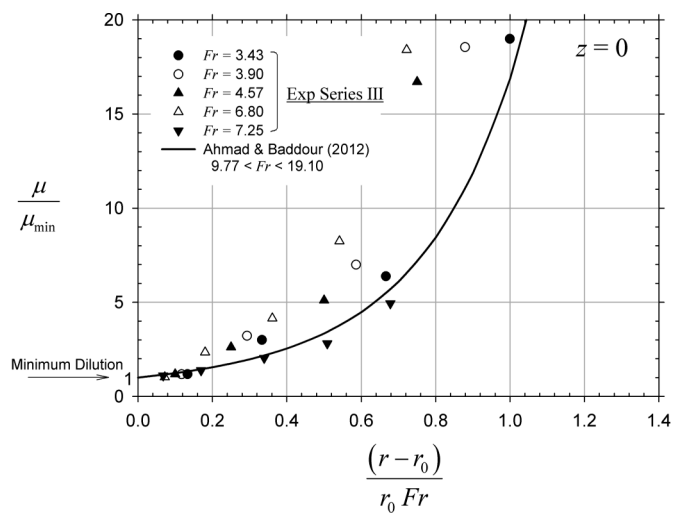


Fig. 5. Horizontal dilution profiles at the level of the source (z = 0) for small and large Froude number fountains.



The results for the normalized minimum dilution μ_{min}/Fr plotted versus *Fr* are presented in Fig. 8. Evidently, the low Froude number fountains have a significantly different behaviour than the high Froude number fountains. While for high Froude number fountains μ_{min}/Fr was constant, for low Froude number fountains μ_{min}/Fr decreased with the Froude number. A best linear fit of the low Froude number data in Fig. 8 is

$$\frac{\mu_{min}}{Fr} = 1.24 - 0.15\, Fr \quad \text{for } Fr < 5 \tag{7}$$

Fig. 6. Horizontal intermittency profiles at the level of the source (z = 0) for small Froude number fountains.

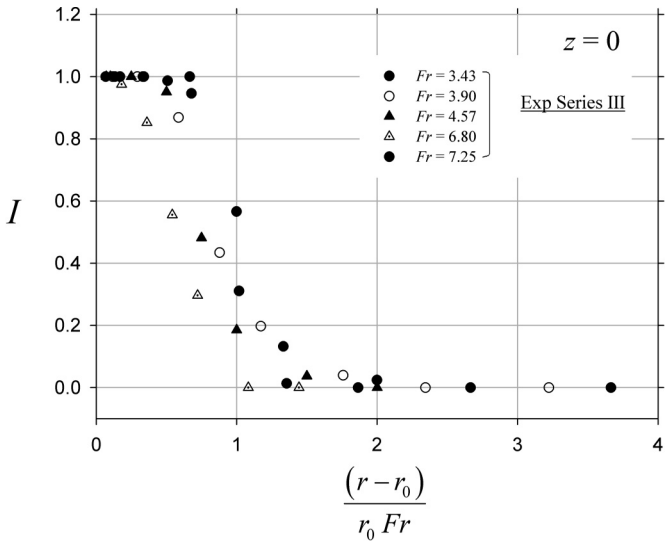
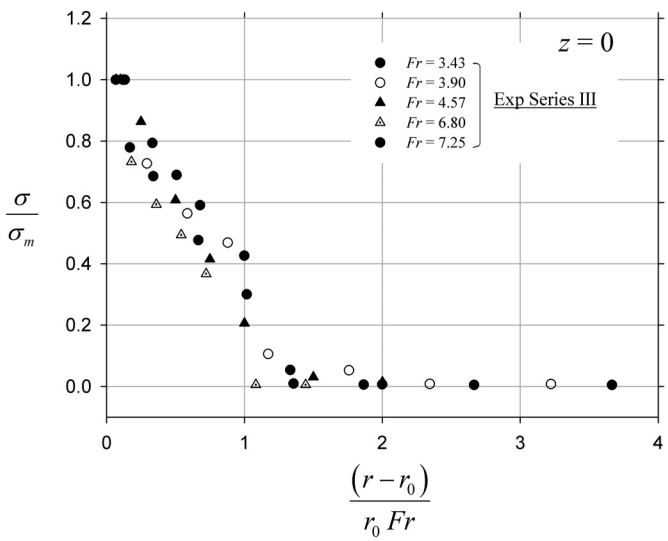


Fig. 7. Horizontal turbulence intensity profiles at the level of the source (z = 0) for small Froude number fountains.



Note, for all practical purposes the high Froude number behavior given in eq. (3) may be used for $Fr > 5$. Also the minimum dilution in Fig. 8 obtained using the horizontal temperature profiles of Experimental Series III would suggest a lower asymptote behavior for high Froude number fountains than obtained by Ahmad and Baddour (2012). The closely spaced array of probes in the present study has allowed measurements of temperature closer to the nozzle than in Ahmad and Baddour (2012) (i.e., larger temperature and lower dilution at the outer edge of the nozzle).

Equations (3) and (7) provide a pair of modeling equations that can be used to design a vertical fountain of brine to comply with any required regulatory minimum return dilution.

Furthermore, the normalized maximum excess temperature data ($\Delta T_{max}/\Delta T_0$) for low and high Froude number fountains are plotted in Fig. 9 versus the Froude number (Fr) using a logarithmic scale. There is a clear demarcation in Fig. 9 between low and high Froude number behaviour. The power-law trend lines drawn in Fig. 9, for the low and high Froude number regimes, are, respectively,

Fig. 8. Minimum return dilution for small and large Froude number fountains.

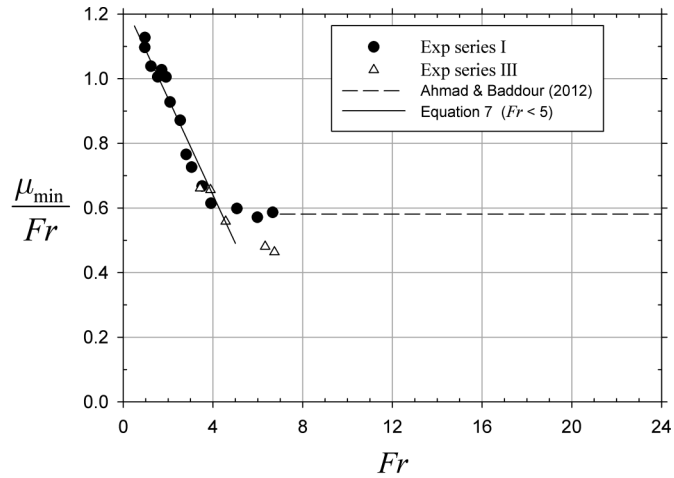
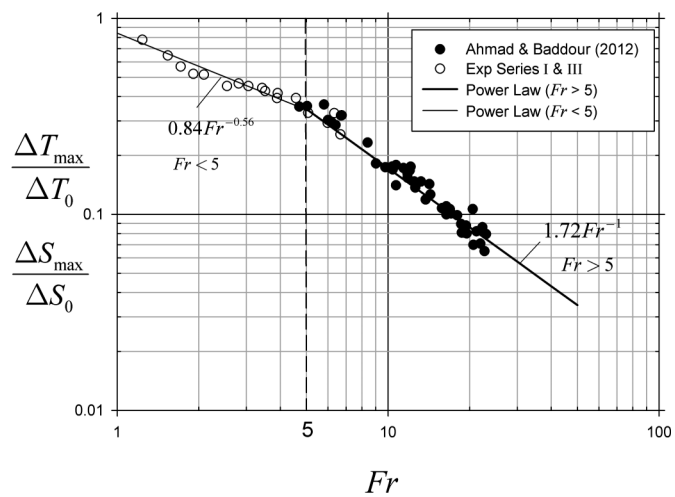


Fig. 9. Maximum excess temperature (or salinity) at the level of the source for small and large Froude number fountains.



$$\frac{\Delta T_{max}}{\Delta T_0} = \frac{\Delta S_{max}}{\Delta S_0} = 0.84\ Fr^{-0.56} \quad \text{for } Fr < 5 \quad \text{and} \tag{8}$$

$$\frac{\Delta T_{max}}{\Delta T_0} = \frac{\Delta S_{max}}{\Delta S_0} = 1.72\ Fr^{-1} \quad \text{for } Fr > 5 \tag{9}$$

Equations (8) and (9) could be used to predict the maximum excess temperature and salinity in the near field of any vertical fountain. These equations are particularly useful when environmental regulations are stipulated in terms of allowable excess temperature and excess salinity above prevailing ambient conditions.

Minimum return dilution for inclined dense discharge

The basic properties of inclined dense discharges have been extensively studied (Zeitoun et al. 1970; Pincince and List 1973; Chu 1975; Roberts and Toms 1987; Roberts et al. 1997; Nemlioglu and Roberts 2006; Kikkert et al. 2007; Gungor and Roberts 2009; Shao and Law 2010; Marti et al. 2011; Papakonstantis et al. 2011; Lai and Lee 2012). It is well understood that the minimum dilution at $z = 0$ for an inclined discharge is located some distance away from the source and in the central region of the returning fountain (see Fig. 10). This minimum return dilution is a function of the

Fig. 10. Definition sketch of an inclined dense fountain showing the minimum return dilution at some distance away from the source.

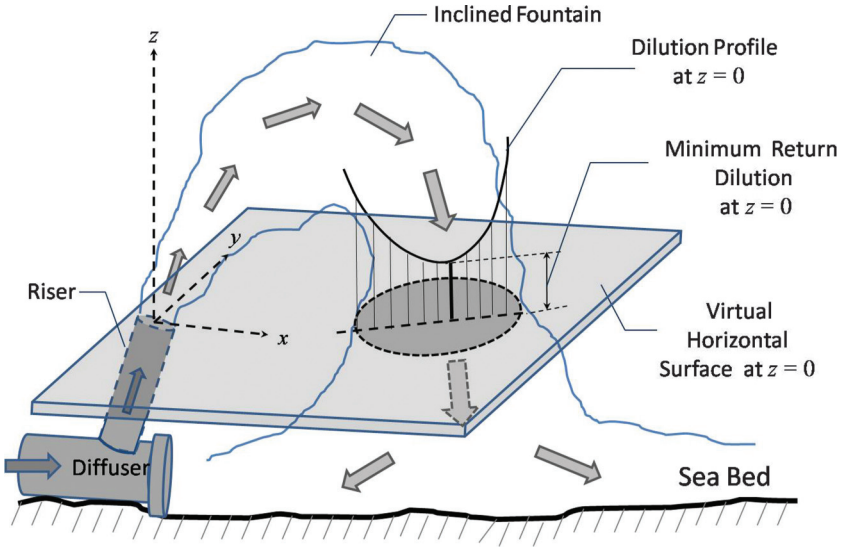
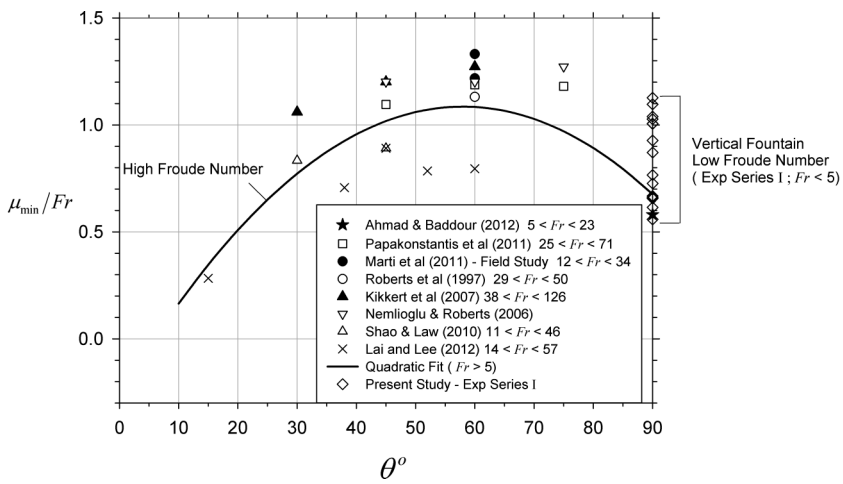


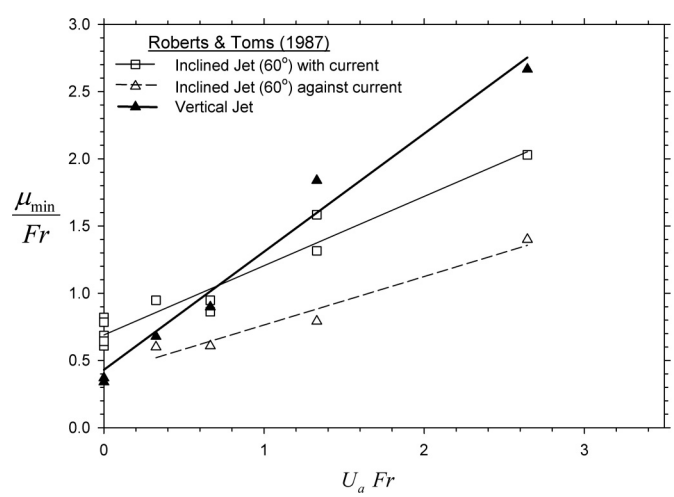
Fig. 11. Effect of discharge orientation on minimum return dilution of dense fountains in calm water.



discharge Froude number Fr and the angle θ of the discharge with the horizontal.

The normalized minimum return dilution (μ_{min}/Fr) obtained in previous studies of inclined dense fountains in calm water (Roberts et al. 1997; Nemlioglu and Roberts 2006; Kikkert et al. 2007; Shao and Law 2010; Marti et al. 2011; Papakonstantis et al. 2011; Lai and Lee 2012) is plotted in Fig. 11 versus the angle θ. For completeness, the present low Froude number data (Exp Series I) and high Froude number data of Ahmad and Baddour (2012) for vertical fountains ($\theta = 90^o$) are also plotted in Fig. 11. Understandably, the present low Froude experiments at $\theta = 90^o$ are showing a large range in dilution due to effect of Froude number, as explained in Fig. 8. Also all previous inclined jet data in Fig. 11 correspond to high Froude number jets. The quadratic fit to high Froude number behavior shown in Fig. 11 suggests a maximum value of μ_{min}/Fr when θ is about 60°. This maximum value is almost twice the dilution of a high Froude number vertical fountain. Of course, when calm water is prevailing all the time, an inclined fountain will achieve a higher return dilution than the vertical fountain. However, a problem with the inclined fountain may occur when the ambient current in the area of the discharge is not constant, or changes in direction with tides and winds along and (or) perpendicular to the shore. In this case, it is possible that the inclined fountain may achieve a smaller return dilution than

Fig. 12. Effect of discharge orientation on minimum return dilution of dense fountains with varying velocity currents and directions.



the vertical fountain. As demonstrated below, smaller dilutions compared to vertical fountains may occur with strong co-currents and weak counter-currents.

The data of Roberts and Toms (1987) are plotted in Fig. 12 to demonstrate the effect of current strength and direction on the return dilution of vertical ($\theta = 90°$) and inclined ($\theta = 60°$) fountains. Figure 12 shows that dilution of the inclined fountain ($\theta = 60°$) is higher when oriented with the current than against the current. Also, the return dilution achieved by the inclined fountain when oriented against the current can be seen to be less than the dilution achieved by a vertical fountain. It is also interesting to note in Fig. 12 that the vertical fountain is achieving the highest dilution at high velocity currents. In the presence of tides and variable along-shore currents, it is advisable, therefore, to discharge the brine vertically upwards to take full advantage of the currents in any direction.

Conclusion

Desalination plants are the main source of brine discharges. With the continuous increase of desalination capacity in the world, brine disposal is intensifying and becoming a major global environmental concern. It is now well recognized that even small excess salinities and temperatures above seawater standard values may cause harmful effects on marine life.

Several governmental documents in North America (US EPA 1994; Rutherford et al. 1994; IMDs 2007; CCME 2008) have recognized the limitations of mixing zones in sensitive areas, such as areas close to drinking water intakes, fish habitat, recreation, and sensitive biota.

The concept of minimum return dilution at the source is proposed to control the salinity and temperature of brine in environmentally sensitive areas. This concept would also be suitable for regulating toxic brine and other negatively-buoyant industrial discharges. This study showed that the minimum return dilution of a vertical fountain of brine in calm water (worst case scenario) occurs always at the outer edge of the discharge pipe. Equations (3) and (7) can be used to determine, respectively, the minimum return dilution of large and small Froude number fountains.

For variable ambient current conditions caused by wind, tides and along shore currents, it is recommended to discharge the brine vertically upwards. This design avoids possible higher than normal concentrations of brine on the sea bed, while taking full advantage of the currents in any direction.

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